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# The Cost of Jointness: Insights from Environmental Monitoring Systems in Low-Earth Orbit

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Prepared by
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# The Cost of Jointness: Insights from Environmental Monitoring Systems in Low-Earth Orbit

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Research done under the MIT-Sandia Excellence in Engineering Fellowship for

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**Abstract**

This report summarizes the results of doctoral research that explored the cost impact of acquiring complex government systems jointly. The report begins by reviewing recent evidence that suggests that joint programs experience greater cost growth than non-joint programs. It continues by proposing an alternative approach for studying cost growth on government acquisition programs and demonstrates the utility of this approach by applying it to study the cost of jointness on three past programs that developed environmental monitoring systems for low-Earth orbit. Ultimately, the report concludes that joint programs' costs grow when the collaborating government agencies take action to retain or regain their autonomy. The report provides detailed qualitative and quantitative data in support of this conclusion and generalizes its findings to other joint programs that were not explicitly studied here. Finally, it concludes by presenting a quantitative model that assesses the cost impacts of jointness and by demonstrating how government agencies can more effectively architect joint programs in the future.

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# Terminology

**ADCS|** Attitude Determination and Control Subsystem
*A spacecraft subsystem.*

**AEHF |** Advanced Extremely High Frequency
*DoD communications satellite system.*

**AFWA |** Air Force Weather Agency
*One of the four NPOESS Centrals.*

**AIRS |** Atmospheric Infrared Sounder
*Infrared sounder on NASA's EOS; predecessor to NPOESS's CrIS.*

**AMSU-A |** Advanced Microwave Sounding Unit
*Cross-track microwave sounder on NASA's EOS & NOAA's POES; predecessor to NPOESS's ATMS.*

**AMSU-B |** Advanced Microwave Sounding Unit
*Cross-track microwave sounder on NASA's EOS & NOAA's POES; predecessor to NPOESS's ATMS.*

**AMSR-E |** Advanced Microwave Scanning Radiometer-EOS
*Conical microwave imager-sounder on NASA's EOS; predecessor to NPOESS's CMIS.*

**AT&L |** Acquisition, Technology, and Logistics
*Division in the Offie of the Secretary of Defense that is responsible for acquiring systems for the DoD.*

**ATMS |** Advanced Technology Microwave Sounder
*NPOESS cross-track microwave sounder that was procured by NASA.*
**APS |** Aerosol Polarimetry Sensor
*NPOESS instrument that was added in the IORD-II but deleted after Nunn-McCurdy.*
**AVHRR |** Advanced Very High Resolution Radiometer
*Visible-infrared radiometer on NOAA's POES; heritage predecessor to NPOESS's VIIRS.*
**C3 |** Command, Control, and Communications Segment
*Component of the NPOESS ground system.*
**CDR |** Critical Design Review
*Milestone in a typical acquisition program.*
**CERES |** Clouds and the Earth's Radiant Energy System
*Earth radiation budget sensor on NASA's EOS; heritage predecessor to NPOESS's ERBS.*
**CGS |** Common Ground System
*The shared JPSS-DWSS ground system that was established after NPOESS was cancelled.*
**CLASS |** Comprehensive Large Array-Data Stewardship System
*NOAA's storage facility for environmental data.*
**CMIS |** Conical Microwave Imager Sounder
*Conical microwave imager-sounder on NPOESS.*
**CrIS |** Cross-Track Infrared Sounder
*Cross-track infrared sounder on NPOESS.*
**DCS |** Data Collection System
*Non-EDR producing instrument on NPOESS that was also on NOAA's POES.*
**DMSP |** Defense Meteorological Support Program
*DoD's operational weather satellite program; predecessor to NPOESS.*
**DoC |** Department of Commerce
*One of the three collaborating agencies on the NPOESS program; the DoC houses NOAA.*
**DoD |** Department of Defense
*One of the three collaborating agencies on the NPOESS program.*
**DoE|** Department of Energy
*Government agency that participated in the joint Fermi program.*
**DoT|** Department of Transportation
*Government agency that participates in the joint GPS program.*
**DSP|** Defense Support Program
*Satellite system supporting missile early-warning; predecessor to SBIRS.*
**DWSS |** Defense Weather Satellite System
*The DoD's weather satellite program after NPOESS was cancelled.*
**EDR |** Environmental Data Record
*Final data product produced by the NPOESS system; specified by the IORD.*
**EMI |** Electromagnetic Interference
*A type of interaction that induces architectural complexity on spacecraft.*
**EOS |** Earth Observing System
*NASA's climate science satellite program; predecessor to NPOESS.*
**ERBS |** Earth Radiation Budget Sensor
*Earth radiation budget instrument on NPOESS.*
**ESPC |** Environmental Satellite Processing Center
*NOAA's system that interfaced with the IDPS and housed the NDE.*
**EXCOM |** Executive Committee
*Highest decision making body on the NPOESS program.*
**EUMETSAT |** European Organization for the Exploitation of Meteorological Satellites
*Consortium of European nations that supplies environmental data.*
**FNMOC |** Fleet Numerical Meteorology and Oceanography Center
*One of NPOESS's four Centrals.*
**GAO |** Government Accountability Office

*Independent agency that conducts oversight and investigations for Congress.*

**GOES|** Geostationary Operational Environmental Satellite
*NOAA's environmental monitoring satellite in geostationary orbit.*

**GPS |** Global Positioning System
*DoD navigation and timing satellite system.*

**GSFC |** Goddard Space Flight Center
*NASA Center responsible for managing programs like EOS, POES, and NPP.*

**HIRS |** High Resolution Infrared Sounder
*Cross-track infrared sounder on NOAA's POES; predecessor to NPOESS's CrIS.*

**IDPS |** Interface Data Processing Segment
*Component of the NPOESS ground system.*

**IORD |** Integrated Operational Requirements Document
*NPOESS's requirements document that defined the program's EDRs*

**IPO |** Integrated Program Office
*NPOESS program's joint program office composed of representatives from the collaborating agencies.*

**IRT |** Independent Review Team
*Independent teams tasked to review government programs.*

**JARC |** Joint Agency Requirements Council
*One of NPOESS's user groups.*

**JARG |** Joint Agency Requirements Group
*One of NPOESS's user groups.*

**JPSS |** Joint Polar Satellite System
*NOAA's weather satellite program after NPOESS was cancelled.*

**JROC |** Joint Requirements Oversight Council
*Joint governance body formed by Goldwater-Nichols.*

**JWCA |** Joint Warfighting Capabilities Assessment
*Joint governance body formed by Goldwater-Nichols.*

**LDCM |** Landsat Data Continuity Mission
*Next-generation Landsat system.*

**LTAN |** Longitude of Ascending Node
*Variable that specifies the time that polar-orbiting spacecraft cross the equator.*

**METOP |** Meteorological Operational Satellite
*Environmental monitoring satellites developed and operated by EUMETSAT.*

**MHS |** Microwave Humidity Sounder
*Cross-track microwave sounder on NASA's EOS & NOAA's POES; predecessor to ATMS*

**MIS |** Microwave Imager/Sounder
*Conical microwave imager-sounder that replaced CMIS on NPOESS.*

**MODIS |** Moderate-Resolution Imaging Spectrometer
*Visible-Infrared Imager-Radiometer on NASA's MODIS; predecessor to VIIRS.*

**NASA |** National Aeronautics & Space Administration
*One of the three collaborating agencies on the NPOESS program.*

**NAVOCEANO |** Naval Oceanographic Office
*One of the four NPOESS Centrals.*

**NDE |** NPOESS Data Exploitation
*NOAA-developed ground processing system that interfaced with the NPOESS IDPS.*

**NDS |** Nuclear Detection System
*Nuclear detection sensor hosted on the GPS satellites.*

**NESDIS |** National Environmental Satellite, Data, and Information Service
*Component of NOAA that manages satellite development & operation.*

**NOAA |** National Oceanic & Atmospheric Administration
*One of the three collaborating agencies on the NPOESS program.*

**NJO |** NOAA JPSS Program Office
*NOAA's office for over-seeing the JPSS program.*

**NPOESS |** National Polar-Orbiting Operational Satellite System
*Collaboration between NOAA, NASA, & the DoD to execute operational climate, weather, and climate science missions.*
**NPP |** NPOESS Preparatory Project
*Risk reduction and climate science data continuity mission that was executed by NASA and the IPO.*
**NRC |** National Research Council
*Advisory board for the U.S. government.*
**NRO|** National Reconnaissance Office
*Government agency that develops intelligence satellites.*
**OLS |** Operational Line Scanner
*Visible-infrared imager on the DoD's DMSP; predecessor for NPOESS's VIIRS.*
**OMPS |** Ozone Mapping and Profiler Suite
*Ozone instrument on NPOESS.*
**OSIP |** Operational Satellite Improvement Program
*Program where NASA developed instruments for later use on NOAA operational systems.*
**OSTP |** Office of Science and Technology Policy
*Science advisory board for the White House.*
**PA&E |** Program Analysis and Evaluation
*Division in the Office of the Secretary of Defense that was responsible for program evaluation.*
**PDR |** Preliminary Design Review
*Milestone in a typical acquisition program.*
**PEO |** Program Executive Officer
*Position created after Nunn-McCurdy in order to mediate between the IPO and NPP program office.*
**POES |** Polar-orbiting Operational Environmental Satellite Program
*NOAA's operational weather & climate program; predecessor to NPOESS.*
**RDR |** Raw Data Records
*Raw data transmitted from sensors that was converted to SDRs by NPOESS IDPS*
**SARSAT |** Search and Rescue Satellite-Aided Tracking
*Non-EDR producing instrument on NPOESS that was also on NOAA's POES.*
**SBIRS|** Space-Based Infrared System
*Satellite system that supports missile early-warning; successor to DSP.*
**SBUV |** Solar Backscatter Ultraviolet Radiometer
*Ozone instrument on NOAA's POES; predecessor to OMPS.*
**SDR |** Sensor Data Records
*Geo-located calibrated radiances that were converted from RDRs and to EDRs by NPOESS IDPS.*
**SDS |** Science Data Segment
*NASA ground system that interfaced with the NPOESS IDPS.*
**SEM |** Space Environmental Monitor
*Space environment sensor on NOAA's POES; predecessor to SESS.*
**SES |** Space Environmental Sensor
*Space environment sensor on DoD's DMSP; predecessor to SESS.*
**SESS |** Space Environmental Sensor Suite
*Space environment sensor on NPOESS.*
**SSMIS |** Special Sensor Microwave Imager Sounder
*Conical microwave imager-sounder on DoD's DMSP; predecessor to CMIS.*
**SPD |** System Program Director
*Head of the NPOESS IPO.*
**SSCM |** Small Satellite Cost Model
*A cost model for spacecraft.*
**SSPR |** Shared System Performance Responsibility
*NPOESS acquisition strategy; a variation of TSPR.*
**SUAG |** Senior Users Advisory Group
*One of NPOESS's user groups.*

**STAR** | Center for Satellite Applications and Research
*The scientific division of NOAA NESDIS.*
**TOMS |** Total Ozone Mapping Spectrometer
*Ozone monitor on NASA's TOMS Earth Probe system; predecessor to NPOESS's OMPS.*
**TRL |** Technology Readiness Level
*A measure of a component's technical maturity.*
**TSC |** Tri-Agency Steering Committee
*Committee of agency representative to NPOESS; reported to the EXCOM.*
**TSIS |** Total Solar Irradiance Sensor
*Total solar irradiance monitor on NPOESS.*
**TSPR |** Total System Performance Responsibility
*DoD acquisition strategy that cedes most programmatic decisions to a single prime contractor.*
**USCOM |** Unmanned Space Vehicle Cost Model
*A cost model for spacecraft.*
**USGS |** U.S. Geological Survey
*Government agency that uses the Landsat system.*
**VIIRS |** Visible Infrared Imager Radiometer Suite
*Visible-infrared imager/radiometer on NPOESS.*
**VIS-NIR |** Visible Near-Infrared
*The wavelength range at which instruments like VIIRS or MODIS operate.*
**WSF |** Weather System Follow-on
*DoD's replacement program after DWSS was cancelled.*

# 1 Introduction

> *We have really come to a point where we do extraordinarily well in terms of joint operations, but we do not do well in terms of joint procurement. It is still very Service-centered. So that's an area—both analytically and in the way we conduct our business—where I think we need to do better.*
>
> --Former Secretary of Defense Robert Gates [1]

The *Department of Defense Dictionary of Military and Associated Terms* defines the concept of *jointness* as "activities, operations, organizations, etc. in which elements of two or more Military Departments participate" [2]. Although joint military operations can be traced all the way back to the Peloponnesian War in the 5$^{th}$ century B.C. [3], jointness was not formalized into the United States' military establishment until the National Security Act of 1947 [4-5]. The Act's primary purpose was to unify previously separate and semi-autonomous military departments under the direction of a single civilian leader, the Secretary of Defense, and to establish the Joint Chiefs of Staff as the president's principal military advisers [4]. Importantly, in addition to providing a mechanism that enhanced jointness *within* the Department of Defense (DoD), by creating the National Security Council, the National Security Act also enabled the DoD to participate in joint *interagency* operations [6]. Since its formation, the National Security Council, which was originally composed only of representatives from the DoD and the Department of State [7], has expanded to include representatives from the Treasury Department and the intelligence community [8]. Today, the joint National Security Council serves as the principal forum in which the President coordinates national security and foreign policy operations across federal government agencies [8].

Despite the National Security Act's intentions, several military flawed military operations—including the 1979 Iran hostage crisis, the 1983 Beirut embassy bombing, and the 1983 invasion of Grenada—demonstrated the need for increased jointness in military operations [3-5]. The defense reorganization act that resulted, the 1986 Goldwater-Nichols Act, attempted to correct noted flaws within the DoD and to strengthen interservice unity [3-5]; importantly, the Goldwater-Nichols Act also defined the concept of jointness as it is used in the present day. Specifically, Goldwater-Nichols further consolidated and strengthened the Secretary of Defense's authority over each of the services and identified the chairman of the Joint Chiefs of Staff as the single and unified source of military advice to the President [4-5]. Goldwater-Nichols also unified military operations outside of Washington by enhancing Combatant Commanders' authority over individual services with overlapping missions [4-5]; today, Combatant Commanders lead nine unified commands which contain troops from all service departments that execute missions jointly [9].

Although Goldwater-Nichols' primary goal was to improve service *interoperability*, by enhancing the role of the Joint Requirements Oversight Council (JROC) and the Joint Warfighting Capabilities Assessment (JWCA), the Act also provided a mechanism for future technical systems to be developed and acquired jointly [5, 10-11]. Specifically, by using forums like the JROC and JWCA to unify requirements across the services, the DoD was able to identify interservice requirement synergies and opportunities to procure weapons systems more efficiently [5, 10]. Furthermore, by developing common systems that could be used by more than one service, joint procurement also presented an opportunity to improve interoperability across the services: one of the goals of Goldwater-Nichols [10, 12]. Despite the relationship between Goldwater-Nichols' intentions and joint system procurement, the Center for Strategic and International Studies noted that "while the passage of Goldwater-Nichols has significantly advanced joint perspectives in the policy arena, jointness in the procurement and defense allocation process has lagged substantially and is one of the few unrecognized dimensions of the 1986 legislation" [5]. The Center's analysis of Goldwater-Nichols goes on to attribute several failures during Operation Enduring Freedom in Afghanistan and Operation Iraqi Freedom to a lack of interservice system interoperability and suggested that the lack of jointness in military procurement continues to hinder military operations [5].

In spite of this call for increased jointness in system procurement, several major weapons systems *have* been defined, developed, and procured jointly since the 1986 act. The most notable joint program is the F-35 Joint Strike Fighter, a program that uses three variants of a common aircraft design to meet a diverse set of requirements that were levied by the Air Force, the Navy, and the Marines. Today, the F-35 is credited as being the most expensive aircraft acquisition in the DoD's history [13] and the program's rampant cost growth led the RAND Corporation to conclude that developing three separate aircraft to meet individual service needs would have been less costly than jointly developing the single shared system [14]. While extreme, the DoD's experience developing the F-35 is not unique and statistical analyses suggest that generally, joint programs incur larger cost growth than single service programs [14-17].

Despite the noted challenges with the F-35 and other joint systems' development, the need for joint operations and interoperable systems appears to be persistent and increasing [18-19]. In particular, today's threat environment not only requires that the services operate jointly under the a unified combatant commander, but also that they coordinate their operations with civilian agencies like the Department of State and the U.S. Agency for International Development [18, 20-21] and with the intelligence community through the recently formed National Intelligence Council [22]. Outside of interagency jointness in military operations, the DoD has and continues to develop and procure systems by partnering with civilian government agencies; for example, NEXRAD, a network of Doppler radar systems, was produced jointly by the DoD and the National Oceanic and Atmospheric Administration (NOAA). Besides the DoD, other government agencies also develop systems jointly; for example, the National Aeronautics and Space Administration (NASA) has partnered with the U.S. Geological Survey (USGS) to develop the Landsat satellites and has formed international partnerships to develop major manned systems like the International Space Station. Finally, partnerships between domestic law enforcement agencies appear to be increasing in number and in a recent review of these efforts, legal scholars Freeman & Rossi suggested that "interagency coordination is one of the great challenges of modern governance" [23].

This dissertation presents results from an investigation that explored one of those challenges: the challenge of developing and acquiring systems jointly. In the remainder of this chapter, I present the definition of jointness that guided my research and review the benefits and costs that are associated with systems that are developed jointly. Next, I present the research design that I used to study the cost of jointness and finally, I conclude by reviewing the structure of the dissertation's subsequent chapters.

## 1.1 Defining Jointness

In response to today's more expansive concept of jointness, this dissertation defines jointness to include *both* interservice and interagency collaboration and employs the concept of organizational and technical *architectures* to distinguish joint programs from those that involve only one service department or one government agency. Crawley et al. define architecture as "an abstract description of the entities of a system and the relationships between those entities" [24]: essentially, a system's architecture is defined by the system's components and by the relationships between them. While the field of system architecture has traditionally focused on the architecture of technical systems [25], organizational theorists often study organizations as systems [26] which can also be defined in terms of their components and component relationships. Therefore, in this dissertation, I use distinct characteristics of organizational and technical architectures to determine whether a program is or is not joint and I focus solely on joint programs that develop and acquire technical systems.

A joint technical architecture is multi-functional and capable of meeting a diverse set of requirements that are levied by distinct user groups. Joint technical architectures can also be defined by their ability to be *disaggregated*; specifically, a joint system executes an aggregated set of missions or requirements that could alternatively be executed by multiple distinct systems. The F-35 system is technically joint because it meets the requirements of three separate user groups—the Air Force, the Navy, and the Marines—and could be disaggregated and developed as three separate technical systems.[1]

A joint organizational architecture is one that allows more than one agency to participate. Like technical jointness, joint organizational architectures are also aggregated and can be *disaggregated* if government agencies develop systems independently instead of collaboratively. The Landsat program is organizationally joint because it meets requirements specified by *only one agency* but is developed by NASA for the USGS. The Landsat program could be *disaggregated* if NASA assumed the responsibility for defining the system's requirements and developed it independently. Furthermore, if NASA attempted to levy requirements on the Landsat system (as it has in the in the past [27]), Landsat would be classified as *both* an organizationally and a technically joint program. As such, according to my definition of jointness, programs can be *either* organizationally or technically joint or can exhibit *both* types of jointness.

Historically, government agencies have employed several strategies to develop systems jointly and these strategies vary depending on the degree of jointness that they employ. Technical architectures are fully joint when a single system meets the needs of *all* of the program's distinct users. Technical architectures are partially joint when multiple variants of a common core system are employed to meet different users' requirements. Partial jointness is also known as commonality, or "the sharing of parts or processes across different products" [28]; commonality is a cost saving strategy that is also frequently employed in commercial industries [29]. By sharing components from a common core system across three distinct variants, the F-35 program is partially joint. If the F-35 program had developed only a single aircraft to meet the needs of all three of its users, it would be classified as fully joint; fully joint systems are commonly employed in the government space sector, where high launch costs motivate agencies to fully integrate their systems.

Organizational architectures are fully joint when a distinct joint program office is formed and staffed by the collaborating agencies. Organizational architectures are partially joint when one agency serves as an acquisition agent; in this role, one agency develops a system that is defined and ultimately operated by another. The most recent Landsat program (the Landsat Data Continuity Mission, LDCM) was partially joint, since NASA was USGS's acquisition agent. If USGS or another agency sought a greater role in Landsat's development, the agencies' interactions and interdependencies may have been best facilitated by a fully integrated joint program office. Both the National Research Council (NRC) and the RAND Corporation have suggested additional strategies for structuring organizationally joint programs [17, 30] and the NRC classified these strategies in terms of partner interdependency; partners that interact through a joint program office were defined to have the greatest amount of partner interdependence [17].

[1] For clarity, in this dissertation, I classify interservice programs as technically—but not organizationally—joint because the services are all part of the same agency: the Department of Defense.

### 1.1.1 Jointness in the Government Space Sector

By using a program's organizational and technical architecture as its defining characteristic, my definition of jointness is intentionally broad. However, despite this generality, this dissertation focuses soley on jointness in the government space sector. Specifically, I limit my discussion to unmanned, Earth orbiting satellite systems that were developed primarily by domestic government agencies. This necessarily excludes joint programs for manned spaceflight or planetary exploration and those that were developed with an international government agency as the primary collaborating partner. Within the remaining set of joint programs, there are six major mission types: communications, navigation and timing, missile defense, intelligence, scientific, and operational earth observing. Figure 1 identifies examples of each mission type and classifies them according to the type of jointness that they exhibit.

As shown in Figure 1, communication missions like the DoD's Advanced Extremely High Frequency (AEHF) system are classified as technically joint systems. AEHF currently supports two distinct missions. First, it serves tactical users who use its communications links to transmit videos, battlefield maps, and targeting maps in real-time [31]. Second, it serves strategic users, who require protected and nuclear hardened communications links for their highly classified transmissions [31]. AEHF's development was managed by the Air Force and the system was designed to meet the needs of multiple distinct user groups within the DoD.

Navigation and timing missions are executed by the Global Positioning System (GPS) which can be classified both as a technically and an organizationally joint program. Originally, GPS was a technically joint program, since the Air Force developed the system to meet the navigation and timing needs of multiple users in the DoD [32]. Today, GPS is organizationally joint as well, since the Department of Transportation (DoT) has begun levying civilian requirements on the system and playing a more active role in its management [32]. GPS also continues to support a secondary missile defense mission by hosting a Nuclear Detection System (NDS) payload. The NDS payload on GPS consists of optical, x-ray, and electromagnetic pulse sensors that continuously monitor the Earth for signatures of a nuclear detonation [33]. The NDS payload on GPS supplements a larger constellation of sensors previously hosted by the Defense Support Program (DSP) and currently supported by the Space-Based Infrared System (SBIRS) [34].

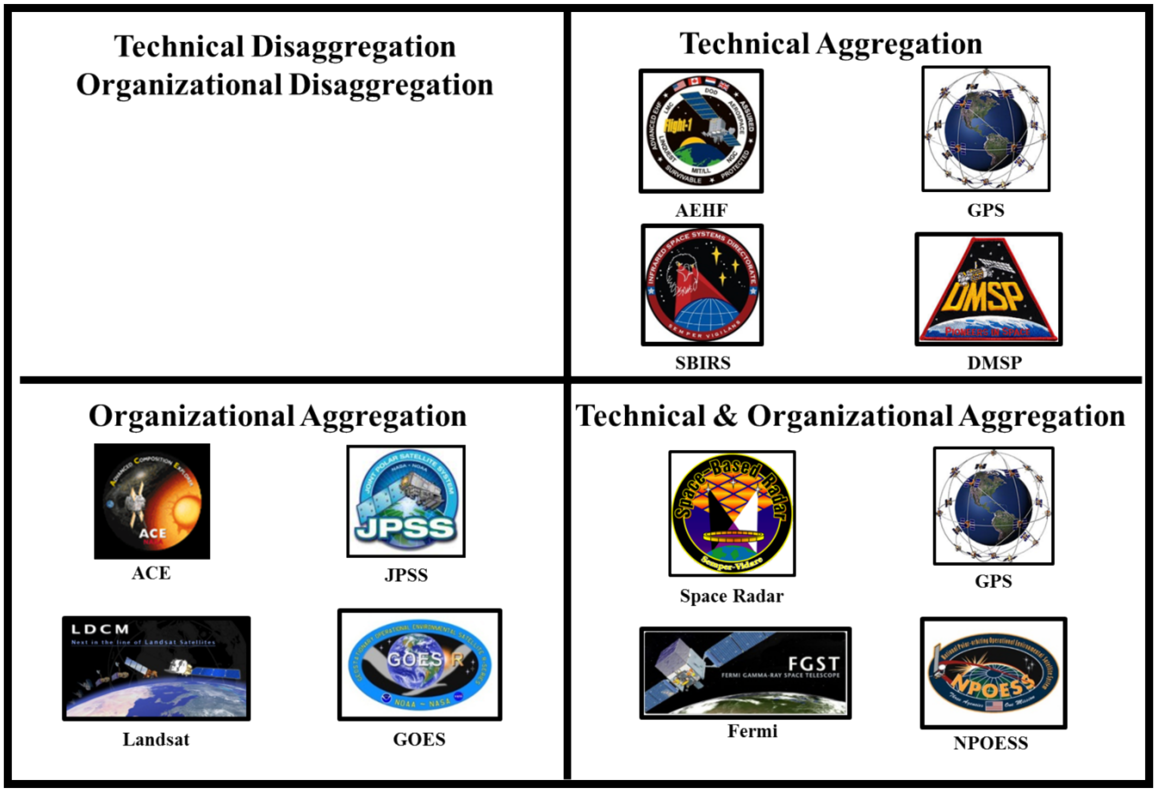



**Figure 1: Examples of Jointness in the Government Space Sector**

As noted above, today's primary missile defense system, SBIRS, is a technically joint program. In addition to supporting an NDS payload, SBIRS also has two sensors that support distinct and separable missions. The staring sensor supports a strategic mission of detecting missile launch and the scanning sensor supports a tactical mission of tracking missiles in support of real-time military operations [35]. The intelligence community, which primarily executes strategic missions, typically utilizes organizationally joint programs where the National Reconnaissance Office (NRO) serves as the acquisition agent for the intelligence community [36]. A notable and unclassified exception to this statement is the cancelled Space Radar program. Space Radar was a joint program between the NRO and the Air Force and since both agencies levied requirements on the technical system [37-38], Space Radar can be classified as both an organizationally and a technically joint program.

As shown in Figure 1, science missions also fall in more than one jointness category. NASA's Advanced Composition Explorer (ACE), a scientific mission that studied the solar wind, can be classified as organizationally joint since the system was developed by NASA but NOAA provided limited funding to enhance its data transmission capabilities [17]. The Fermi Gamma Ray Telescope was both technically and organizationally joint since both NASA and the Department of Energy (DoE) levied requirements on the system and managed its development [17].

Finally, operational earth observing satellites have also exhibited all three types of jointness. For example, at different points during its history, the Landsat program has exhibited organizational and both organizational and technical jointness. The NOAA-NASA Geostationary Operational Environmental Satellite (GOES) program is organizationally joint, since NASA serves as NOAA's acquisition agent.

And most importantly for this dissertation, environmental monitoring satellites that fly in low Earth orbit can also be classified according to all three types of jointness. The NOAA-DoD-NASA National Polar-orbiting Operational Satellite System (NPOESS) was both organizationally and technically joint, today's NOAA-NASA Joint Polar-orbiting Satellite System (JPSS) is organizationally joint, and the cancelled DoD Defense Weather Satellite System (DWSS) was technically joint. These three programs and the jointness that they exhibit are the focus of this dissertation.

### 1.1.2 The Benefits of Jointness

By reviewing the histories of joint programs in the government space sector, I identified several common motivations for developing space systems jointly. These motivations, which will be discussed using examples from the programs shown in Figure 1, include:

- Interoperability,
- Expanded user communities,
- Mission synergies,
- Agency unique capabilities,
- Political imperative,
- And cost savings.

As noted previously, the primary intent of the Goldwater-Nichols Act was to improve military departments' interoperability. Technically joint systems achieve this goal by using a single system to provide a common capability to all branches of the military. For example, AEHF unifies the communication networks of multiple distinct user groups and as a result, enhances user interoperability in the field [39].

Although Goldwater-Nichols' primary aim was to improve interoperability, in the government space sector, one of the more common motivations for developing systems jointly is the expansion of an existing system's user community. For example, GPS was originally developed for military users; however, once civilians began using the data and realized its tremendous utility, civilian government agencies like the DoT sought a greater role in future systems' development and management [32]. Similarly, SBIRS's predecessor, DSP, primarily executed a single strategic mission that constantly monitored the Earth for missile launches and nuclear detonations executed by the U.S.'s Cold War adversaries [40]. However, DSP demonstrated its utility to tactical users during the Iran-Iraq War and the Persian Gulf War, when its data was used to detect the short range missiles fired during these regional conflicts [40]. After demonstrating its utility to the DoD's tactical users, these users sought a greater role in the next generation system's development [30]; as noted previously, SBIRS now executes both a strategic and a tactical mission. The Landsat program shares a similar history, since the DoD increased its involvement in Landsat 7's development and management after utilizing Landsat data in during Operation Desert Shield and Desert Storm [17].

In all of the examples cited above, programs were initiated as disaggregated systems that were managed by single government agencies. However, as the original program's data was made available to other users, it became critical missions that were outside of the program's original scope. So when the original program office began planning for a follow-on system, its new users pursued a larger role so as to insure that future systems would continue to support their unique missions. This history suggests a *trend towards increased jointness in the government space sector*: essentially, as users recognize the utility of space systems' data, they tend to seek increased involvement in developing and managing future systems.

Organizational and technical jointness have also been motivated by mission synergies. Particularly for Earth science missions and operational Earth observing missions, data product quality can be improved by hosting multiple instruments on a large aggregated spacecraft [41-42]. Similarly, synergies between the detector technologies used by the particle physics and astrophysics research communities motivated technical jointness on the Fermi program [17]: since the requirements of both users were similar, they could be converged on shared joint system.

The unique technical capabilities and expertise of each partner further increased Fermi's jointness by involving both NASA (which represented the astrophysics community) and the DoE (which represented particle physicists). Specifically, given its considerable experience developing space systems, NASA developed the Fermi spacecraft. The DoE-managed SLAC National Accelerator Laboratory developed Fermi's primary instrument, the Large Area Telescope, because it utilized technology that was similar to SLAC's ground-based particle physics experiments. Agency expertise also motivates organizationally joint programs in the intelligence community, since the NRO has the unique capability of developing satellites; similarly, in operational Earth observation, NASA is uniquely capable of developing NOAA's GOES and USGS's Landsat systems. NASA's interactions with these two agencies are often characterized by the transition from research to operations, since NASA specializes in the development of new technologies that are later fielded by NOAA and USGS's operational systems [17].

Finally, joint programs are often politically motivated. By aggregating capabilities that are required by multiple user groups, technically joint programs have larger political advocacy groups and as a result, are harder to cancel [11, 17]. Furthermore, by proposing to partner with another agency and to jointly share a system's cost, organizationally joint programs may be more likely to get funded by their parent agencies, since the cost-per-agency is reduced. Relatedly, joint programs are often encouraged by agencies and their political stakeholders; indeed, the 2010 National Space Policy of the United States directed NASA to expand international cooperation in space and to "enhance collection and partnership in sharing of space-derived information" [43]. Finally, joint programs have also been political motivated [30]; for example, the NPOESS program was formed by a presidential decision directive [D43].

### 1.1.3 The Cost Saving Benefit of Jointness

Related to joint programs' political benefit is their potential for cost savings; in fact, cost savings was the primary motivation for the presidential decision directive that formed NPOESS [D43]. Joint programs' technical architectures enable cost savings in two distinct ways. First, a joint technical architecture enables cost savings by reducing the number of systems and system components that need to be developed and operated by the government. Joint technical architectures' ability to save money can be illustrated using the NPOESS program as an example. Prior to forming the joint NPOESS program, NOAA planned to execute its mission using a NASA-developed Polar Operational Environmental Satellite (POES) system and the DoD planned to execute its mission using the Defense Meteorological Satellite Program (DMSP). As shown in Figure 2, had the government maintained separate POES and DSMP systems, it would have developed, produced, launched, and operated a constellation of four satellites in low Earth orbit. However, by defining a joint technical architecture that was capable of executing both NOAA and the DoD's missions, NPOESS reduced the size of the operational constellation from four to three satellites, used a single ground system, and correspondingly reduced the number of instruments and launches. In this way, the joint technical architecture enabled cost savings by reducing the number of components in the operational technical system. Joint technical architectures can also enable recurring cost savings by capitalizing on economies of scale and other savings that can be achieved through large scale production of common parts [44].

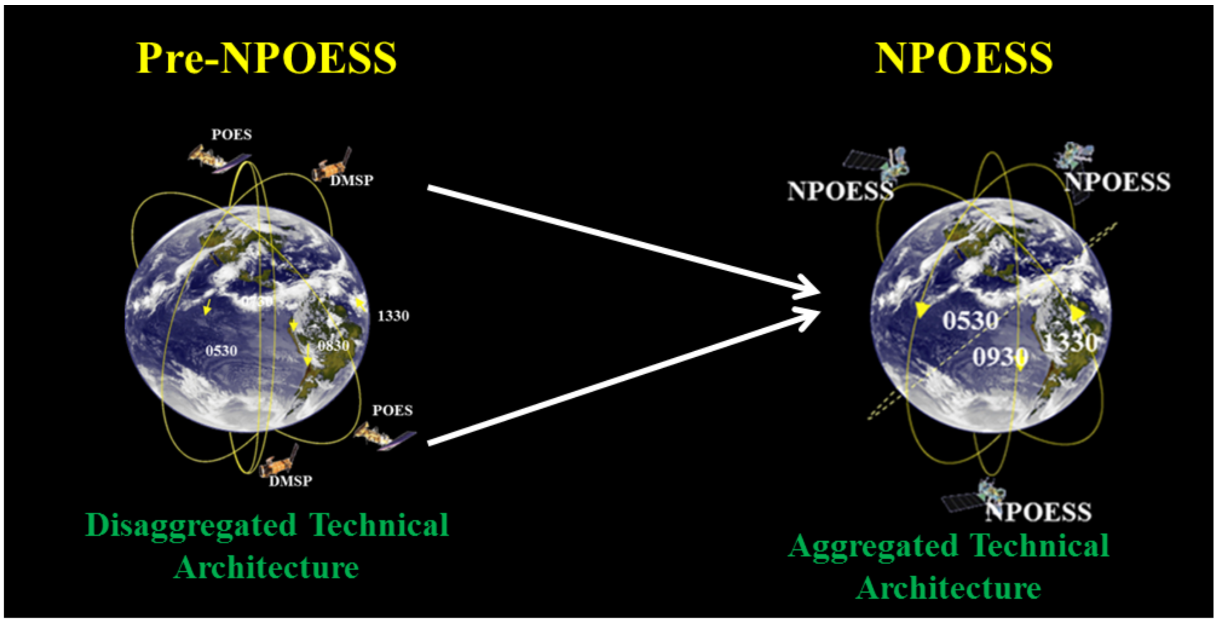



**Figure 2: Formation of the NPOESS Program (Image of Satellite Constellation Taken from [D86])**

Joint organizational architectures can enable cost savings by increasing the number of agencies that fund a system's development. In the case of the NPOESS program, instead of funding separate systems independently, NOAA and the DoD formed an organizationally joint program that allowed them to *share* the costs of a single system. Thus, for both organizational and technical jointness:

***It is a joint program's <u>architecture</u> which enables cost savings.***

The close relationship between my proposed definition of jointness and the mechanism by which jointness enables cost savings is intentional; indeed, today, many authors note that one of the most significant motivations for forming a joint program is cost savings [12, 14, 30, 45].

## 1.2 The Costs of Jointness

Despite the cost savings potential of jointness, recent studies found that joint programs experience larger cost growth than non-joint programs and have suggested that instead of reducing cost, jointness actually *induces* it. For example, a report by the RAND Corporation compared cost growth between four non-joint and four joint military aircraft programs and found that the joint programs experienced an average of 41% more cost growth than their non-joint counterparts [14]. While the study acknowledged that its data set was limited, it did suggest that cost growth experienced by joint programs during non-recurring development can ultimately overwhelm any potential for recurring cost savings [14]. The report went on to conclude that although the cost growth experienced on joint programs like the F-35 cannot be entirely attributed to jointness, "the evidence indicates that jointness is an important factor in the higher cost growth experienced by [the F-35] than for historical single service fighters" [14].

Brown, Flowe, & Hamel used a larger data set containing 39 single-service and 45 joint programs to produce similar conclusions [16]. Specifically, the authors compared the frequency of three types of cost and schedule breaches between joint and non-joint programs; breaches were reported when schedule, non-recurring costs, or recurring costs exceeded 15% [16]. Using these definitions, the authors found that joint programs experienced an average of 8.6, 5.95, and 11.59 schedule, non-recurring and overall lifecycle cost growth breaches while non-joint programs experienced 4.58, 1.65, and 7.85 breaches, respectively [16]. Importantly, the differences between the joint and non-joint programs were also statistically significant for the schedule and non-recurring cost growth breaches at the $p<0.025$ and $p<0.001$ levels [16]. The authors used these results to conclude that joint programs are more likely to experience schedule and non-recurring cost growth and to call for future research that explores *why* joint programs are more susceptible to cost and schedule growth [16]. Cameron performed a similar analysis and concluded that defense acquisition programs that employed partial technical jointness (i.e. commonality) experienced, on average, 28% more cost growth than programs that did not employ commonality [15]. Cameron's results were significant at the $p<0.04$ level and his subsequent research explored why programs that utilized commonality experienced these higher rates of cost growth [15].

Finally, a recent NRC report also concluded that on average, joint programs in the government space sector experience higher rates of cost and schedule growth [17]. Since the NRC did not report the statistical significance of their findings, I independently reconstructed their analysis using a set of 79 unmanned satellite programs where NASA was primary government agency. Using this data set, which contained 15 interagency joint programs and 16 international joint programs, I observed a statistically significant difference between the joint and non-joint programs' cost growth. Specifically, the joint programs experienced a statistically significant ($p<0.05$) 21% more cost growth than the non-joint programs.[2] These results suggest that when a government agency (in this case, NASA) develops programs jointly, it is more likely to experience cost growth; the results of this analysis are presented in Figure 3.

Although the cited statistical analyses do suggest a relationship between jointness and cost growth, as noted by Brown, Flowe, & Hamel [16], little research has explored the mechanisms by which jointness actually *induces* cost. Consequently, the acquisition community's current understanding of *how* jointness induces cost growth is limited to findings that have been reported by large government-sponsored reviews on the topic rather than by more detailed academic work. In the following sections, I summarize the community's current understanding of jointness and the knowledge and methodological gaps that motivate my research.

[2] Since the underlying distribution of the data was found to be non-normal, I used bootstrap sampling with 1,000 resamples to generate the statistics that are quoted above.

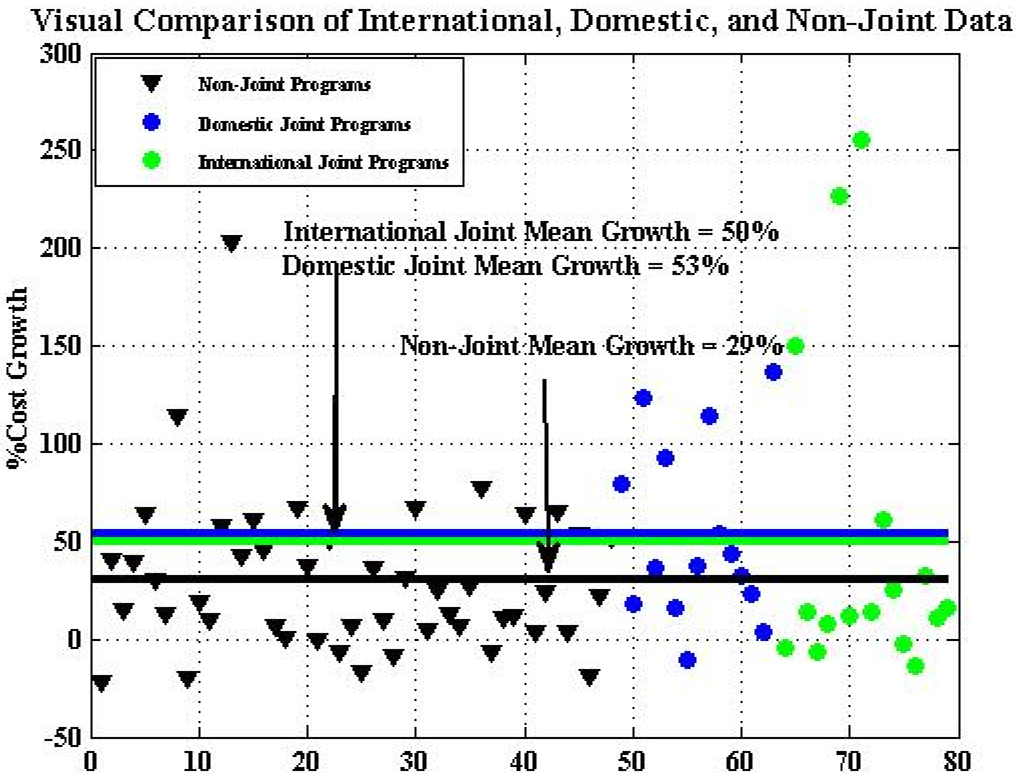



**Figure 3: Cost Growth on NASA Programs**

### 1.2.1 The Technical Costs of Jointness

The space acquisition community's understanding of the technical costs of jointness is best captured by its current interest in *disaggregation.* Disaggregation, or "the dispersion of space-based missions, functions, or sensors across multiple systems," [46] is the opposite of technical jointness. Leaders in the government sector, particularly those focused on defense-related missions, suggest that disaggregated technical architectures may be less complex and costly than the joint, highly aggregated technical architectures of the past [46-50]. Thus, the current disaggregation movement suggests a hypothesis that connects jointness to cost growth; specifically, that:

> **Aggregated technical architectures are more complex than disaggregated architectures and that when this complexity is unanticipated, it induces cost growth on joint programs.**

The belief that past programs' aggregated technical architectures induced costly technical complexity has motivated multiple recent studies to explore disaggregating future government satellite systems. For example, in 2013, the Senate Armed Services Committee requested that the Government Accountability Office (GAO) explore options for disaggregating SBIRS's scanning and staring sensors by assigning them to separate spacecraft [51]. Also in 2013, General William Shelton, Commander of Air Force Space Command, suggested that GPS could be disaggregated by flying the nuclear detection and navigation and payloads on separate spacecraft [52]. Two years prior, analysis by Burch suggested that disaggregating

AEHF's strategic and tactical communications payloads could reduce the system's complexity and cost [48]. Finally, the Air Force is currently studying options for cost-effectively disaggregating future environmental weather satellites [53]. In each of the cited examples, cost savings was a major motivation to disaggregate historically joint systems; increased resiliency, responsiveness, and flexibility are additional benefits that are also associated with disaggregation [46-48].

Current proponents of disaggregation suggest that it can reduce joint programs' cost in two related ways: by reducing system complexity and by stimulating the industrial base [46-50]. Authors agree that when requirements and missions are aggregated onto a system, its technical architecture becomes more complex; as complexity increases, system integration becomes more challenging [47], as does establishing and sustaining a stable program baseline [48-49]. As a result, complex systems tend to have higher non-recurring costs. Other than noting this relationship, disaggregation literature is largely silent on the topic of complexity mechanisms—or the specific elements within aggregated technical architectures that increase complexity—and that can be eliminated through disaggregation. Notable exceptions include several authors who note that conflicting performance requirements can induce complexity in aggregated technical architectures [14, 50, 54, 55].

Taverney's proposed "Vicious Circle of Space Acquisition" [50] provides the conceptual link between aggregated systems' complexity and the weak industrial base that disaggregation seeks to correct. Specifically, as past joint systems' complexity and costs increased, the government was unable to fund spare systems and its tolerance for failure decreased [50]. This further slowed program development schedules by adding costly risk-minimizing development activities and weakened the industrial base by reducing the number of systems that were produced [50]. Authors suggest that by disaggregating, the government will be able to reduce system development time and purchase systems more frequently [48-50]; in this way, disaggregation will be able to capitalize on the recurring cost benefits that are associated with more frequent production and that went unrealized on past joint programs.

Importantly, the cost saving potential of disaggregation has only been theorized and plans to disaggregate GPS, SBIRS, AEHF, and DWSS have neither been formalized nor approved. In order to make effective decisions on whether future systems should be disaggregated, the space acquisition community requires an improved understanding of how jointness has induced cost growth in the past and whether disaggregation can actually reduce cost in the future. Specifically, future government decision makers require:

- Knowledge of the specific complexity mechanisms that increased aggregated technical architectures' non-recurring costs,
- The ability to quantitatively compare the non-recurring and recurring cost growth or savings that are enabled by aggregation and disaggregation,
- And the ability to evaluate cost across a spectrum of jointness that spans from fully aggregated to fully disaggregated.

The above knowledge and methodological gaps are addressed by this dissertation.

### 1.2.2 The Organizational Costs of Jointness

The space acquisition community's understanding of the organizational cost of jointness is best captured by a recent recommendation by the NRC, which suggested that government agencies *disaggregate* their organizations and collaborate only when there are compelling reasons to do so [17]. The NRC's recommendation derived from the observation, noted by several others [16, 20, 30, 45], that joint organizations are more complex than non-joint organizations. Thus, the recommendation suggests a hypothesis that connects jointness to cost growth; specifically, that:

> **Aggregated organizational architectures are more complex than disaggregated ones and that this complexity induces and enables cost growth on joint programs.**

Complexity induces and enables cost growth by hindering an organization's decision making process. Several sources noted that the efficiency of an organization's decision making process is primarily affected by size: as a joint organization's size increases, so do the transaction costs associated with coordinating and making decisions [12, 16, 17, 30, 45]. Specifically, authors suggested that as the number of organizational components, interfaces, and interdependencies increase on a joint program, so does the effort required to manage and to coordinate components' activities and decisions. The *Joint Program Management Handbook* even went so far as to suggest that due to their increased organizational complexity, the decision making process on joint programs is longer than non-joint programs by at least one third [12]; of course, slow decision making can induce schedule delays and cost growth. Another commonly cited complexity mechanism is a joint organization's authority structure. Specifically, authors note that in order to make effective decisions, joint programs require clear and integrated lines of authority: a characteristic that has eluded past joint organizations [10, 12, 17, 56].

Importantly, although the organizational complexity of joint programs has been noted, other than identifying the number of components and component relationships as complexity mechanisms, the acquisition community lacks a comprehensive understanding of organizational complexity and how it affects programmatic decisions. Furthermore, without an understanding of the mechanisms that increase complexity, the acquisition community lacks the ability to assess the complexity and costs associated with a given organizational architecture [16] and to evaluate the trade-offs between organizational aggregation versus disaggregation. Specifically, in order to make more effective decisions to aggregate or disaggregate space programs in the future, government decision makers require:

- Knowledge of the specific complexity mechanisms that are inherent to aggregated organizational architectures,
- An improved understanding of complexity's impact on organizational decision making,
- And the ability to assess organizational complexity across multiple architectures that span from fully aggregated to fully disaggregated.

The above knowledge and methodological gaps are addressed by this dissertation.

### 1.2.3 The Politics of Jointness

Separate from joint programs' organizational and technical complexity are the policy-making—and oftentimes political—challenges associated with jointness; in fact, these challenges have been so great in the past that historian Beaumont noted that "A central paradox of jointness is the hostility that it has often generated" [3]. Past studies of joint programs reported that reconciling numerous stakeholders misaligned and competing needs is a key hostility-generating challenge induced by jointness [12, 19, 45, 56]. Since joint programs serve more users and agencies than non-joint programs, they experience more political pressure [12] that can also induce conflict. Other policy challenges associated with jointness include differing user or agency cultures [17, 30], and budget and oversight mechanisms [17].

Although many of the noted challenges are byproducts of the American political system, the acquisition community could benefit from an improved understanding of how the political dynamics of agency interactions with each other and with a joint program office can induce complexity in a program's organizational and technical architectures. This dissertation addresses this knowledge gap by exploring the relationship between agency actions and organizational and technical complexity.

## 1.3 Research Approach

In the above discussion, I reviewed literature that hypothesized a relationship between joint programs' organizational and technical architectures and cost growth. This hypothesis suggested that aggregated organizational and technical architectures are more complex than disaggregated ones and that this complexity induces and enables cost growth. The reviewed literature also suggested a relationship between agency actions and joint programs' organizational and technical complexity. Using these hypotheses as a motivation, this dissertation addresses the research question:

***How does jointness induce cost growth?***

To address this question, I employed a small-N case study design and utilized a mix of qualitative and quantitative methods. George & Bennett defined a case study as a detailed examination of a historic episode that is used to develop or to test explanations that can be generalized to other events [57]. By using case studies to explore the relationship between jointness and cost growth, I was able to investigate existing hypotheses, to build new theory inductively, and to suggest generalizable conclusions that may be applicable to other joint programs. Importantly, in addition to enabling cross-case generalizations, case study research designs also maintain contextual details [58] that are critical to understanding cost growth, which can be induced by a myriad of factors [15].

Case studies have been employed to study related topics both internal and external to the government space sector. Outside of government space, Cameron [15] utilized case studies to explore the relationship between commonality and cost growth and Cote [59] used a similar research design to propose a relationship between interservice interactions and programmatic outcomes. Within government space, both Selva and Leshner used a case study of NASA's Earth Observing System (EOS) to identify several costs of mission aggregation [41] and to explore NASA's decision making processes during the program's formulation [60]. This dissertation presents the results of the first investigation to employ detailed case studies to explore the relationship between jointness and cost growth.

### 1.3.1 Research Design

When using a case study-based research design, researchers must first determine the number of cases to include and then select the specific cases to be studied. The primary trade-off associated with the number of cases that are studied is one breath versus depth. Yin suggested several reasons for focusing on a single case; for example, if a case is a critical test of an established theory, is particularly unique or revelatory, or is typical example of the theory under examination, a single case study design may be appropriate [58]. Despite these reasons for studying a single case, Yin also noted that multiple cases allow for replication and therefore, can increase the generalizability of a researcher's conclusions [58].

In an argument that is particularly salient for this research, Falletti noted that if selecting fewer cases enables the researcher to gain a better understanding of the complexities of the phenomena under study, then depth should be valued over breadth [61]. By using plausibility probe [62] cases to supplement a single case study, the researcher can both improve his generalizability *and* preserve the complexities of the critical case under study. Levy suggested that plausibility probe cases "allow the researcher to sharpen a hypothesis or theory, to refine the operationalization or measurement of key variables," and to "probe the details of a particular case in order to shed light on a broader theoretical argument" [63]. Eckstein suggested that plausibility probes are typically less extensive cases that are used to further build up or to invalidate theories that are generated from the detailed study of a single case [62].

After settling on the number of cases to study, Eisenhardt & Graebner suggested that researchers should select cases using theoretical sampling [64]. Unlike the random or stratified sampling approaches used in large-N studies that test existing theory, the authors argued that in order to *build* theory, the researcher should select cases according to their ability to illuminate and to extend the relationships and logic among theoretical constructs [64]. Although case studies are often used to build theory, Yin suggested that researchers should begin with a proposed theory and use dimensions of that theory to guide initial case selection and cross-case comparisons [58]. Finally, Geddes cautioned against selecting cases along the dependent variable [65]; in this research, the dependent variable is cost growth, and to avoid Geddes' selection bias, the selected cases have all experienced cost growth to-date.

This dissertation presents three case studies that were selected according to the hypotheses discussed above: that technical and organizational aggregation induce complexity that ultimately contributes to cost growth. Using these hypotheses as a guide, as shown in Figure 4, I selected one case of organizational aggregation (JPSS), one case of technical aggregation (DWSS), and one central case study that exhibited *both* technical and organizational aggregation (NPOESS). The JPSS and DWSS programs served as plausibility probe cases for the central case study and provided an isolated environment to investigate only the technical or the organizational costs of jointness. The costs on the plausibility probe cases were then compared to the more complicated NPOESS program, where organizational and technical factors coupled and jointly affected cost. I selected NPOESS as a central case study because its extensive 16-year was extremely complex and thus, provided a unique vehicle for examining the cost impacts of jointness; additionally, NPOESS has yet to be formally studied in an academic environment.

The selected cases are all environmental monitoring systems that execute their missions from low Earth orbit for the DoD, NOAA, and NASA. While the programs shown in Figure 1 (and others) were initially considered candidate cases as for this thesis, I intentionally omitted programs that were pure research, single spacecraft, or weakly integrated because their timelines, program composition, and development processes are drastically different than the multi-spacecraft, operational, and highly integrated programs that are the focus of this study. I further controlled for mission and agency type by focusing only on environmental monitoring systems. By limiting my sample in this way, I increased my study's internal validity by controlling additional variables that may have affected program cost. While this decision necessarily limited my external validity, since the aforementioned agencies will likely continue partnering to collect environmental data in the future, this thesis addresses a persistent problem in national space policy.

It is also important to note the boundaries of the selected cases: each case was studied from program initiation to either cancellation or to the year 2012. The NPOESS program spanned from 1993 to 2010, produced a significant amount of ground and space hardware, and had completed its mission critical design review (CDR) prior to its cancellation. JPSS and DWSS both planned to use hardware that was developed by NPOESS. As a result, both programs used similar technology that was at commensurate levels of technical maturity and these similarities facilitated comparisons across programs. Furthermore, although the JPSS program continues to this day, DWSS was cancelled in 2012; to enable comparison between the plausibility probe cases, my analysis of JPSS focused on the years prior to 2012. Finally, within each case, my analysis focused primarily on the costs associated with each program's ***space segment***. Although ground system costs are discussed, NOAA, NASA, and the DoD operated their systems jointly and shared data on the ground prior to NPOESS; therefore, the primary technical component that was affected by jointness was the programs' space segment.

| | |
|---|---|
| **Technical Disaggregation**<br>**Organizational Disaggregation** | **Technical Aggregation**<br><br>**Defense Weather Satellite System (DWSS)** |
| **Organizational Aggregation**<br><br>**Joint Polar Satellite System (JPSS)** | **Technical Aggregation**<br>**Organizational Aggregation**<br><br>**National Polar-orbiting Operational Satellite System (NPOESS)** |

**Figure 4: Selected Case Studies**

Importantly, JPSS and DWSS were formed in an attempt to *reduce* NPOESS's cost. By comparing JPSS to NPOESS, I isolated costs that were attributable to organizational aggregation. Similarly, by comparing DWSS to NPOESS, I isolated costs that were attributable to technical aggregation. Thus, using JPSS and DWSS as comparison plausibility probe cases, I was able to more clearly distinguish between costs that were *induced* by either technical or organizational aggregation and those which uniquely emerged on NPOESS and were a function of the interaction and couplings between both types of jointness.

### 1.3.2 Research Methods

The primary source of data for this dissertation was qualitative interviews with experts who had experience working on or with the NPOESS, JPSS, and DWSS programs. Interview data was supplemented by primary and secondary source documents and by independently-executed quantitative analyses of the programs' costs. A mixed-methods approach to addressing the research question was selected because mixing qualitative and quantitative methods can increase the breadth and depth of a researcher's understanding [66]. Mixed methods research can provide the investigator with a richer data set and enable him or her to generate new modes of analysis and unique insights [67]. Using both qualitative and quantitative data also enables methodological triangulation [67-69] and improves a researchers' confidence that his or her findings are not artifacts of the methodology that was used [69]. In this dissertation, I use qualitative process-tracing and quantitative metrics and models to address my research questions and I present a more detailed discussion of these methods in Chapters 3 and 9, respectively.

### 1.3.3 Threats to Validity

This study's research design and methods were selected for their ability to control threats to validity; therefore, in this section, I explicitly review Campbell & Stanley's [70] list of threats to validity and discuss how they were controlled. Campbell & Stanley identify seven threats to internal validity: history, maturation, instrumentation, regression, selection, experimental mortality, and investigator bias [70]. Of these threats, regression, testing, and experimental mortality were not applicable since statistical sampling nor testing were used. George & Bennett noted that process tracing controls for both the history and maturation threats [57] and I controlled for possible selection bias by selecting a representative set of interviewees. Finally, I accounted for possible investigator bias by acknowledging that I have previously worked for a contractor and on government programs but that I have no prior experience working on any of the joint programs that were studied.

Campbell & Stanley also identified four threats to external validity: reactive effects of experimental arrangements, interaction of selection biases, reactive or interaction effects, and multiple treatment interference [70]. Of these threats, reactive effects of experiment arrangements and multiple treatment interference were not applicable. I controlled for the reactive and interactive effects threats through data triangulation [58] and interaction of selection biases by theoretically sampling cases [71] and by selecting interviewees from different organizations and roles. Finally, another important limitation of this dissertation is the generalizability of its conclusions. As noted previously, I purposefully selected cases to improve internal validity; however, to enable some level of generalization, I compared my results to theory and found my conclusions to be consistent [72].

## 1.4 Overview of Dissertation

The remainder of this dissertation is structured into four main sections. The first section continues my introduction to jointness and to the research approach that was used to study it. First, Chapter 2 reviews literature that provides insights into the challenges of acquiring systems jointly. Next, Chapter 3 outlines a new approach for studying complex acquisition programs and provides an overview of the research methodology that was used.

The next section—Chapters 4-7—presents data from my case studies. Chapter 4 provides a descriptive history of the cases and identifies key events and components of the programs' technical and organizational architectures. Chapters 5 and 6 apply the research approach that I proposed in Chapter 3 to create an analytic chronology of the NPOESS program and to study its technical and organizational costs. Chapter 7 reviews the technical and organizational costs of JPSS and DWSS and presents a cross-case comparison of the costs on all three programs. Overall, the purpose of these chapters is to demonstrate the utility of Chapter 3's new research approach and to review the empirical evidence from which I subsequently draw my conclusions.

Chapter 8 constitutes the next major section, wherein I synthesize my case study analysis and present the Agency Action Model to address my research question and to explain how and why cost growth occurs on joint programs. The final major section in Chapter 9 uses a trade space analysis tool, the lessons learned from the case studies, and the Agency Action Model to explore future opportunities for jointness.

# 2 Theoretical Perspectives on the Impacts of Jointness

> *Organization is everything. It's not the technology. It's not the technical problems that can't be solved; it's the organizations that are tantamount. And I don't think they have been given enough time in the literature.*
>
> –Interviewee 31

Government agencies often form joint programs in response to policies that require or encourage them to do so. As a result, in addressing the research question of—*How does jointness induce cost growth*—fundamentally, this dissertation examines the cost impacts of government policy; or more generally, the cost impacts of the government's policy making and political actions. Previous work by Weigel provides a starting point for understanding the relationship between government action and system architecture; specifically, Weigel demonstrated [73-75] that the technical impacts of policy can be observed and assessed through a system's architecture. Although I will present evidence to support Weigel's claim, I argue that her perspective is fundamentally incomplete and that in addition to directly impacting a system's architecture, government actions also impact it indirectly, through the organization that manages the system. Therefore, in this thesis, I demonstrate that in order to understand the cost impacts of jointness—or more broadly, the impact that any government action has on the acquisition of a complex technical system—

***One must consider how that action affects both the technical and the organizational architecture, as well as the relationship between them.***

In this chapter, I review literature that captures our current understanding of architecture and its relationship to the politics of policy-making. This literature necessarily spans multiple disciplines; therefore, it is my goal to review only the fundamentals from each discipline and then to highlight key elements that are shared across disciplines and that will contribute to an understanding of the cost impacts of jointness. I begin by reviewing public administration theory, continue with a review of organization theory, and conclude with the theory of system architecture. Importantly, before drawing on theory to understand of the cost impacts of jointness, I review other causes of cost growth in the space acquisition community and identify a literature gap that is critical to understanding how jointness has also contributed to cost growth in the past.

## 2.1 Cost Growth: Current Understanding and Literature Gaps

To understand how jointness induces cost growth, one must also understand how it does not—or rather, how multiple causes of cost growth can work together and affect a program's cost simultaneously. For example, although joint programs appear to incur larger cost growth than non-joint programs, cost growth is an endemic problem in the space acquisition community: in 2012 alone, cost estimates for NASA and

DoD space systems increased by $2.5 billion and $11.6 billion, respectively [76-77]. In response to persistent cost growth, government agencies, independent committees, and academics have analyzed past programs and identified four primary and four secondary root causes for cost growth in the government space sector. The four primary root causes for cost growth are:

- Requirements,
- Immature technology,
- Poor system engineering,
- And unrealistic cost estimates.

The four secondary root causes for cost growth are:

- Program length,
- Budget and schedule uncertainty,
- Contracting mechanisms,
- And a weak industrial base.

In this section, I describe each of these root causes so that they can be identified and distinguished from cost growth that is induced by jointness. I conclude by providing an overview of the literature that will be discussed in the remaining sections and by identifying the literature gap to which this dissertation contributes.

### 2.1.1 Cost Growth: Primary Root Causes

The first primary root cause—requirements—has two distinct components: initial requirements and requirements creep. First, several studies noted that government space programs—particularly in the defense and intelligence communities—attempt to satisfy all of their users' requirements in a single step [77-79]. The GAO noted that when requirements are defined in this way, the resulting system is typically a complex "Battle star Galactica-like" satellite, rather than a constellation of "smaller, less complex satellites that gradually increase in sophistication" [78]. The GAO also identified a relationship between requirements and technical maturity, noting that technology development is often necessary to meet a program's ambitious requirements [79-80]; as will be discussed below, technology development also contributes to cost growth. To combat the cost growth that can occur when a program's requirements are too ambitious, the GAO recommended that the space acquisition community define requirements incrementally and develop systems using a blocked approach that enables technology to be matured slowly and integrated into operational systems gradually [78].

Even if a program's initial requirements are not overly ambitious, requirements creep, or changes to those initial requirements, has also been observed to induce cost growth [11, 78, 81]. Requirements creep is particularly prevalent when a program's requirements are not well-defined initially [11] or there is not sufficient understanding of the complexity and cost impacts of those requirements [80].

The studies that identified requirements as a root cause of cost growth also noted that ambitious requirements or requirements creep have been induced by the acquisition process itself, which incentivizes programs to accept all user requirements as a means to expand their constituency and political support [80, 82]. Nowinski & Kohler vividly described how expanding a program's constituency can impact its cost by noting that: “the present requirements process hampers rational program development. The process today requires so many interested parties to ‘buy in’ that the really important national needs get lost and/or marginalized in a myriad of *desires* that have to be reconciled to get everybody on-board. The result is that there are too many ‘critical’ requirements, which drastically limit a program manager’s ability to balance performance, costs, and schedules” [82]. Rather than requiring systems to meet a “myriad” of user desires, Nowinski & Kohler recommended that that government should simply and specifically define only a handful of critical requirements for its systems so that program managers can more effectively control their costs in the future [82]. The GAO has also noted that high launch costs often incentivize users to levy too many requirements on single systems, since doing so reduces the number of launches required to meet their needs [80].

As noted above, ambitious requirements necessitate technology development, the second primary root cause for cost growth. The time and cost required to develop immature technologies has been shown to be variable; as a result, the cost and schedule of any program that incorporates immature technologies is similarly uncertain [78, 83]. Multiple studies have shown that when programs are established or allowed to pass acquisition milestones with technically immature components, their subsequent development is plagued by cost growth and schedule delays [76, 78-80, 83]. As with requirements definition, programs’ decision to incorporate immature technologies is often incentivized by the acquisition process itself: since the funding available to support technology development outside of a formal program is limited, programs are often left with no choice but to include immature technologies in their systems’ baseline [78, 84].

Third, multiple reports have cited poor system engineering—both by the government and by its contractors—as another root cause for cost growth. The Defense Science Board found that the government itself lacked the ability “to manage the overall acquisition process, approve program definition, establish, manage, and control requirements, budget and allocate program funding, manage and control the budget, assure responsible management of risk, [and] participate in trade-off studies” [11]. The Board suggested that the government’s ability to manage space acquisitions eroded as a function of Total System Performance Responsibility (TSPR), an acquisition strategy that was popular in the 1990s [11]. Using TSPR, the government ceded a significant amount of control over the system development and production process to its contractors and limited their oversight of contractor activities; the intent of TSPR was to enable cost savings by minimizing costly oversight and by allowing contractors to use commercial best practices [81]. Despite these intentions, contractor performance on TSPR programs was often poor and the combination of limited government oversight and poor contractor performance ultimately enabled cost growth on TSPR programs [81].

Outside of TSPR programs, several other factors have hindered system engineering and enabled cost growth. For example, the Defense Science Board noted that in the 1990s and early 2000s, program offices were often staffed by inexperienced military personnel on two-year rotations [11] and RAND also found that government program offices were insufficiently staffed [85]. Of course, system engineering and program management suffers when it is executed by inexperienced, insufficient, or temporary staff. Other studies found additional system engineering deficiencies such as an inability to flow down requirements into testable specifications [86] and a failure to hold decision reviews at key points in a system’s lifecycle [76]. In each case, weak system engineering was identified as a root cause for the cost growth that was observed.

Finally, poor cost estimates are the final primary root cause for cost growth. Historically, programs have underestimated their technical, cost, and schedule risks and therefore produced unrealistic cost estimates and included an insufficient amount of management reserve and contingency funding in their budgets [11, 81, 82, 85-87]. RAND noted that in the context of a complex system's development, the cost impacts of technical risks can be magnified by the complicated relationships between components, noting that: "[technical] risks had ripple effects due to the complex interrelationships of the various components and subsystems" [81]. Further exacerbating the cost impacts of technical risks, past programs also estimated their costs at the 50% confidence level, giving them a 50% probability that their final costs would exceed their initial estimate [11].

As with the other root causes, poor cost estimates are a noted outcome of the acquisition system, which incentivizes programs to underestimate their costs in order to get approved and contractors to under-bid their proposals in order to win final contracts [87]. Augustine noted that despite a rigorous cost estimating process by both the government and prospective contractors, cost estimates often become "cost desire-ments" as contractors develop low bids in order to win and the government wants to believe that the cost of the system will actually be low [87]. To reduce this optimism, RAND suggested that cost estimates be developed outside of program offices [85] and the Defense Science Board suggested that programs develop budgets according to the 80% confidence level [11].

## 2.1.2 Cost Growth: Secondary Root Causes

Secondary root causes were labeled as such because they were identified as contributing to cost growth in the past or were recently targeted by acquisition reform efforts. However, unlike the primary root causes, there is less consensus in the acquisition community on how significantly these factors affect cost. The results presented in this dissertation contribute to this ongoing debate.

First, program length is a secondary root cause of cost growth because the longer it takes to develop and produce a system, the more likely that its initial requirements will be ambitious or will change during its lifecycle [78]; as a result, program length can affect cost through a program's requirements and have the impacts that were described above. Augustine also noted the relationship between program length and cost by stating that "if projects are stretched out ad infinitum, their costs, even in non-inflated dollars, will increase substantially" [87]. Furthermore, the relationship between program length and cost motivated NASA's "Better, Faster, Cheaper" movement in the 1990s, which sought to reduce the time required to develop systems as a means to reduce their costs. However, not only was "Better, Faster, Cheaper" discontinued in the wake of several system failures, but a subsequent analysis of 59 programs from the Selected Acquisition Reports found no statistically significant relationship between a program's length and cost or between its length and its cost growth [88].

Second, both the GAO and RAND noted that funding and schedule instability have contributed to cost growth on programs [76-77, 85] and Augustine's analyses of past programs also supported this claim [87]. Weigel's research on the impact of government policies on space system design further supported this relationship [75]; however, Coleman, Summerville, & Dameron found no statistically significant relationship between changes to a program's schedule and increases in its cost [88].

Another secondary root cause that lacks statistically significant evidence is the relationship between contract type and cost growth. Traditionally, two general contracting mechanisms are used to develop government space systems: fixed-price and cost-plus. Fixed price contracts establish the system's price up-front and any cost growth above that price is paid by the contractor. Alternatively, in a cost-plus contract, the government fully reimburses the contractor for its costs and pays a fee, which becomes the contractor's profit. Fixed price contracts are appropriate when there is little technical risk to developing the system and its costs can be accurately estimated, whereas cost-plus contracts are used when there is greater technical risk and cost uncertainty. Despite these distinctions, contract type has been the focus of a considerable amount of acquisition reform; in fact, Cancian noted that the DoD "has continuously wavered between the two, drawn to fixed-price contracts because of the incentives they give the contractor, yet stumbling on the high uncertainty in major weapons acquisitions that makes fixed-price terms hard to set" [89]. Although programs' contracting mechanisms have garnered the attention of acquisition reformers, analysis of 433 contracts from 1970 to 2011 showed no statistically significant relationship between contract type and cost growth [86].

Finally, the weakness of the space industrial base is also often blamed for cost growth. Specifically, RAND described the conditions of the industrial base as "turbulent" and found that, lacking sufficient business, contractors were incentivized to underbid their proposals as a means to preserve their companies [81]. RAND also noted that a consolidated industrial base "reduces the potential for future competition, may discourage innovation, and make costs more difficult to control." Interestingly, RAND also posited a relationship between increased jointness and industry consolidation [14]. Despite these proposed relationships, Augustine argued that cost is independent of the industrial base and in his seventh law claimed that "Decreased business base increases overhead. So does increased business base" [87].

### 2.1.3 Theoretical Perspectives on Cost Growth

A critical gap in the acquisition community's current understanding of cost growth is *how* and *why* it happens in the first place. The root causes discussed above are all fairly obvious and as result, they fail to provide actionable recommendations. Taken at face value, it seems that all future programs need to do is levy good requirements, avoid technology development, and use proper system engineering practices and cost estimating methods. However, if staying on cost and schedule is that easy, why have so many programs failed to do so?

In this dissertation, I demonstrate that the answer to that question can be found in how the government architects its technical systems and the organizations that acquire them. Specifically, I argue that defining requirements, managing technology development, and using proper system engineering and cost estimating methods are all activities that occur *within* an acquisition organization—the strength of which depends on the government policies and actions that established it. For example, "poor system engineering" is not a fundamental root cause of cost growth; instead, it is a symptom of poorly a constructed organization that hindered the system engineering process.

Similarly, government agencies often demand ambitious requirements, requirements creep, and new technology. Their acquisition programs accept those demands because they lack an explicit understanding of how they induced cost growth on past programs. Without an ability to recognize how much technology development is too much or how and when requirements creep will result in a significant cost increase, government decision makers cannot effectively assess the costs and benefits of their actions.

In order to gain this ability in the future, it is necessary to change the perspective with which we study cost growth. Instead of identifying superficial root causes, I argue that the acquisition community could benefit from analysis done at even more fundamental level. To do this, I suggest considering how agency actions influence acquisition organizations and their ability to effectively manage system development. Figure 5 illustrates the alternative perspective that I propose to study the cost impacts of government action. As shown, agency actions affect acquisition programs' organizational architectures. When agency actions increase organizational complexity, they can directly induce cost growth by making the organization's decision making process less efficient. They can also indirectly enable cost growth by hindering the program's ability to manage its technical system. Finally, as suggested by Weigel, agency actions can also directly affect the system's technical architecture [73] and induce cost growth in this way as well.

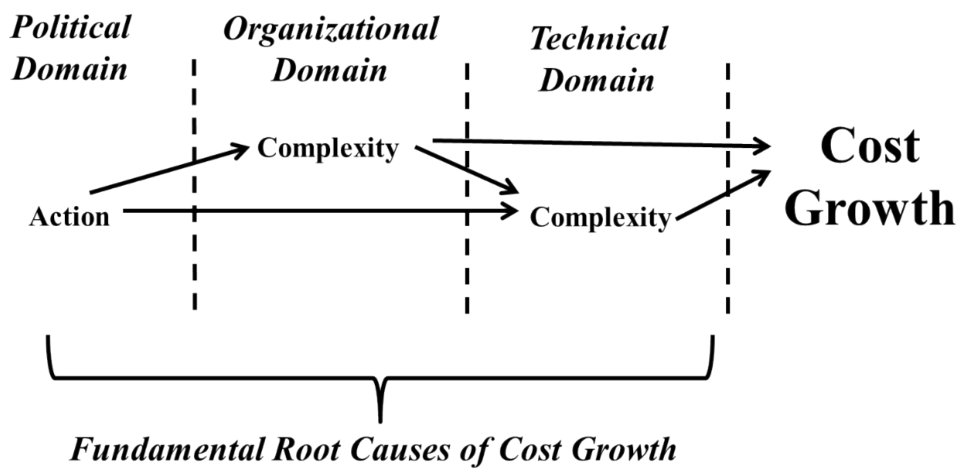



**Figure 5: Relationship Between Government Policy, Organizations, Technology, Complexity, and Cost**

Public administration, organization, and system architecture theories all contribute to the holistic perspective that is depicted in Figure 5 and advanced by this dissertation. Beginning with Weigel's work, which suggested that a system's technical architecture provides a means to translate between the policy and the technical domains [73], I draw on both system architecture and public administration theories. Ultimately, this dissertation expands upon Weigel's initial claim by incorporating formal theories of public administration—which suggest that all policy decisions are all fundamentally *political*—into our understanding of policy's relationship to system architecture. This dissertation also contributes to the literature stream focused on the management of technical systems, or the overlap between system and organizational architectures. But most significantly, this dissertation contributes to the space that spans all three domains—technical, organizational, and political—and makes the claim that in order to understand the impacts of government action, one must understand not only how the action affects the system but also how the action affects the organization and its relationship to the system that it manages. The following sections review each literature stream and highlight the gaps and relationships between them which are critical to understanding the cost of jointness.

## 2.2 Public Administration: Theory and Impacts

The aspects of public administration theory that are most relevant to this dissertation are motivated by rational choice theory, which suggests that government agencies' actions and decisions are based on institutional interest [90-91]. The four key characteristics of government bureaucracies that motivate their institutionally interested actions and are particularly important for this research include:

- Hierarchical authority structures,
- Unique agency missions,
- Agency budgets and budget size,
- And agency expertise.

Works by Weber [92], Downs [93], and Wilson [94], provide further description of characteristics that are not listed above, but that remain important variables to consider when studying how government agencies operate outside of a joint program environment.

Within my focus on joint program costs, three theories—which are derived from the above characteristics—are particularly enlightening. The first, Downs' "law of inter-organizational conflict" suggests that every government agency is in partial conflict with one another over its authority, mission, budget, and relative expertise [93]. Although Downs' law has not independently motivated a formal literature stream, past studies of interagency relationships have echoed Downs' proposition [59, 95-97]. Most literature that evokes Downs' law does so using a bureaucratic politics framework, the second theory that is applicable to this research. Bureaucratic politics theory argues that government policy is the result of a bargaining game amongst government officials, each of whom pursues his own self interest [98]; this interest, which is intimately connected to the defining characteristics identified above, often pits government agencies against one another and forces them into conflict. Finally, political control theory discusses bureaucratic behavior in the context of a principal-agent problem, where elected officials are the principal and bureaucracy the agent [90, 99-101]. In this literature, the agent possesses expertise that elected officials do not and the relationship between the principal and agent ultimately affects the agent's authority, mission, and budget.

### 2.2.1 Defining Characteristics of Government Bureaucracies

Even more fundamental to government bureaucracies than the four characteristics listed above, is the fact that government agencies are non-market organizations. Indeed, it is government agencies' inability to respond to market-based signals that distinguishes public organizations from private ones and that increases the salience of the characteristics discussed below. Specifically, public organizations use hierarchical—and oftentimes inefficient—authority structures because their organizational architectures are not affected by market forces that that could drive them to assume a more efficient form [90, 93]. Furthermore, because government agencies cannot use market signals to assess the utility of the services or products that they provide to the public, they focus instead on promoting the salience and uniqueness of their missions [94, 95, 102]. Importantly, despite the widely discussed disadvantages to public administration, public bureaucracies exist to provide essential functions that cannot be sustained in the private sector, usually because they involve multi-dimensional tasks or complex and conflicting stakeholder networks [93, 103].

Downs' "Law of Hierarchy" suggests that, absent market forces, the only way for public organizations to execute complex and large-scale tasks is through a hierarchical authority structure [93]. Seidman echoed the importance of hierarchy by noting that when government agencies reorganize, it is the resulting power structure—rather than the reforms' impact on agency efficiency or effectiveness—that most concerns agency leaders [97]. Downs' suggested that government bureaucracies are most effectively managed by hierarchy because a single and streamlined authority structure enables leaders to coordinate the agencies' two key activities—executing its missions and developing its budgets—most effectively [93].

Specifically, Downs noted that because decisions on the bureau's budget are inherently linked to the activities that the bureau performs in support of its mission, government agencies are best managed by a single authority structure where its decisions can be tightly coordinated [93]. In addition to highlighting the importance of aligning budget and mission decisions within an agency, Downs also emphasized that such decisions require the input of agency experts; therefore, Downs suggested that agencies' hierarchical authority structures are usually aligned with internal information channels that enable an agency's experts to advise its decision makers [93].

The importance of hierarchy is echoed by other authors (e.g. [92, 104-105]) as are the relationships between agencies' decision making structures, missions, budgets, and information channels [94, 96, 106-108]. Ultimately, the relationship between each characteristic can be understood simply in terms of agencies' interest in maintaining their autonomy both from elected officials and from each other [59, 93-94, 108]. For example, Downs noted that interagency coordination is particularly challenging because it disturbs agencies' hierarchical authority structures and threatens their autonomy to make and execute decisions independently [93].

The uniqueness of an agency's mission is also of critical importance to its autonomy: by executing a unique mission, agencies can eliminate their bureaucratic rivals and establish a monopoly over its mission [93-94, 107-108]. A key challenge for agencies is ensuring that their jurisdiction matches their mission [94] or rather, that they have full decision authority to execute a unique mission for the government. Wilson noted that a mission-jurisdiction match is best achieved when an agency is first formed and that several undesirable outcomes can result when mission and jurisdiction are not matched [94]. For example, when agencies' missions overlap, they may find themselves in conflict with one another over which agency has decision authority—or jurisdiction—to execute the mission [94]. Agencies will also resist new missions that differ significantly from their unique, core mission [97] and will oppose other agencies that attempt to gain jurisdiction over that mission [93]; interagency conflicts of this type will be discussed further in below.

Also critical to an agency's autonomy is the size of its budget: a large budget signals that an agency's mission is critical to the government and ensures that the agency can continue effectively executing that mission [94, 96, 106]. Nickansen argued that the size of an agency's budget is so critical that it can serve as a proxy for the agency's utility function: just as private firms aim to maximize profits, government agencies aim to maximize the budgets that they are allocated [106]. While Rouke and Wilson echoed the importance of budget size, they argued that budget maximization is simply a means to increase autonomy: agencies' primary goal [94, 96]. Specifically, Rouke argued that agencies seek more resources so that they can strengthen their political position with respect to bureaucratic rivals and enhance their ability to execute their missions [96].

Finally, a great source of agencies' power and ability to maintain their decision making autonomy comes from their expertise; indeed, bureaucracy exists to implement government policies that require specialized knowledge and expertise that elected officials do not possess. Government bureaucracies are experts on mission execution and it is this expertise—which exists only within an agency—that provides a significant source of agency power over elected officials [96, 102, 109]. Expertise can increase agency power in two ways. First, by providing expert advice, agencies can influence elected officials' decisions and second, agencies can exercise discretion as to how they implement elected officials' policies [110]. Agencies can also use the power of their expertise to emphasize the salience of their mission [93, 95, 96], to request larger budgets [96, 106], and to gain greater autonomy in their decision making and mission implementation processes [101]; thus, agencies' expertise and unique technical capabilities provide them with a significant source of power over one another and over elected officials themselves.

### 2.2.2 Bureaucratic Politics

As noted above, agencies struggle for autonomy both from their bureaucratic rivals and from elected officials; however, Downs' "law of inter-organizational conflict" is primarily concerned with the former. With respect to other agencies, individual agencies seek a distinct area of expertise, a clearly defined and unique mission, and jurisdiction (or decision authority) over that mission [93]. Bureaucratic rivals are other agencies that threaten any of those things; by seeking autonomy, agencies attempt to establish a permanent claim over their resources, missions, and jurisdiction by eliminating external threats that are posed by their rivals [93-94].

Downs described agencies' struggle for autonomy using the concept of territoriality, illustrated in Figure 6. Specifically, Downs defined the concept of "policy space" as an N-dimensional space composed of the N functions that are performed by the government bureaucracy. Policy space can be occupied by several bureaus simultaneously and the bureaus' proximity to each other represents the similarity of their mission [93]; as noted by Downs and others [93-94, 96], the probability of interagency conflict increases as agencies' functions—or missions—increase in similarity. The similarity of agency missions is illustrated by the interior and exterior territorial zones shown in Figure 6. In the interior, Downs defined the heartland to be the region of policy space over which one agency is wholly dominant and the interior fringe to still dominated by one agency but to also to be influenced by others. Alternatively, the exterior is the region in which other agencies exert influence. In the periphery, another agency is dominant, but our agency of interest still exerts some influence. Our agency of interest has no influence in alien territory, which is fully dominated by another agency and no agencies dominate "no man's land," although several may exert influence there.

According to Downs, agencies are fundamentally territorial and imperialistic, since they both resist encroachment into their space and try to influence other agencies' activities by "invading" their interior fringe or heartland [93]. Using this metaphor, Downs noted that agency conflict affects the potential for cooperation because "whenever social agents interact, their individual imperialisms are bound to create some conflicts between them, although their relations as a whole may be dominated by cooperation" [93]. Particularly important for this research, Downs also noted that territoriality induces "bureaus to consume a great deal of time and energy in territorial struggles that create no socially useful products" [93]. A key gap in this literature is a connection between Downs' the not socially useful products theorized by Downs and the cost of jointness.

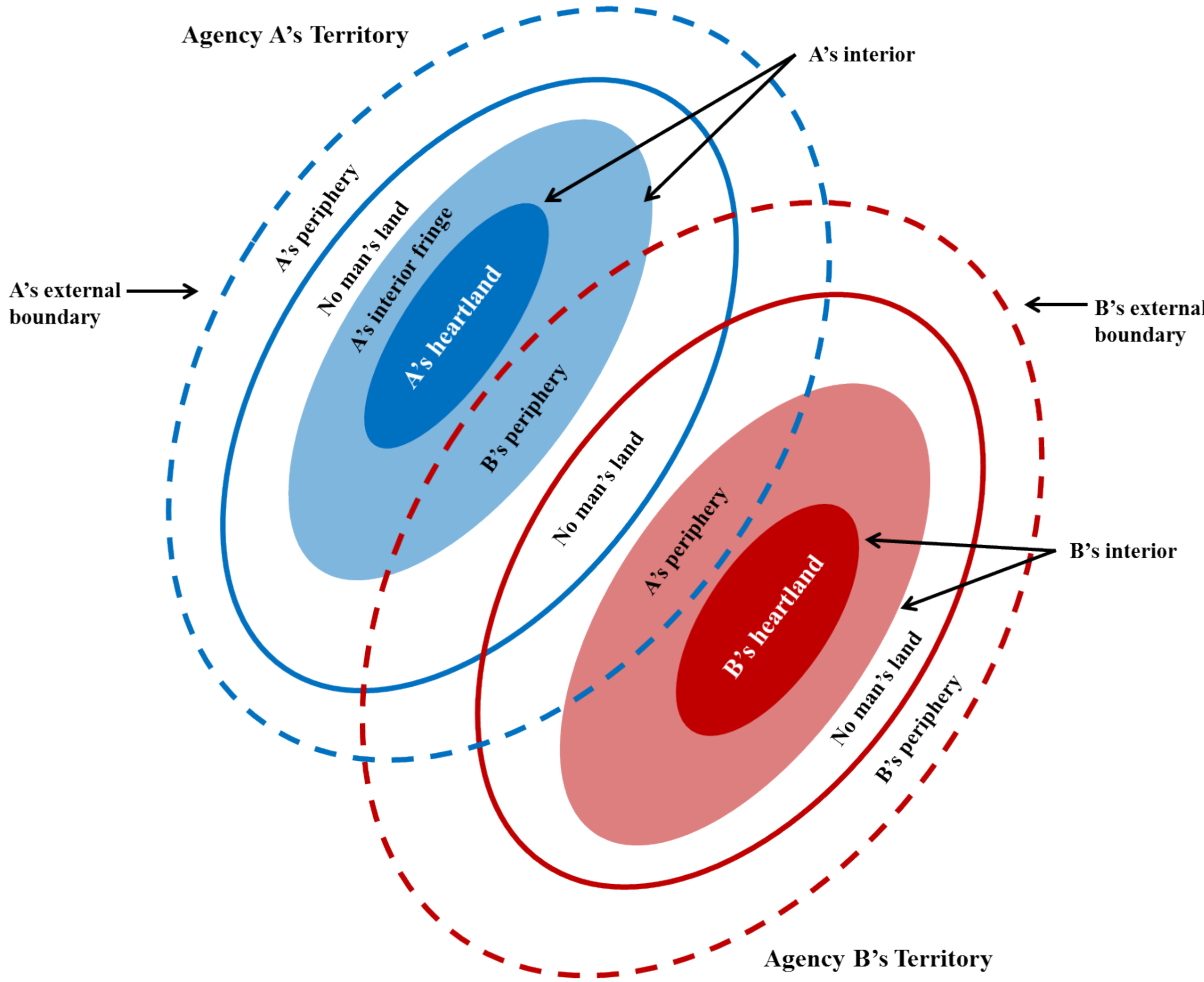



**Figure 6: Downs' Law of Inter-Organizational Conflict (Recreated from Downs, 1972)**

Wilson, Rouke, and Seidman also discussed Downs' "law of inter-organizational conflict" and its implications for interagency coordination and jointness. Wilson noted that agencies view joint activities as a threat to their autonomy and therefore, will resist cooperating or will define interagency cooperation agreements to specifically protect their individual autonomy [94]. Rouke extended Downs' concept of territoriality using a war metaphor and described interagency committees as "the gray and bloodless ground of bureaucratic warfare, a warfare of position, not of decisive battles" [96]. Rouke also warned that when interagency activities are forced, cooperation simply "masks bitter and protracted warfare" [96]. Finally, Seidman noted that interagency collaboration is "rarely neutral" because it can only occur when one agency gains territory at the expense of another [97]. Like Rouke, Seidman militarized Downs' territory analogy and warned that when agencies coordinate, "the battle for position is never-ending and grows more intense as agencies seek to gain control or at least to exercise influence over the growing number of new and important programs that cut across established jurisdictional lines" [97]. Like the other authors, Seidman suggested that interagency conflict is primarily motivated by agencies' struggle for autonomy [97].

Several authors have analyzed the outcomes of interagency conflict using a bureaucratic politics framework [59, 95, 100] which suggests that government decisions are the result of "compromise, coalition, competition, and confusion among government officials who see different faces of an issue" [98]. Allison's "Model III" (i.e. his bureaucratic politics framework) illustrated how policy outcomes are the result of bargaining games at various levels of the government [98]. By alluding to "bargaining games," Allison intentionally connected his model to game theory, where every player in the game acts according to his own self-interest. For an excellent review of self-interested decision making in the context of general bargaining games, please refer to Luce & Raiffa [111].

Within the specific context of Model III, Allison said that bargaining games are structured according to *power*, which is shared by players that have separate responsibilities [98]. Players' ability to reach outcomes that maximize their self-interest depends on their ability to exert their power over one another; as Allison noted, "the context of shared power but separate judgments concerning important choices determines that politics is the mechanism of choice" [98]. Allison's bureaucratic politics can be understood in terms of Downs' "law of inter-organizational conflict" by interpreting power struggles between agencies as their attempt to defend and to expand their autonomous jurisdiction over regions of policy space.

Other authors who have studied interagency conflict have done just that; however, unlike Downs, who suggested that interagency conflict only has negative outcomes, several authors have observed its positive impacts. For example, Sapolsky attributed the success of the Polaris ballistic missile program to its use of four bureaucratic politics strategies that enabled it to generate a unique demand for its mission and to obtain the autonomy that was necessary to develop the new and complex system quickly and effectively [95]. Using its first strategy, "differentiation," the program distinguished itself from other weapons systems and articulated the uniqueness and criticality of its mission [95]. Using its second strategy, "co-optation," the program sought to eliminate competition and to manage bureaucratic rivals by integrating them into the program, or at the very least, by keeping them apprised of its progress [95]. Finally, using "moderation" and "managerial innovation," the program focused on long term goals and employed new management techniques to ensure that it was more successful than its rivals in the long-run [95]. Thus, by acknowledging that the other military services were each competing to develop missile systems and by developing strategies to gain power over those competitors, Sapolsky argued that the Polaris program was able to achieve both technical and management success [95].

Inspired by Sapolsky's work, Cote demonstrated how interservice rivalries positively affected the Polaris program by inspiring doctrinal innovation [59]. Temple also used the bureaucratic politics framework to illustrate how competition between the Air Force, the Navy, and the Central Intelligence Agency ultimately resulted in the creation of a separate agency, the National Reconnaissance Office, to manage the new and unique mission of collecting intelligence data from space [100]. While the cited authors have successfully used a bureaucratic politics framework to explain interagency competition and its outcomes, it is important to note that empirical evidence for Allison's Model III remains limited [90]; for example, Rhodes attempted to use the model to explain budget decisions in the Navy and found that alternative models more accurately explained and predicted his observations [112]. Despite its limitation, bureaucratic politics remains an important analytic framework which has yet to be applied to understand the cost impacts of jointness.

### 2.2.3 The Principal-Agent Problem

Unlike the literature discussed above, which primarily addresses agencies' quest for autonomy from each other, principal-agent theory is largely concerned with agencies' interest in maintaining autonomy from elected officials. The general structure of a principal-agent problem has an agent performing a task on behalf of a principal; however, because at least some portion of both actors' self-interest is misaligned, the agent's actions may conflict with the principal's interests [99]. Typically, this results in the agent "shirking" his responsibility to perform the task, even though the principal is paying him to do so [99]. The central problem considered by principal-agent theory is how the principal can insure that the agent completes the task according to the principal's interest, even if that interest conflicts with his own [101, 113].

Information asymmetry complicates the principal's ability to resolve this problem. Information asymmetry occurs when the agent possesses expertise on how to execute the principal's task or when it possesses private information on how it executed that task [99]. Typically, the principal has two strategies to overcome information asymmetry: by investing in information systems to monitor the agent or by establishing an outcome-based contract. In the latter case, the principal monitors the agent's actions to insure that they are aligned with its interest and in the former, the principal only rewards the agent if its actions result in a desired outcome [99]. A key issues that affect the principal's chosen strategy are cost and uncertainty, since information systems are expensive and outcome-based contracts may fail to insure the principal's desired outcome if there is uncertainty associated with the agent's task [99].

In the context of public administration, principal-agent problems typically assign the legislature and executive the role of the principal and the government bureaucracy the role of the agent. Information asymmetry is a particularly salient challenge in this type of principal-agent problem because government agencies possess information that elected officials do not. As noted by Moe, bureaucratic agents have "substantive expertise and experience, information about what they actually do on the job and how it affects valued outcomes;" as a result, Moe identified information asymmetry as presenting a significant control problem for the principal [101]. Many authors have analyzed this control problem (e.g. see [114-116]), which is typically managed by monitoring the agencies and by levying reporting requirements on them [117].

Particularly important for this research, Moe argued for a paradigm shift in how scholars analyze the principal-agent problem in public administration [101]. Specifically, he noted that political control theories usually treat government bureaucracies as subordinate to their principals' control; however, he suggested that government agencies are political actors in their own right and therefore, can exert power over their principals, even when they are officially in an agent role [101]. Moe suggested that future work should consider the political power of the agent by recognizing that control in a principal-agent relationship can "run both ways" and that in particular, "asymmetric information is an important basis for bureaucratic power" [101]. Dixit also noted a characteristic of principal-agent problems that is important for this research: that these problems can involve a single principal whose task is executed by multiple agents that are organized hierarchically [103]. Taken together, Moe and Dixit's work motivates a claim made by this thesis, that hierarchical principal-agent problems exist *between* agencies collaborating on joint programs and that a key control problem facing joint programs is asymmetric information and the ability of one agency to exert the power of its expertise over the other.

## 2.3 Organizational Architecture: Theory and Implications

A key short-coming of the literature discussed above is that it often overlooks the role that organizational architecture plays in both bureaucratic politics and in principal-agent problems [101, 118]. For example, Hammond noted that bureaucratic politics literature typically considers horizontal relationships between power players, rather than the politicking that can occur within an agency's hierarchical authority structure; he then illustrated how organizational architecture can influence the outcome bureaucratic politics using an example of interservice rivalry in the military [118]. Similarly, Moe suggested that elected officials can control agencies ex ante, by structuring their organizational architectures so that both the principal and the agent's interests are aligned [101]. Finally, Moe emphasized that the initial definition of a government bureaucracies' organizational architecture has profound implications on its subsequent performance and noted that "the choices about structure that are made in the first period, when the agency is designed and empowered with a mandate, are normally far more enduring and consequential than those that will be made later" [119].

To supplement the above literature and gain an improved understanding of organizational design and its implications, I draw on literature from organizational theory and product design and management. Using this literature, I identify information processing to be organizations' primary purpose [120-121] and suggest that as an organization's complexity increases, its ability to process information declines. I then identify two theoretical propositions that contribute to our understanding of organizational complexity: the congruence model and the mirroring hypothesis. Both propositions are important for understanding how organizations can be architected to manage complexity; therefore, both support my research on how jointness can induce organizational complexity and cost growth. Importantly, both propositions are also related to the four characteristics of government bureaucracy that were discussed above; in this way, the literature reviewed in this section ties directly back to the previous and informs my explicit focus on the architectures of *government* organizations.

### 2.3.1 Defining Characteristics of Organizations

Organizational theorists often define organizations as open social systems that transform inputs into outputs and that function under uncertainty [26, 122]. Critical to this transformation process and an organization's ability to cope with uncertainty is information processing, which many authors define as organizations' key purpose [120-121]. Nadler & Tushman connected the abstract concept of information processing to decision making by defining it as "the gathering, interpreting, and synthesis of information in the context of organizational decision making" [121]. When an organization manages a complex technical system, its ability to process information and to make decisions is intimately connected to the system's development, since engineering itself is fundamentally a decision making process [123].

Galbraith suggested three methods to help organizations deal with uncertainty and to enhance their ability to process information: rules and procedures, organizational hierarchy, and targeting or goal setting [120]. Rules and procedures refer to an organization's standard processes that help its members make decisions when they are confronted with situations that can be anticipated [120]. When confronted with decisions that were not anticipated (as is to be expected under uncertainty), an organization requires a chain-of-command that enables its members to elevate decisions to the organization's leaders [120]. Alternatively, to prevent all decisions from getting elevated, organizations require a consistent set of targets and goals to guide decisions and to enable them to be made at lower levels of the organization's hierarchy [120].

Galbraith's concept of hierarchy and goal setting connects directly to an organization's architecture because organizations can be decomposed into a set of interdependent components [120, 122] and it is these components and the interdependencies between them which define an organization's architecture. As noted by Galbraith and others [120-122], components depend on one another for decisions, since the authority to make decisions is either delegated downwards in an organization's hierarchy or is retained by components at the top. Components also depend on one another for task execution, since one component's output may constitute another's input [122]. As will be discussed below, when an organization is responsible for developing a technical system, the task interdependencies in the organization often "mirror" the technical interdependencies of the system [124]. Furthermore, task interdependencies typically relate to the organization's overall goal—to develop a system that executes a mission—and when this mission is clearly defined in an organization, it enables decision authority to be delegated.

Finally, organizational components depend on one another for resources [121]. A key resource in an organization is expertise so typically organizations are decomposed into components that contain experts who specialize in executing a particular task [125]. Of course, in addition to expertise, components of all social systems require money to execute their tasks; therefore, funding constitutes a final important interdependency between components in an organization's architecture [126]. Importantly, each of these interdependencies can also be connected directly to the key characteristics of government bureaucracies that were discussed above: hierarchical decision authority, agency missions, budgets, and expertise.

Organizations' architectures directly affect their ability to process information effectively. Specifically, Nadler & Tushman noted that "different organizational structures have different capacities for effective informational processing," which they define as "the collection of appropriate information, the movement of information in a timely fashion, and its transition without distortion" [121]. Because organizations can be designed [120, 126], the goal of an organization's architect is to define components and interdependencies that enable effective information processing. Failure to do so can result in an organization that is unresponsive to stimuli, that inefficiently uses its resources, and that contains components which are poorly coordinated or in conflict [126].

In this dissertation, I define organizational complexity along these lines and suggest that as an organization's architecture becomes more complex, its ability to process information and to make decisions is reduced: as a result, many of the above symptoms—which can cause the organization to make costly decisions or hinder its decision making efficiency—are observed. Motivated by the two theoretical propositions discussed below, I also suggest that complexity is induced by misaligned interdependencies between an organization's components. The literature reviewed below discusses several important misalignments that contribute to organizational complexity.

### 2.3.2 The Congruence Model

The congruence model, which was proposed by Nadler & Tushman, supposes that the degree of alignment between an organization's components determines its performance [126]. The authors defined congruence to be a measure of how well components "fit" together [126] or how aligned their interdependencies are; the key argument is that when components are aligned, the organization can effectively transform inputs into outputs and process information [126]. In this dissertation, I relate the concept of congruence to complexity and suggest that a decrease is congruence is synonymous with an increase in organizational complexity.

Nadler & Tushman's congruence model is largely concerned with the alignment between four key variables: the organization's work, employees, architecture, and culture [126]. However, in this dissertation, I specifically focus on alignment within an organization's architecture and use additional literature to understand how misaligned component interdependencies can hinder an organization's performance. From this literature, I identified two basic misalignments that can hinder information processing and decision making in an organization:

- The misalignment of responsibility and authority,
- And the misalignment of expertise and authority

The importance of aligning responsibility and authority is often stressed in strategic management literature [122, 125]; indeed, Fayol stressed the importance of their alignment by noting that "responsibility is a corollary of authority, it is its natural consequence and essential counterpart, and wherever authority is exercised, responsibility is also present" [125]. Fayol defined authority as "the right to give orders and the power to exact obedience" [125]. Contrary this definition, in the context of an organization's architecture, I define authority as a component's ability to make and sustain decisions; however, the relationship between decision authority and power is particularly salient in government organizations where principal-agent problems and bureaucratic politics abound.

Fayol defined responsibility as "the rewards or penalties that go with the exercise of power" [125] and I decompose this definition to identify two types of responsibility that are important for joint programs. The first is mission responsibility, or an agency's commitment to executing its unique mission. In the context of this research, missions are executed by technical systems; therefore, a system's mission should be aligned with its managing organization's authority structure; this type of alignment will be discussed further below. The second is budget responsibility, or an agency's financial commitment to fund a program and the decisions that its organization makes. The alignment of authority and budget responsibility is a key issue in principal-agent problems and much of the literature on this topic focuses on devising contracts between the principal and its agent that align the financial incentives of both parties with the authority that is delegated to the agent [99]. Of course, a principal-agent problem can also occur if the agent has a separate mission than its principal and it pursues that mission even though its actions may be contrary to the principal's interest. This type of principal-agent problem is also noted by Fayol, who stressed that organizations require "unity of direction" or a single goal and plan for achieving it [125].

Fayol also noted that power and authority can be derived from knowledge and expertise [125]. Particularly in organizations that manage technical systems, technical expertise may be separated from decision authority. If this is the case, Fayol warned that "a subordinate could find himself receiving orders from a person with formal authority that contradict the "orders" from another individual who has superior knowledge about (or "functional" authority) over such matters" [125]. In these situations, Fayol argued that formal decision authority is eroded and that as a result, "disorder increases" [125]. This situation is also analogous to principal-agent problems that occur in government bureaucracies, where the agent has greater expertise than the principal and as a result, can exert power over him [101]. Again, in both cases, I observe that key complexity mechanisms—or sources of misalignment—can be directly derived from the four characteristics that define government bureaucracy: authority, mission, budget, and expertise.

### 2.3.3 The Mirroring Hypothesis

Unlike my discussion of the congruence model, which drew on literature from several disciplines, my discussion of the mirroring hypothesis is grounded in a more substantial theoretical and empirical literature that specifically focuses on the topic. This literature hypothesizes that an organization's architecture mirrors the architecture of the technical system that it develops, or rather, that there is a one-to-one mapping between organizational and technical architectures [124, 127-128]. Baldwin & Clark illustrated this concept using Design Structure Matrices (DSMs) to represent a system's technical architecture and Task Structure Matrices (TSMs) to represent the interdependencies between system development tasks [124]. As illustrated in Figure 7, Baldwin & Clark claimed that the DSM and TSM are "isomorphic" and that the TSM is an "image" of its corresponding DSM [124].

Since I have defined organizations to be information-processing and decision making systems, I suggest that Baldwin & Clark's task structure refers to an organization's hierarchical authority structure, which determines how it makes decisions. Similarly, as I noted above, systems are designed to execute an agency's mission. Therefore, in the context of this dissertation, I suggest that the mirroring hypothesis corresponds to an alignment between an agency's mission responsibility and its decision authority. Importantly, this interpretation of the mirroring hypothesis also relates to agencies' desire to match their missions with their jurisdiction [94], or their authority with their ability to execute their unique missions.

The consequences of breaking the mirror—or of misaligning authority and mission responsibility—have largely been discussed only in theory [124, 127]. For example, Henderson & Clark noted that when systems' architectures fundamentally change (i.e. they undergo "architectural innovation"), the firm that manages those systems loses much of their embedded knowledge about how to manage the system [127]. The authors attributed this loss to the fact that firms structure their tasks to mirror their system's architecture and that once this architecture changes, the firm's knowledge and understanding of how to complete those tasks is lost [127]. Baldwin & Clark also suggested that mirroring between the organization and system is an essential prerequisite for the design process to work effectively [124]. These theoretical suggestions have motivated empirical studies which confirmed that in practice, organizational architectures mirror technical ones, particularly when technical systems are developed within a single firm [129-132]. A key gap in this literature is an understanding of the consequences of breaking the mirror, or how an organization's decision making is affected when decision authority and mission responsibility are misaligned. This dissertation contributes to this understanding and as above, suggests that a misalignment contributes to organizational complexity.

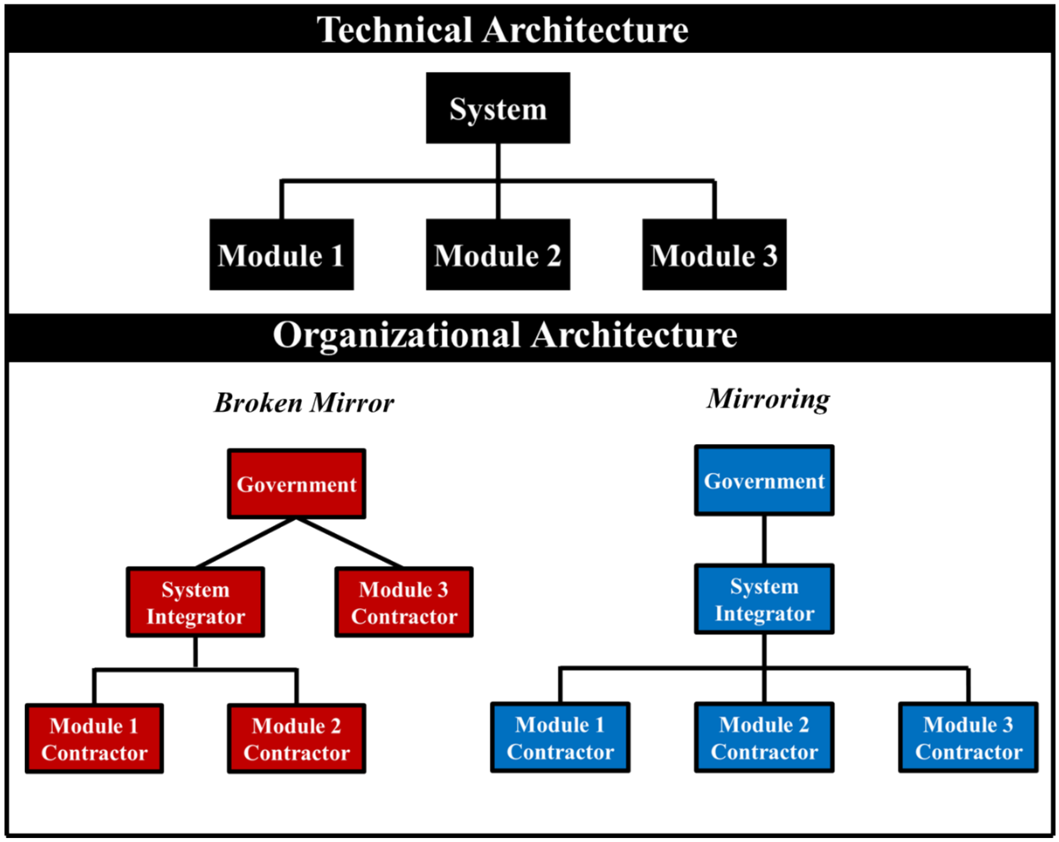



**Figure 7: Mirroring Hypothesis Illustrated**

## 2.4 Technical Architecture: Theory and Impacts

To enable the mirroring discussed above, technical architectures employ modularity, a design strategy that decomposes a system into loosely coupled components that are connected by standardized interfaces [124]; put another way, a modular system architecture is the opposite of an integrated one [133]. By modularizing a system, the system architect decomposes and decouples the tasks required to complete its development; as a result, modules can be developed in parallel by separate organizational components [134]. The degree to which a system is modular or integral is intimately connected to its architecture, which I previously defined as the components within the system and the relationships between those components [24]: if an architecture is modular, inter-component relationships are weak, however, if an architecture is integral, those relationships are strong.

Literature in this field typically focuses on two benefits of modularity: its ability to manage complexity and to enable innovation. Modularity enables complexity management by allowing complex design problems to be decomposed into simpler, smaller problems that can be handled independently [134]: essentially, modular systems "hide" complexity within their modules [124]. Since the relationship between technical complexity and jointness is a key focus of this dissertation, I review literature that discusses complexity in the context of a system's architecture here. Before reviewing this literature, I begin with a general definition of technical systems and their architectures.

### 2.4.1 Defining Characteristics of Technical Systems

A technical system can be defined in terms of the value that it provides to its stakeholders; and the architect's goal is to maximize value by maximizing benefit and minimizing cost [24]. In the context of this research, I define a system's benefit in terms of its mission: the level of benefit generated by a system depends on how well it performs its mission and how much of that mission it actually executes (i.e. it executes the entire mission or some portion of it). In the simplest sense, missions are defined by elected officials and are delegated to government agencies for execution; in reality, this process is much more complex and has motivated a separate field of research on stakeholder analysis that is not explicitly considered here (for examples, refer to [135-137]). Instead, in this dissertation, I use the simplistic conceptualization of mission definition and focus primarily on how the system itself is architected to execute the mission that it has been given.

Given a set mission, several authors have described the process for architecting a system to execute that mission, to maximize benefit, and to minimize cost. For example, Ulrich defines the system architecting process in three steps: (1) the arrangement of functional elements in a system, (2) the mapping of functional elements to physical components, and (3) the definition of interfaces between those components [133]. Ulrich then goes on to describe potential outputs of the system architecting process by defining an architecture typology that classifies systems according to their modularity schemes [133]. Baldwin & Clark also contribute to this literature by defining six modular operators that can be used by system architects to define components in their systems and the relationships between them [124].

Particularly salient for research on joint programs are the splitting, augmenting, excluding, and porting modular operators. Splitting refers to the decision to separate modules within a system [124]; by definition, joint systems *combine* rather than split when they execute more than one mission using a single system. Joint systems are also the result of augmentation, or adding new modules to a system [124], and they may port modules, or use them across multiple systems even though doing so may increase the modules' cost [124]. Finally, excluding modules from a system [124] has an obvious effect on its cost because it changes the system's boundary. In recent years, work led by Crawley has incorporated the design processes described by Ulrich, Baldwin, and Clark into quantitative models that automate the system architecting process and generate numerous options for a system's architecture using the process and the modular operators described above (for examples, see [138-140]).

In the context of this research, a system's architecture is important because it provides a venue to observe the impacts of integrating separate agency missions into a single joint system. The technical architecture also provides a starting point for studying the joint organization and the impacts of mirroring or mirror breaking. Despite these important connections to organization and administration theory, in the remainder of this section, I focus specifically on the technical architecture itself and how that architecture relates to complexity.

### 2.4.2 Technical Complexity Theory

The literature on complex systems and systems architecting contains numerous definitions of *complexity* (for example, see [24, 134, 141]). Although the specifics of these definitions vary, many share common themes that a system's complexity is a function its components, the interactions between those components, and the environment in which those components are developed or operated. In this section, I organize literature according to these three themes—or types of complexity—which I classify as:

- Architectural complexity,
- Design complexity,
- And process complexity.

Authors also generally agree that *emergence* is a key impact of complexity. For example, Simon noted that components in a complex system "interact in a non-simple way" [134] and Sussman suggested complex systems' "overall emergent behavior is difficult to predict, even when subsystem behavior is readily predictable" [142]. System emergent behavior can take many forms (for example, Leveson argued that the system safety is an emergent property [143]), however this dissertation focuses specifically on cost as an emergent property of a complex system.

The relationship between space systems' complexity and cost has been the focus of both government studies and of academic inquiries. For example, reports on the status of government space acquisitions have noted that a system's complexity correlates with its cost [78-79, 83] and that when programs underestimate their technical complexity, they experience cost growth [144-145]. Bearden confirmed this relationship in an analysis of 45 government space programs that quantified each program's technical complexity and demonstrated that a program's cost increased as an exponential function of its complexity [146]. Motivated by this finding, Filippazzo proposed a methodology to incorporate Bearden's complexity metric into system cost estimates [147] and both Alibay [148] and Selva [41] proposed alternative methods to account for complexity's cost early in the system development process—during the system architecting phase.

Theorists outside of the space acquisition community have also observed a relationship between system complexity and cost. For example, information theorists define complexity in terms of the amount of resources—in their case, time and space—that it takes to represent and complete complex computational tasks: the greater the complexity, the larger the resource demand [149-150]. Sinha also demonstrated a relationship between the time required to complete a task and the task's complexity and used this to motivate his proposal that the complexity of a system correlates super-linearly with its cost [151].

Importantly, although this dissertation focuses on cost—a negative emergent property of complex systems—complexity also has positive impacts. Often, system architects trade the cost of complexity against its benefits, since complexity can enable increased system performance or functionality [152]; indeed, Crawley argued that some of a system's complexity is *essential* to meeting its performance and functional goals [24]. However, in order to effectively trade the cost of complexity against its benefits, system architects need to understand how and why their system's complexity increases or decreases. The literature reviewed below provides some insight into architectural, design, and process complexity, and how each type of complexity can contribute to a system's cost.

#### 2.4.2.1 Architectural Complexity

The first complexity type, architectural complexity, refers both to the number of components in a system and to those components' relationships with one another. Meyer defined complexity to be function of the number of components in a system, the diversity of those components (i.e. the number of part types), and the organization of components within the system (i.e. the number of interfaces) [153]. Meyer further assumed that each component, component type, and interface contributed equally to a system's overall complexity [153].

In her complexity typology for system engineering, Sheard defined structural complexity similarly: as a function of the number of components and component types and of the components' organization within a system [154]. Importantly though, Sheard noted that component interfaces do not all contribute to a system's complexity equally. Furthermore, she suggested that that complexity is not only a function of pair-wise interfaces between components but instead, is also a function of how those components are organized in a system's architecture [154].

Sinha echoed Sheard's claim and proposed a structural complexity metric that includes *both* the complexity induced by pairwise component interactions and the complexity induced by a system's architecture [151]. Sinha used Figure 8 to illustrate how a system's architecture can contribute to its overall complexity. In the figure, both systems have the same number of components and component interfaces but have different architectures. According to Sinha's metric, System B has greater architectural complexity than System A; as a result, Sinha suggests that the cost of integrating System B will be greater than System A [151]. One of this dissertation's contributions is extending the application of Sinha's metric to organizations and developing a methodology to assign weights to interfaces between components in an organization.

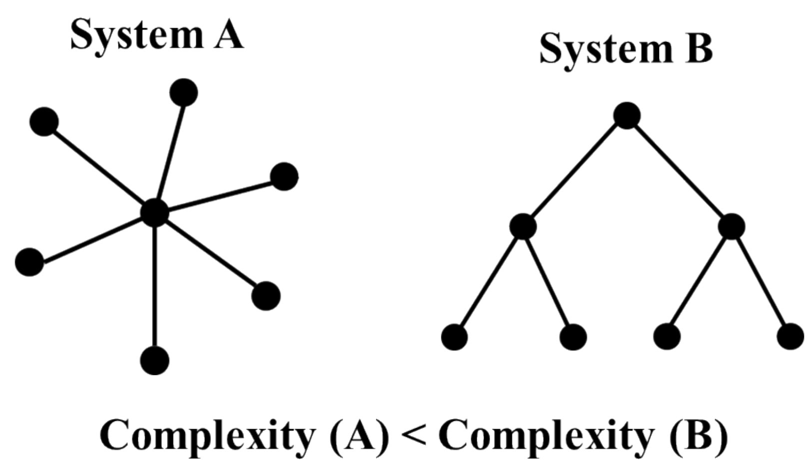



**Figure 8: Architectural Complexity Illustrated (Figure Recreated from Sinha, 2013)**

Several complexity metrics that were developed to improve the cost estimates of space systems also focus on this concept of architectural complexity. For example, Malone & Smoker suggested that cost estimates can be improved by accounting for a system's Integration Readiness Level (IRL), an analog to component technology readiness level (TRL) that focuses on the complexity of managing component interfaces during system development [155]. Additionally, both Alibay and Selva's metrics accounted for the complexity that is induced by negative interference between instruments that are hosted on the same spacecraft bus [41, 148]. In both cases, the presence of interference was assumed to increase a system's cost, since an additional investment would be required to insure that instruments interactions did not interfere with a system's overall performance. The technical complexity metric that is applied in this dissertation is derived from the one proposed by Alibay [148].

#### 2.4.2.2 Design Complexity

The second complexity type, design complexity, refers to the individual complexity of each of a system's components. Although Meyer's definition of complexity treats components equally, Sinha's does not; in fact, Sinha and other authors (for example [84, 146, 151]) have suggested that TRL can be a proxy for component design complexity. The relationship between a component's technical maturity and its complexity is echoed by Suh, who defined complexity as "a measure of uncertainty in achieving the functional requirements of a system due…to lack of understanding and knowledge about a system" [141]. Given this definition, one can argue that as a component's design matures and designers gain improved understanding and knowledge of its physical and functional properties, its complexity is reduced.

However, even if a component's design complexity decreases as its design maturity increases, as noted previously, some complexity is essential [24] and will remain constant throughout the system development process. Bearden's spacecraft complexity metrics captured several of the design variables that contribute to essential spacecraft design complexity; these include design variables that have a significant impact on system cost such as spacecraft mass and system data-rate [146]. Selva's complexity metric identified similar design variables that are available during the early system architecting process [41].

#### 2.4.2.3 Process Complexity

The third type of complexity is not a function of a technical system itself, but rather, is a function of the external processes by which a system is developed. The idea of process complexity was discussed by Sussman, who introduced the concept of "nested complexity" which, as illustrated in Figure 9, refers to a complex technical system that is "embedded within an institutional system that exhibits…complexity all on its own" [156]. The government system acquisition process has been institutionalized by strict requirements that are levied to control quality and to reduce risk during the system development process. Therefore, in the context of this dissertation, process complexity refers specifically to requirements that are levied on the system development process.

Like the other types of complexity, process complexity is also hypothesized to correlate with cost and cost growth. For example, Wertz & Larson suggested that the quality control and mission assurance requirements levied on government space systems are so stringent and numerous, that they significantly increase system cost [157]. Sheard also demonstrated that when there is "requirements difficulty" or "a fog of conflicting data and cognitive overload" on a government program, then it is more likely to experience cost and schedule growth [158]. Therefore, I suggest that process complexity can be induced both by the number and the stringency of requirements that are levied on the system development process and by conflicts in those requirements. Finally, the proposed relationship between process complexity and cost is further supported by process-based cost models that have been used—both in the government space sector [159] and in other technology intensive domains [160]—to estimate a program's costs using a bottoms-up assessment of its processes.

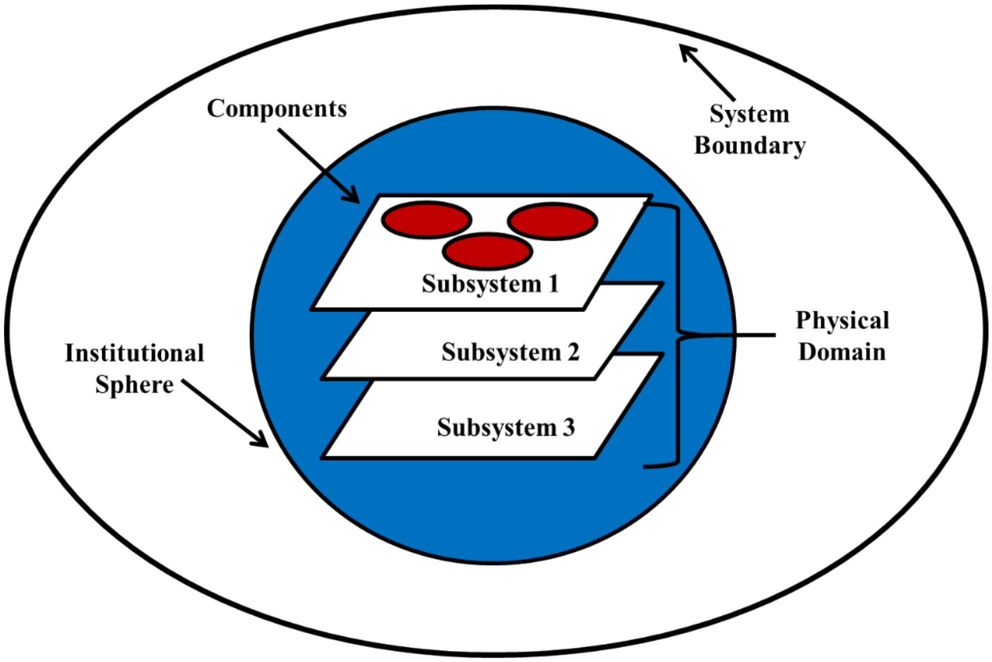



**Figure 9: Process Complexity Illustrated (Recreated from Sussman et al 2009 [156])**

## 2.5 Conclusion

In this chapter, I reviewed literature that identified common sources of cost growth on government programs. I also reviewed literature from public administration, organization, and system architecture theories and introduced key characteristics of government bureaucracies and of technical and organizational complexity. Figure 10 illustrates the relationship between the three bodies of literature that were reviewed and the direction that this dissertation expands them.

Again, I begin with Weigel's work, which suggested that a system's technical architecture provides a means to translate between the policy and the technical domains [73]. This proposed relationship motivates my focus on public administration and system architecture theories. Ultimately, this dissertation expands upon Weigel's initial claim by incorporating formal theories of public administration—which suggest that all policy decisions are all fundamentally *political*—into our understanding of policy's relationship to system architecture. This dissertation also contributes to the literature stream concerned with the management of technical systems, which is shown in Figure 10 as the overlap between system architecture and organizational theories. But most significantly, this dissertation contributes to the space that spans all three domains—technical, organizational, and political—and makes the claim that in order to understand the impacts of the government's actions, one must understand not only how an action affects the system but also how the action affects the organization and its relationship to the system that is manages. Using the theoretical literature from this chapter as motivation, in the next chapter, I propose an alternative approach for studying complex acquisition programs.

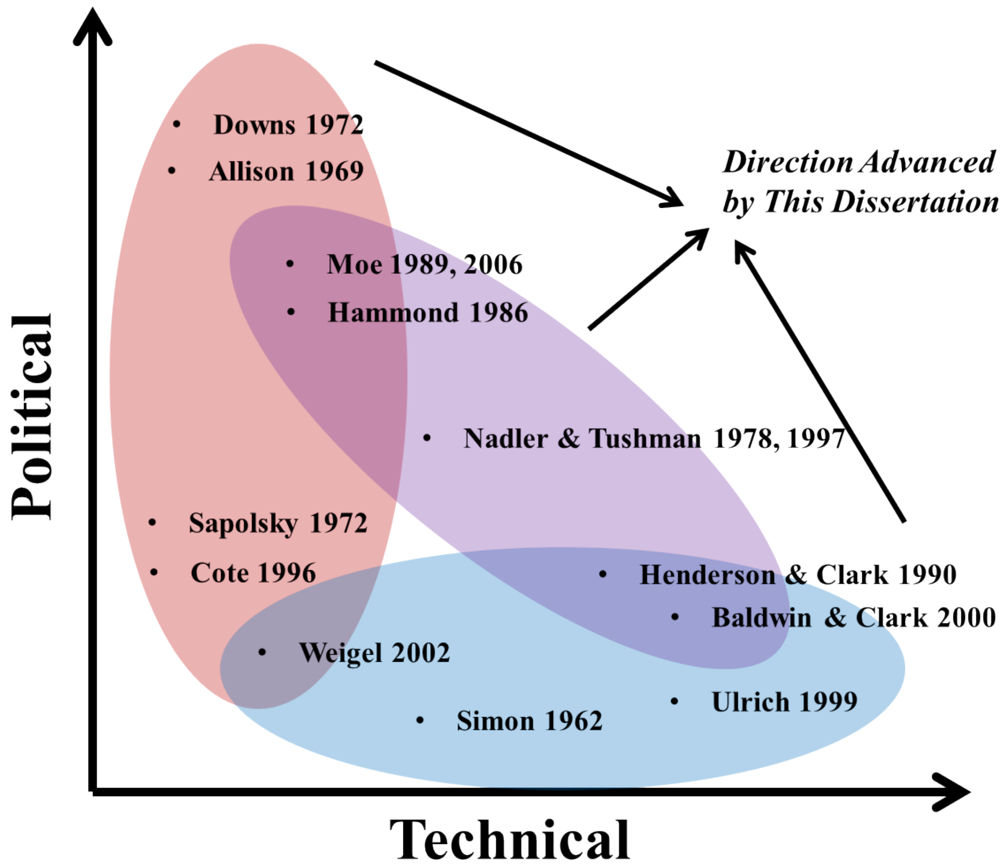



**Figure 10: Relationship Between All Three Literature Domains and The Contribution Made By This Research**

# 3 An Alternative Approach for Studying Complex Acquisition Programs

> *A common question is why JPSS costs so much. This question also applies to GOES-R. The Independent Review Team also believes this question is appropriate. Considerable attention was given to this question during the review with a total lack of success in achieving and understanding as to the answer.*
>
> –NOAA-NESDIS Independent Review Team, Chaired by Tom Young, 2012 [D142]

As described in Chapter 2, past studies of cost growth on government acquisition programs have failed to generate actionable policy recommendations because they tend to address the symptoms of cost growth, rather than its fundamental root causes. This dissertation demonstrates that in order to understand how cost growth might be induced by the government's own policies or behavior, one must consider how the government's actions affect an acquisition program's organizational and technical architectures, as well as the relationship between them. Past studies have failed to take this perspective because their data and analysis methods precluded them from doing so; therefore, in this chapter, I suggest an alternative approach for studying complex acquisition programs that addresses the short-comings of previous studies and is able to generate a unique perspective on cost growth.

Previous qualitative studies of acquisition programs have been limited by the depth and breadth of their data. Most major studies have been conducted either by the government itself (e.g. see [76-80, 83]), by advisory panels (e.g. see [11, 161]), or by independent research organizations (e.g. see [14, 81, 85]). When these groups use interviews to collect qualitative data, they tend to use structured interview formats and to primarily interview agency officials and program managers. By doing so, past studies have all but guaranteed that they will identify only the *symptoms* of cost growth. Given their location near the top of acquisition programs' organizational hierarchies, program managers and agency officials are often unable to observe the root causes of cost growth because they are too far removed from them or too busy *responding* to them. Furthermore, if managers *are* able to identify root causes, their interpretation may be colored by their role on the program.

Therefore, although management's perspective is invaluable, its value increases when it is analyzed alongside the perspectives of other staff members who were assigned to lower levels of an organization's hierarchy. Furthermore, new and more fundamental perspectives on cost growth can be gained by observing how government actions affect a staff's ability to execute their tasks efficiently and effectively. Additionally, by using structured interviews or surveys, past studies have constrained interviewees' ability to offer new insights or to do anything other than reinforce the community's accepted and already identified cost growth root causes. Clearly, the acquisition community could benefit from a research approach that surveys staff from all levels of a program's organizational hierarcy and does so in a less structured and more technically focused manner.

Past quantitative studies of cost growth were often interested in the idea of complexity and in its potential relationship to program cost; indeed, it is the hypothesized relationship between complexity and aggregation that motivated this study. Unfortunately, many researchers took a deductive approach to studying complexity and have used mathematical measures derived from complexity theory to assess the complexity of acquisition programs (e.g. see [16, 162, 163]). But in the context of an acquisition program, what does complexity actually mean? And does that practical definition resonate with mathematical theory? In an attempt to quantify and to gain statistics that relate their theoretical measures of complexity to cost, researchers often overlook these questions. Another often over-looked question concerns complexity's relationship and dependence on time: is complexity constant? Or does it, like cost, grow and evolve throughout an acquisition program's lifecycle? Without a better understanding of *what* complexity is and *how* dynamic it is, I argue that attempts to use existing complexity metrics as static assessment measures or as predictive tools is premature.

Responding to these qualitative and quantitative short-comings, I suggest an alternative approach for studying complex acquisition programs whereby the researcher collects a broader qualitative data set and organizes their data using a quantitative framework. The purpose of this approach is to enable the researcher to obtain a unique perspective on cost growth, to assess the cost impacts of government actions, and to generate actionable policy recommendations. In the remainder of this chapter, I review this alternative approach and how I applied it to study the cost of jointness.

## 3.1 Qualitative Methods

Qualitative data collection and analysis methods enable theory building and in this research, they allowed me to inductively generate practical definitions of technical and organizational complexity. Quite simply, I started my research by defining technical complexity to be anything that made a system's cost increase (expectedly or unexpectedly) and organizational complexity to be anything that hindered the organization's ability to effectively and efficiently manage a system's development. To identify these "things," which will henceforth be referred to as *mechanisms* or elements of a program's technical and organizational architectures that increased their complexity, I conducted process-centric interviews with representatives from all levels of the programs' organizational hierarchies and analyzed data both within and across cases. During data collection and analysis, I treated cost as an emergent property of the system development process that was induced by complexity.

### 3.1.1 Qualitative Data Sources

Interviews were the primary data source for the case studies. Eisenhardt & Graeber noted that although case studies can accommodate varied qualitative data sources, interviews are often case studies' primary source because they provide "a highly efficient way to gather rich, empirical data" [64]. Despite this advantage, interview data can be biased by what the authors call the "knee-jerk reactions" and "retrospective sense-making" of the interviewees [64]. To mitigate this bias, the authors recommended including organizational actors from different hierarchical levels, functions, and geographies; they also recommended interviewing analysts outside of the organization under study [64]. Following this suggestion, I selected interviewees from all three government agencies, from the programs' contractors, and from both technical and management roles. Several outside experts who served as independent program reviewers were also consulted. Initial interviewees were identified by a contact at one of the three government agencies and subsequent interviewees were identified using the method of snowball sampling.

#### 3.1.1.1 Data Sample

Table 1 provides additional description of the interviewees and their organizational affiliation and roles. Many of the people consulted for this study held multiple roles or worked for several organizations so Table 1 classifies interviewees according to the role and organization in which the interviewees spent most of their time or that were the focus of our discussion. In total, 70 different people were interviewed and over 95 hours of data were collected.

**Table 1: Summary of Interviews Conducted**

| Interviewee Classification | Number of Interviewees |
|---|---|
| **Distribution Across Cases** | |
| NPOESS Case Study | 55 |
| Plausibility Probe Case 1 | 3 |
| NPOESS & Case 1 | 3 |
| Plausibility Probe Case 2 | 7 |
| NPOESS & Case 2 | 2 |
| **Organizational Affiliation** | |
| Agency A | 19 |
| Agency B | 18 |
| Agency C | 14 |
| Contractors | 13 |
| External | 6 |
| **Programmatic Roles** | |
| Management | 8 |
| Technical--System | 28 |
| Technical--Components | 17 |
| Non-Technical | 2 |
| Oversight | 15 |
| **TOTAL Interviewees** | **70** |
| **TOTAL Hours** | **95** |

Interview data was treated as highly sensitive and confidential throughout this study. NPOESS and its predecessor programs are under political scrutiny that could have discouraged interviewees from participating if full confidentiality had not insured. Furthermore, in order to prevent deductive disclosure, which occurs when traits of an individual makes him or her identifiable [164], I have opted not only to omit interviewees' names, but to also conceal their organizational affiliation and detailed descriptions of their programmatic roles. The government space community, and particularly the portion focused on environmental monitoring, is small; therefore, I deemed it too risky to identify interviewees by anything other than the numbering system that is used throughout this dissertation.

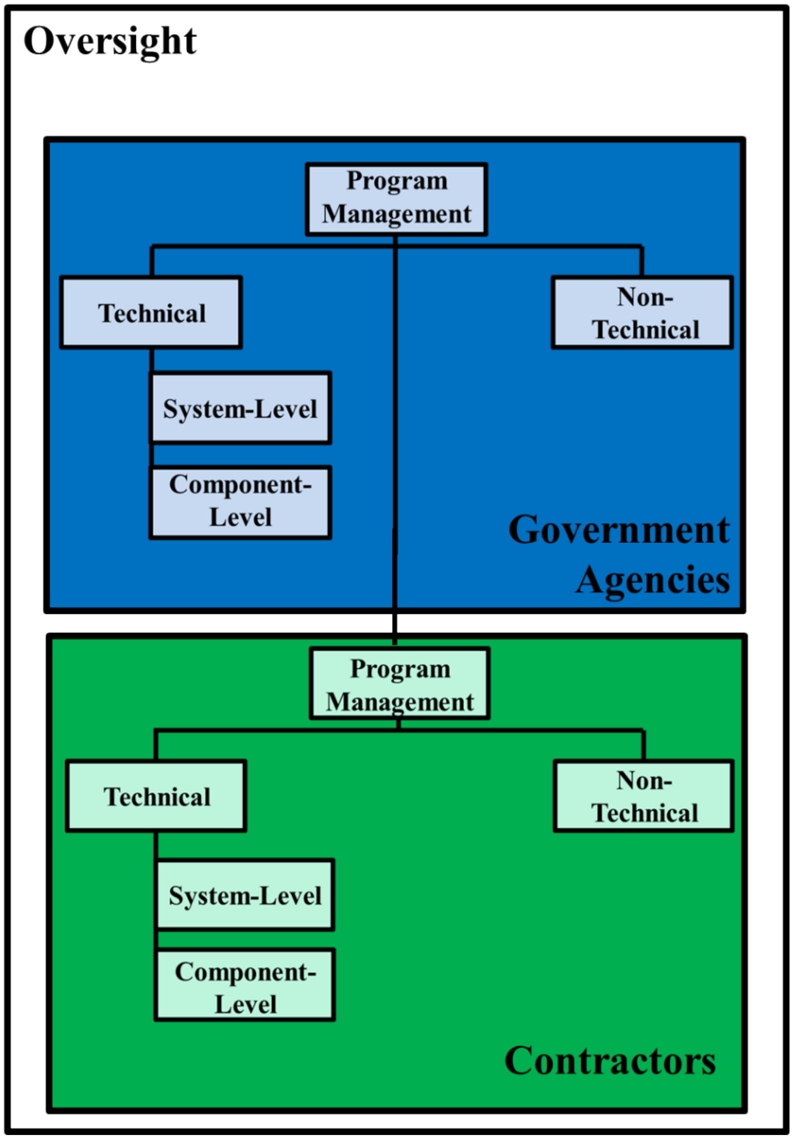



**Figure 11: Simplified Organizational Hierarchy for Interviewee Classification**

Of course, researchers must also balance interviewees' confidentiality with the need to demonstrate that their data sample is representative and comprehensive. In support of this goal, I distinguished interviewees according to the three agencies with which they worked. Interviewees were classified as working for an agency if they were a civil servant, if they worked as a government support contractor, or if they worked at a federally funded research and development center (FFRDC);. Government interviewees are distinct from contractors which include the interviewees who worked at organizations like Northrop Grumman, Lockheed Martin, and Raytheon.

Within these two categories, interviewees were further classified into four groups according to their general role and the focus of our discussion. Interviewees were classified as management if their job title was "program manager" or if they directly reported to the program manager or he directly reported to them. Outside of these managers, interviewees were classified as technical or non-technical. Technical interviewees worked either at the system-level or at the component-level. Interviewees who worked at the system-level spent the majority of their time working on larger, integrated segments of the system (such as the ground segment or the space segment) or working on the interfaces between them. Interviewees who worked at the component-level spent the majority of their time doing specialized work on a single component, such as an instrument or an algorithm. Non-technical interviewees worked primarily on the programs' budget, schedule, or contracts. Finally, interviewees were classified as external oversight if they worked in management at one of the government agencies; the primary role of these interviewees was overseeing the programs and reporting their status to agency management. External reviewers also oversaw the programs, but did so independently and usually at the request of agency management or Congress.

Figure 11 illustrates the relationship between each of these roles and a notional organizational architecture. As shown in Table 1, my data sample contained approximately equal numbers of interviewees from agencies and contractors and also included representatives from all levels of the organizational hierarchie. For additional information on individual interviewees and the codes that they were assigned, please refer to the Appendix.

#### 3.1.1.2 Data Collection

To tailor each interview to the individual interviewee's unique expertise, experience, and perspective, and I employed a semi-structured, qualitative interview approach. Following Rubin & Rubin [165], each discussion began by introducing the interviewee to my background, general research interests, and goals for the interview. Interviewees were then asked to provide a short description of their roles and responsibilities on the program. I used this information to motivate follow-up questions that were tailored to respond to the interviewees' specific experience and expertise; a copy of the interview consent form, introductory email, and a more detailed template of potential questions is included in the Appendix. Figure 12 also provides a summary of the main topics of discussion.

During each meeting, I asked the interviewee to walk through the decision making *process* associated with the program activities listed in Figure 12. This included recounting the decision point itself, the options and stakeholder preferences for each decision, and finally, how the decision was made, approved, and implemented. I also used interviews to build a detailed timeline of program events and to review and explore the assumptions, motivations, and analysis behind several key primary source documents. Interviewees were *not* asked to speculate on why their programs were cancelled or to hypothesize how jointness induces cost growth; while many interviewees did offer opinions on these topics, their suggestions were only considered if they could be substantiated with an illustrative process-centric example.

**Summary of Interview Discussion Topics**

- **System Definition**
  - Convergence Studies
  - Mission Requirements Development
  - Relationship to Heritage Systems
- **System Development**
  - Trade Studies
  - Cost and Schedule Estimation
  - Program Milestones
- **System Integration and Test**
  - Verification and Validation Requirements Development
  - Test Anomaly Root Cause Corrective Action
- **Program Divergence**
  - Trade Studies
  - Program Reviews

**Figure 12: Interview Discussion Topics**

Interview data was collected in person and over the phone. Interview lengths ranged from one half hour to four hours, although most interviews lasted between one and two hours. The majority of interviews were conducted one-on-one, although group interviews were also conducted if they were requested by the interviewees. After obtaining consent, interviews were recorded using an Olympus DM-420 digital voice recorder. Most interviewees agreed to be recorded, although several asked for the recorder to be switched off during portions of the conversation and others fully declined to be recorded. Finally, interviewees were given the opportunity to review the contents of this dissertation both to insure the validity of its conclusions and that their confidentiality had been appropriately preserved.

After interview data was collected and transcribed, it was triangulated using primary and secondary source documents from the programs [58]. Secondary source documents about the programs are widely and publicly available in the form of Congressional testimony, government reviews, and academic papers; however, several constraints limited the availability of primary source documents. First, many program documents' marking as "for official use only" or "contractor proprietary" prohibits their immediate public release. To address these limitations, I submitted two Freedom of Information Act requests. In both cases, the responsible agency reported that prohibitively expensive fees would be necessary to locate, review, and approve documents for release. Given these restrictions, I collected publicly releasable primary source data, either from the internet or from interviewees. Ultimately, I reviewed approximately 235 documents; a complete list of these documents is provided in the Appendix.

### 3.1.2 Qualitative Data Analysis

After collecting data, I analyzed it first within cases and then across cases to look for patterns and to postulate emerging theory [71]. Although Eisenhardt suggested that data analysis is central to building theory from case studies, she notes that "it is both the most difficult and the least codified part of the process" [71]. As a result, in order to identify new theoretical constructs or evidence that can be used to refine or refute existing ones, she recommended iterating between emerging theory and data and enfolding literature throughout this process [71]. Following this suggestion, I began by constructing an event database to capture the key decisions, decision processes, and the involvement of critical decision makers throughout the programs' lifecycles [58]. Using the event database as a guide, I employed process tracing [166] to identify decision processes that appeared abnormally inefficient, resource intensive, and complex.

George & Bennett described process tracing as a method that "attempts to identify intervening causal process—the causal chain and causal mechanism—between an independent variable and the outcome of a dependent variable" [57]. By tracing the system development process, I was able to identify multiple causal chains that contributed to cost growth and to observe how those chains converged or interacted. Given that multiple factors besides jointness can induce cost growth, I selected the process tracing method because it allowed me to recognize alternate mechanisms' independent and coupled impacts on program cost.

Process data was used to identify complexity mechanisms, or anything that made the systems' technical costs increase or that hindered the organizations' ability to make effective and efficient decisions. Complexity mechanisms were then organized and tracked using the quantitative framework discussed below, which ultimately enabled me to create an analytic chronology [167] of the case studies. The framework also enabled me to compare complexity mechanisms across cases, to refine my definitions of complexity, and to identify common mechanisms.

Finally, the framework facilitated theory building by providing a medium that mapped detailed qualitative process data to the programs' dynamic evolution. Using this perspective, I employed visual mapping [166] to further abstract my data and to represent the large number of dimensions contained in the quantitative framework in an even more concise manner. During the theory building process, the visual codes were rearranged, viewed from multiple perspectives, and augmented as I iterated between qualitative and quantitative data and the emerging theory [71]. Ultimately, this analysis process resulted in the creation of the Agency Action Model that is presented in Chapter 8. To further validate this model, I compared its predictions to outcomes on other joint programs and to the literature that was discussed in Chapter 2.

## 3.3 A New Quantitative Framework

As suggested above, given the extensive amount of qualitative data that was collected, a systematic framework for organizing, analyzing, and discussing the data was required to:

- Capture and categorize technical and organizational complexity mechanisms,
- Assess the relative impact of those complexity mechanisms,
- And enable the evolution of complexity to be observed and compared to cost growth.

In response, I developed a general quantitative framework for studying cost growth on acquisition programs. The framework contains five steps wherein the program's organizational and technical architectures are represented and metrics that assess their complexity are calculated. In the final step, the evolution of the program's complexity and cost is observed by plotting the complexity metrics and cost over time. To represent a program's organizational and technical architectures, I used design structure matrices (DSMs). DSMs are typically NxN matrices that are used to represent product, organizational, or process architectures or some combination of all three [168]. Previous studies [169-170] have demonstrated the utility of using DSM-based metrics to study the evolution of architectures; therefore, in order to study cost growth that was induced by complexity, I calculated metrics using the data contained in the DSMs.

### 3.3.1 Step 1: Represent the Technical Architecture

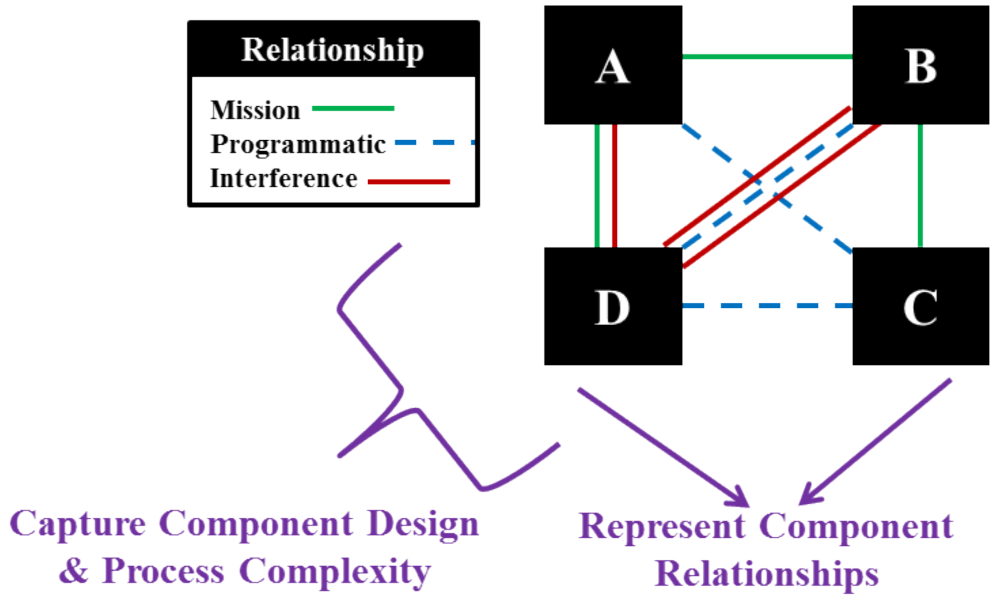
First, all major technical components were represented in the technical architecture DSM ($DSM_T$). Three types of complexity mechanisms—which emerge as a function of the individual components or the relationships between them—were also represented. Consistent with the literature reviewed in Chapter 2, the three complexity types are:

- ***Design complexity***, which is a function of the technical maturity of each component.
- ***Process complexity***, which is a function of the constraints or conflicting requirements that are imposed during the component development process.
- And ***architectural complexity,*** which is a function of the interactions and relationships between components.

As shown in Figure 13, architectural complexity mechanisms were represented using traditional DSM notation where +1 was added to indicate the presence of *any* relationship between two components. Three relationship types were captured—mission, programmatic, and interference—and the presence of each relationship added +1 to the corresponding $DSM_T$ entry; components could share more than one relationship and each relationship type added +1 to the corresponding entry in $DSM_T$.

*Mission relationships* between components include physical, data, or design interfaces as defined in [171]. Physical interfaces mean two components are physically attached and often also share other relationships (such as data or power). Two components have a data (but not a physical) relationship when they communicate at a distance and two components have a design relationship when they are designed to enable parts sharing (e.g. they are designed to maximize commonality).

*Programmatic relationships* indicate that components share management resources like budget, schedule, and staff. Although this relationship is not purely technical, I included it here because it can induce non-recurring cost growth: specifically, even though two components may not share a mission interface, they may still interface programmatically because the budget, schedule, and staff assigned to one component can impact the resources that are allocated to the other. For example, if a component's costs grow but the program's budget is fixed, management may decide to prioritize one component's development at the expense of others, whose budgets will be reduced and schedules lengthened; this decision will ultimately increase the total non-recurring cost of the lower priority components [161]. To capture this behavior, when two components did not have a mission relationship but shared a programmatic relationship, +1 was added to $DSM_T$.




| | Design | Process | | Architectural | | | |
|---|---|---|---|---|---|---|---|
| | | | | A | B | C | D |
| Component A | 5 | 2 | A | | 1 | 1 | 2 |
| Component B | 4 | 1 | B | 1 | | 1 | 3 |
| Component C | 2 | 0 | C | 1 | 1 | | 1 |
| Component D | 1 | 0 | D | 2 | 3 | 1 | |

**Figure 13: Example Technical Architecture DSM**

Finally, +1 was added to $DSM_T$ entries to account for *interferences* between components. As noted by [41, 55, 172], components can interfere electromagnetically, mechanically, optically, and through their system's reliability budget. Interferences induce complexity because they must be actively managed and compensated for during the system development process.

As also shown in Figure 13, $DSM_T$ includes two extra columns that contain a design and process complexity score for each component. The design complexity score captures the degree of cost risk associated with the component's development, since as its technical maturity increases, so does the certainty with which a program can estimate its development cost [84]. Brady & Nightingale previously demonstrated the utility of including technical maturity in a DSM when they developed the technology risk DSM to assess development and operational risk in NASA systems [173]. Although their approach used a standard TRL system to categorize component maturity [173], other rating schemes can also be applied. For example, AIAA categorizes a component's design maturity according to a component's location in the traditional development lifecycle [174].

While there is no formal scheme to categorize a component's process complexity, I suggest that +1 can be added for each process complexity mechanism. The key process complexity mechanism that affects joint programs is *conflicting requirements*. This complexity mechanism captures the costs that emerge when a program has unclear lines of authority [175], misaligned stakeholder objectives [154], or conflicting requirements which hinder its ability to function efficiently. A secondary process complexity mechanism is a function of a program's oversight model. If the government's oversight of the system's development was high, +1 was added to the process complexity score. For example, if a component was developed under a System Engineering and Technical Assistance (SETA) oversight model instead of a TSPR oversight model, +1 was added to its process complexity score. Although process and product architectures have shared DSMs differently in the past [168], because process ultimately affects the cost of the technical system, my framework represents both complexities using a shared DSM.

### 3.3.2 Step 2: Calculate Technical Complexity Metric

After the $DSM_T$ was defined, I used it to calculate a technical complexity metric; again, I define technical complexity to be a function of the number of components in a system, the complexity of the individual components, and the interactions between them. Importantly, I also suggest that as a system's complexity increases, so do its non-recurring costs; as a result, the technical complexity metric is actually an estimate of the technical architecture's lifecycle cost, with penalties applied to its non-recurring costs that account for each design, process, and architectural complexity mechanism.

Equation (1) shows the general form of the complexity-corrected lifecycle cost metric ($L_{cc}$), which includes the non-recurring costs with complexity penalties applied ($N_{cc}$), recurring costs ($R$), and other costs ($O$) which can include launch or operations costs. As shown, $L_{cc}$ is normalized by the cost of a reference disaggregated system.

$$\text{Lcc} = \frac{\text{NCC} + \text{R} + \text{O}}{\text{Baseline Complexity}} \tag{1}$$

The formula for $N_{cc}$ was derived from a complexity metric that was used to study the disaggregation of spacecraft architectures for planetary exploration [55]; while the form of this metric is similar, several of the complexity mechanisms that I identified are unique. More importantly, by classifying mechanisms in terms of three complexity types—design, process, and architectural—this approach is generalizable to other systems as well.

$$\text{Ncc} = \sum_{i=1}^{N} \left\{ \left( \sum_{j=1}^{N} \text{DSM}_{T(i,j)} - 1 \right) * W_A + PC_i * W_P + 1 \right\} * C_i(DC_i) \tag{2}$$

As shown, $N_{cc}$ is calculated using each component's design complexity ($DC_i$), process complexity ($PC_i$), $DSM_T$, and cost penalty weighting for each complexity mechanism ($W_A$ for architectural complexity and $W_P$ for process complexity). Component cost ($C_i$) can be estimated using system-specific parametric cost-estimating relationships and corrected for design complexity ($C_i(DC_i)$) either by adding a penalty to component mass prior to estimating its cost (as in [41, 55]) or by adding a penalty after its costs have been calculated (as in [176]). The weightings that are applied to correct the cost estimate for process and architectural complexity mechanisms are also system specific and should be determined on a case-by-case basis.

The particular functional form of the complexity metric was selected for several reasons. First, by using parametric cost estimating relationships, the metric captures fundamental hardware and software costs. The metric then adds penalties to account for the complexity mechanisms that are present in a system's architecture. Although these mechanisms may not ultimately increase a system's cost, their presence places the system at greater *risk* for cost growth if additional risk *margin* is not included in the *budget*. In this way, my metric calculates the basic cost of the system and adds a complexity budget [177] or a complexity *margin* on top of that cost. The reason for adding this margin is simple: if past programs had recognized complexity in their system and budgeted for it, their costs may not have exceeded their budgets.

To specifically calculate the metric for environmental monitoring systems, I used the complexity of the space segment as a proxy for the complexity of the entire system. Therefore, my metric included space segment and launch costs but excluded ground system and operations costs. For a specific description of the spacecraft design model, the parametric cost equations, and complexity penalties used, please refer to the Appendix.

### 3.3.3 Step 3: Represent the Organizational Architecture

The organizational DSM ($DSM_O$) mapped the key interdependencies between components of an organization, where components were distinct sub-units that included government agencies, user communities, program offices, and contractors. As shown in Figure 14, the $DSM_O$ actually contained four distinct DSMs that mapped four different interdependencies between organizational components. $DSM_O$ also indicated interdependency strength; a score of +2 is used when components' relationship is weak and +1 is used when the relationship is strong. Consistent with the key characteristics of government bureaucracies that were introduced in Chapter 2, the four interdependency types are defined in terms of:

- ***Expertise:*** When a component has expertise (E), it has the knowledge and experience to make decisions effectively. $DSM_E$ is shown in blue.
- ***Responsibility:*** When a component has responsibility (R), it is responsible for delivering a technical system that executes a mission. Responsibility will also be referred to as *mission* responsibility when it is necessary to distinguish between multiple agencies' unique missions. $DSM_R$ is shown in green.
- ***Budget:*** When a component has budget (B), it is responsible for funding the decisions that it makes and the technical system for which it is responsible. $DSM_B$ is shown in yellow.
- ***Authority:*** Finally, when a component has ***authority*** (A), it is able to make and sustain effective decisions. $DSM_A$ is shown in red.

Although the four relationship types are depicted separately, the two relationships that contributed most significantly to the organizational complexity metric (defined in the next step) are *responsibility* and *authority.* An example mission responsibility relationship between two component contractors is illustrated in Figure 15. These contractors share a mission responsibility relationship because the technical components that they produce share an interface: in order to execute their mission, both components need to function. In this way, responsibility relationships between contractors *mirror* [124, 127] the program's technical architecture. However, in addition to this mirroring, mission responsibility relationships on government programs extend throughout the program's organizational hierarchy and ultimately connect agency leaders, who Congress holds responsible for mission execution, to the contractors that agencies hold responsible for a system's development.

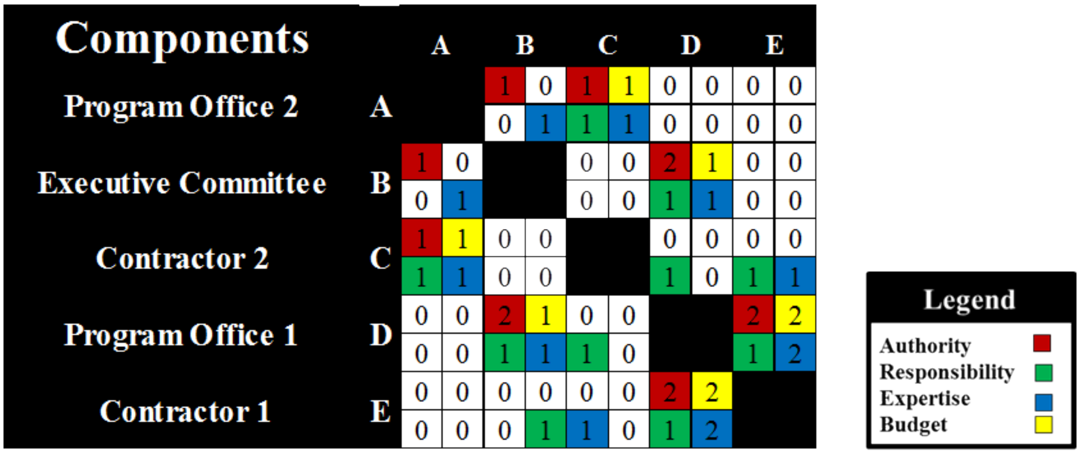



**Figure 14: Example Organizational Architecture DSM**

$DSM_A$ represents the organization's authority structure. As shown in Figure 15, Program Office 1 holds a contract for Component 1 and Program Office 2 holds a contract for Component 2; additional decision authority relationships between components are also illustrated. Figure 15 also notes that although there is a responsibility link between the component contractors, there is no authority relationship. This misalignment of responsibility and authority is critical to the organizational complexity metric that is discussed below; it also echoes the mirroring hypothesis concept and agency interests in matching missions and jurisdictions that were discussed in Chapter 2.

In addition to the misalignment of responsibility and authority, additional misalignments between authority, responsibility, expertise, and budget can also affect an organization by eroding authority. Although these relationships can be conceptualized in terms of their impact on decision authority, they are represented in separate DSMs because they are key characteristics of government bureaucracies and because they all relate to the concept of jointness; as noted previously, the ability to share budget between organizations or to capitalize on one organization's unique expertise are common motivations for jointness.

### 3.3.4 Step 4: Calculate Organizational Complexity Metric

To assess organizational architectures, I used a separate metric and defined organizational complexity *(OC)* to be a function of the number of components in an organization, the interfaces between each component, and components' mission responsibility and decision authority. I suggest that as an organization's complexity increases, it becomes more difficult for the organization to make effective and efficient decisions; as a result, complex organizations are more likely to enable and induce cost growth.

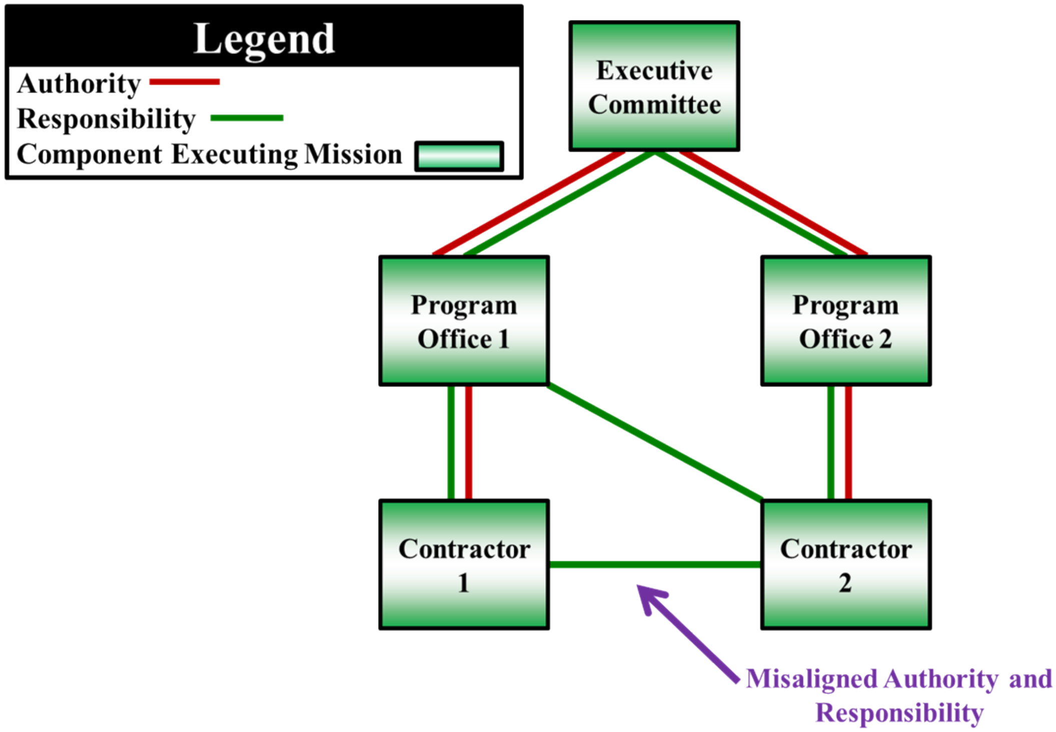



**Figure 15: Misalignment of Responsibility and Authority**

Although recent studies of organizational complexity in government-funded engineering projects have demonstrated that complexity correlates with cost growth [151, 158, 163, 175], within this set of research, authors use different metrics to assess complexity. Despite the quantitative differences between their metrics, authors generally agree that organizational complexity is a function of the number of components and the interfaces between them [151, 163]. Additionally, previous studies have also suggested that convoluted authority structures have contributed to organizational complexity on past joint programs [10, 12, 17, 56]. The metric that I propose to assess organizational complexity accounts both for the number of interfaces, the number of components, and for the authority structure in a joint program's organizational architecture.

The proposed organizational complexity metric, given in Equation (3), is derived from a structural complexity metric proposed and validated by Sinha [151]. Sinha defined structural complexity to be a function of the number of elements in a system and the connectivity structure between those elements [151]; unlike other metrics that have been used to assess organizational complexity, Sinha's metric uniquely captures not only the number of interfaces between components but also the connectivity of those interfaces [151]. This provides a richer measure of the complexity is inherent to an architecture but that is not captured by a simple interface count [151]. Although Sinha's metric has only been applied to assess the complexity of technical architectures, by calculating complexity using $DSM_R$ (which mirrors much of the technical architecture), my proposed metric is only a minor extension of previous work. Furthermore, my definition of complexity is similar to Sinha's, who focused on complexity's impact on the system development process [151].

The most significant difference between my proposed metric and Sinha's is the weighting scheme that I developed to assess the complexity of organizations. The final organizational metric is shown in Equation (3) where $W_A$ corresponds to the weighting scheme, $N$ corresponds to the number of components and $E(DSM_R)$ corresponds to singular values of the $DSM_R$ matrix. Finally, like $L_{cc}$, $OC$ is normalized by a reference disaggregated organization.

$$OC = \frac{N + \left\{ \sum_{i=1}^{N} \sum_{j=1}^{N} W_{ij} * DSM_R(i,j) \right\} * \left[ \frac{1}{N} \right] * E(DSM_R(i,j))}{\text{Baseline } OC} \qquad (3)$$

The process for calculating Equation (3)'s weights began by adjusting $DSM_A$, to account for factors that eroded decision authority. For each factor, a score of +1 was added to each affected decision authority link. The authority erosion factors included in the metric primarily stemmed from misalignments between responsibility, authority, expertise, and budget. Additional case-specific factors that eroded authority were also included in $DSM_A$ by adding +1 to each interface where authority was eroded.

Once $DSM_A$ was adjusted to account for all authority erosion factors, $DSM_A$ and $DSM_R$ were compared and misalignments between the two were identified. If authority and responsibility between two components were misaligned, an additional penalty was calculated and added according to the following process: first, the adjusted $DSM_A$ was transformed into a graph, where components were represented by nodes in the graph and authority links were represented by edges. Edge lengths corresponded to the values in the adjusted $DSM_A$. Next, when a mission responsibility link between two components existed, the weighting, $W_A$, between those components was calculated by determining the shortest path length between components $i$ and $j$ in the authority graph. The length of the authority path between two components with shared responsibility was intended to simulate the efficiency and effectiveness of organizational decision making.

### 3.3.5 Step 5: Observe Evolution of Complexity Over Time

The utility of calculating a single complexity metric to represent a program's organizational and technical architectures is that it enables changes in those architectures and their relationship to the program's reported cost growth to be observed over time. Specifically, I recommend studying acquisition programs in terms of *epochs,* or periods of time when a program's organizational and technical architectures were unique and stable. One organizational and technical architecture should be defined per epoch, a complexity metric for each should be calculated, and complexity should be plotted as a function of time and compared to the program's cost during each epoch. Plotting the complexity metrics in this way enables the researcher to identify epoch shifts that induced complexity and to compare the program's own cost estimates to the complexity that was inherent to its architectures.

Importantly, I also propose that epochs shift and that organizational and technical architectures change in response to government actions that require them to do so. Thus, by identifying actions that induced epoch shifts and observing how complexity changed from one epoch to the next, the framework enables the researcher to observe how government actions impact technical and organizational complexity.

## 3.4 Conclusion

This chapter proposed a new approach for studying complex acquisition programs. The approach recommended collecting a broad range of qualitative, process-centric data from interviewees who worked in all levels of an acquisition program's organizational hierarchy. Next, I recommended that the qualitative data be analyzed to identify complexity mechanisms in an acquisition program's organizational and technical architectures. I then proposed using a quantitative framework to organize those complexity mechanisms, to assess their impact, and to observe how complexity evolves over time.

The goals of this approach were three-fold:

- To generate a practical and more detailed understanding of complexity in the context of government acquisition programs,
- To observe how complexity changes throughout a program's lifecycle and is impacted by government actions,
- And to generate actionable recommendations for future policy.

In the subsequent chapters, I apply this research approach and demonstrate that it meets the above goals. Despite this success, it is important to note the limitations of my proposed approach and how it can be improved by future research. First, my approach used practical definitions of complexity that were generated inductively. Although the definitions of complexity and the identified complexity mechanisms resonate with the literature reviewed in Chapter 2, my practical concept of complexity may not be comprehensive. Future work may use additional qualitative, process-centric data from other programs to enhance the concept of complexity that is used here. Second, the quantitative framework uses two metrics that are intended to aid *observation* rather than *prediction*. The metrics are useful because they enable the researcher to observe the dynamics of complexity throughout a program's lifetime. Since cost estimates are uncertain at different points a system's lifecycle and often grow throughout, for my case studies, it was impossible to calibrate each epoch's metric. If future studies use this approach or it is used to track acquisition programs as they are in progress, these or similar metrics may be calibrated and used as predictive tools in the future.

Despite these limitations, the most important strength of the proposed research approach is that it combines detailed process-centric information about a program's activities during each epoch with a simpler, but global view of a program's evolution across epochs. In this way, the approach enables the researcher gain an understanding of how microscopic within-epoch behavior relates to macroscopic trends across epochs. In doing so, the researcher can gain unique insight into how acquisition programs function and those functions are impacted by government actions.

By recounting the history of the NPOESS, JPSS, and DWSS programs, the next chapter demonstrates the wealth of information that a researcher must collect, analyze, and synthesize in order to study complex acquisition programs. In this way, Chapter 4 further motivates the need for a new research approach that is capable of parsing through detailed within-epoch data, of observing global trends, and of motivating generalizable conclusions. Thus, in the next chapter, I present a history of the NPOESS, JPSS, and DWSS programs by qualitatively describing their organizational and technical architectures. In the chapters that follow, I then dissect those architectures to identify complexity mechanisms, to represent them in DSMs, and to observe how the programs' complexity evolved over time.

# 4 A Review of Environmental Monitoring Systems in Low Earth Orbit

*History is a relentless master. It has no present, only the past rushing into the future. To try to hold fast is to be swept aside.*

– John F. Kennedy [178]

This chapter presents a descriptive history of environmental monitoring in low Earth orbit, from 1993 to 2012. In support of later chapters' analysis, this chapter recounts the history of the NPOESS, JPSS, and DWSS programs with respect to their organizational and technical architectures during seven epochs when those architectures were unique and stable. For each epoch, I begin with an overview of the programs' activities and continue by presenting the reasons that the programs transitioned from one epoch to another. Next, I provide a detailed qualitative description of the epoch's organizational and technical architecture. I also highlight the relationships between agencies and architectural variables that are critical to my subsequent analysis of complexity and cost. Importantly, although the intent of this chapter is *not* to identify complexity mechanisms that contributed to cost growth, this chapter establishes the foundation that is necessary to have that discussion in later chapters. Thus, the purpose of this chapter is to establish the lexicon that is necessary to communicate later chapters' analysis and conclusions, to highlight critical events, and to foreshadow themes that are critical for understanding the cost of jointness.

## 4.1 Introduction to Environmental Monitoring in Low Earth Orbit

It is impossible to divorce the history of the NPOESS, JPSS, and DWSS programs from the multiple programs, missions, and systems that preceded them. Although much of the environmental data collected by the pre-NPOESS systems was common, each agency utilized their polar-orbiting spacecraft to support three distinct missions: operational weather, operational climate, or climate science. A successful operational weather mission provides short to medium term forecasts (less than ten days). These forecasts support military operations by predicting the space, air, land, or sea conditions that affect the DoD's ability to execute its national security missions. They also enable NOAA meteorologists to warn civilians of impending severe weather.

The National Academy of Sciences distinguishes climate from weather by describing climate as "the long term statistics of weather" [D34]; correspondingly, NOAA's operational climate mission enables the agency to produce seasonal and inter-annual forecasts. Finally, NASA's climate science mission studies climate variability and long term climate change; while the climate science mission success criteria are more ambiguous than those used to evaluate operational missions, its goal is to improve scientists' understanding of the processes and key variables that drive long term climate behavior. Although the climate science mission supports scientific research, particularly in Earth observation, there is an extensive history of transitioning the technologies originally developed for research missions into later use on operational systems [D33, D34, D37].

Before the NPOESS program, the DoD executed its operational weather mission primarily by collecting cloud cover imagery using DMSP. The DMSP constellation consisted of two satellites with three main sensors, the Operational Linescan System (OLS), the Special Sensor Microwave Imager Sounder (SSMIS), and the Space Environment Sensor (SES). The OLS collected visible and infrared imagery with constant resolution across its cross-track scan and had the ability to produce optical images in low light [D103]. The SSMIS was a conically scanning microwave imager-sounder that produced temperature, pressure, and humidity profiles and other data products including soil moisture and ocean wind speed [D103]. The SES was a sensor suite that monitored charged particles, ionospheric plasma drift, and geomagnetic fields [D103]. The DoD directly managed DMSP through its Air Force Space and Missile Center, an acquisition center with considerable experience managing technology development and system acquisition for all of the Air Force's satellite programs.

NOAA executed its operational weather mission primarily using radiometric and sounding data POES. The POES constellation was composed of two satellites, each populated by five main sensors: the High Resolution Infrared Sounder (HIRS), the Advanced Very High Resolution Radiometer (AVHRR), the Advanced Microwave Sounding Unit (AMSU), the Space Environmental Monitor (SEM), and the Solar Backscatter Ultraviolet Radiometer (SBUV). HIRS and AMSU were cross-track infrared and microwave sounders that worked together to produce temperature and humidity profiles [D103]. AVHRR provided visible and infrared imagery, and SEM primarily detected charged particles [D103]. While each of these instruments also supported NOAA's operational climate mission, SBUV, which measured ozone profiles and backscatter radiation, was a dedicated climate instrument. POES also carried two secondary payloads, the Data Collection System (DCS) which collected, stored, and then transmitted environmental data from collection sites throughout the world [D39], and the Search and Rescue Satellite-Aided Tracking (SARSAT) system, which detected and located emergency signals [D39].[3] In contrast to the DoD's independent management of DMSP, NOAA used NASA as its acquisition agent and assumed responsibility for the POES mission *after* its satellites had been demonstrated on-orbit.

NASA executed its climate science mission using the diverse instrument suites aboard the Aqua, Aura, and Terra spacecraft in its EOS program; to meet climate scientists' requirement for long term and continuous data, NASA planned to fly three copies of each satellite for a total mission duration of 15 years [D118, I37]. The EOS sensors that later influenced the NPOESS program include the Clouds and the Earth's Radiant Energy System (CERES), the Moderate-Resolution Imaging Spectrometer (MODIS), the Atmospheric Infrared Sounder (AIRS), and the Advanced Microwave Scanning Radiometer-EOS (AMSR-E). CERES provided long term measurements of the earth's radiation budget and AMSR-E produced multiple data products including sea surface temperature and ocean wind fields [D103]. MODIS and AIRS significantly extended the performance and functionality of NOAA's AVHRR and HIRS. Key MODIS data products included aerosol concentration, cloud properties, vegetation index, ocean color, and chlorophyll concentration; and like NOAA's HIRS instrument, AIRS worked with AMSU to produce enhanced temperature and humidity profiles [D103]. Importantly, unlike DMSP and POES, NASA's EOS program was planned to continue after the formation of the NPOESS program; EOS Terra launched first in 1999.

[3] Neither SARSAT nor DCS were developed by NOAA. Both instruments were provided by international partners.

The government's interest in converging POES and DMSP dates back to 1972, when NOAA and the DoD first studied opportunities for converging their systems [D195]. After eight convergence studies [D195], the NPOESS program was finally formed in 1994 as part of President Clinton's National Partnership for Reinventing Government, a policy initiative with the goal of streamlining the government's functions and reducing its spending [D75]. The joint program that resulted was affected by each of the programs and missions described above; therefore, in the next sections, I present key elements of the NPOESS, JPSS, and DWSS organizational and technical architectures and relate these elements to their heritage in DoD, NOAA, and NASA programs. By presenting these relationships explicitly, I hope to enhance the clarity of my subsequent presentation of the programs' history, which requires a working knowledge of the multiple programs, agencies, and technologies that have historically monitored the environment from low Earth orbit.

### 4.1.1 Technical Architectures for Environmental Monitoring in Low Earth Orbit

The NPOESS technical architecture was composed of three major components: the space segment, the Command, Control, and Communications (C3) segment, and the Interface Data Processing (IDPS) segment [D154]. The NPOESS space segment consisted of multiple satellites in sun-synchronous polar orbits and each satellite was populated by approximately the same complement of sensors. The space segment interfaced with the ground system, which was composed of the C3 and IDPS segments. The C3 segment, which consisted of a network of ground-based receivers, interfaced directly with the space segment via an X-band downlink [D192]. The C3 segment transmitted the Raw Data Records (RDRs) that it received from the space segment to the IDPS segment using a network of dedicated and commercial antennas [D192]. Finally, the IDPS converted the RDRs first to Sensor Data Records (SDRs), or geolocated and calibrated temperatures or radiances, and then finally to Environmental Data Records (EDRs), or environmental variables referenced to their source location, which were the system's final product [D162]. NPOESS planned to install the IDPS system at four locations (referred to as Centrals): NOAA's Satellite and Information Service (NESDIS) in Suitland, Maryland, the Air Force Weather Agency (AFWA) in Omaha, Nebraska, the Fleet Numerical Meteorological and Oceanography Center (FNMOC) in Monterey, CA, and the Naval Oceanographic Office (NAVOCEANO) in Mississippi [D39]. Figure 16 illustrates a simplified schematic of the NPOESS technical architecture.

NPOESS satellites populated orbits with early morning, mid-morning, and afternoon equatorial crossing times and after the program's cancellation, JPSS and DWSS satellites were planned for the early morning and afternoon orbits.[4] The NPOESS, DWSS, and JPSS satellites were populated by different complements of the following instruments: the Visible Infrared Imager Radiometer Suite (VIIRS), the Cross-Track Infrared Sounder (CrIS), the Advanced Technology Microwave Sounder (ATMS), the Conical Microwave Imager Sounder (CMIS), the Ozone Mapping and Profiler Suite (OMPS), the Space Environmental Sensor Suite (SESS), the Earth Radiation Budget Sensor (ERBS), the Total Solar Irradiance Sensor (TSIS), the Aerosol Polarimetry Sensor (APS), the radar altimeter (ALT), and NOAA's SARSAT and DCS. Further discussion of the 13$^{th}$ instrument, the survivability sensor, is omitted from this dissertation because some of its functions were classified. Table 2 provides further information on the

[4] Note that the morning and afternoon orbits are also identified by the exact times that they cross the equator. On NPOESS, the early morning orbit had a 5:30 crossing time and the afternoon orbit had a 13:30 crossing time.

relationship between NPOESS, JPSS, and DWSS instruments and the predecessor NOAA, DoD, and NASA instruments from which they derive their functional and performance heritage.

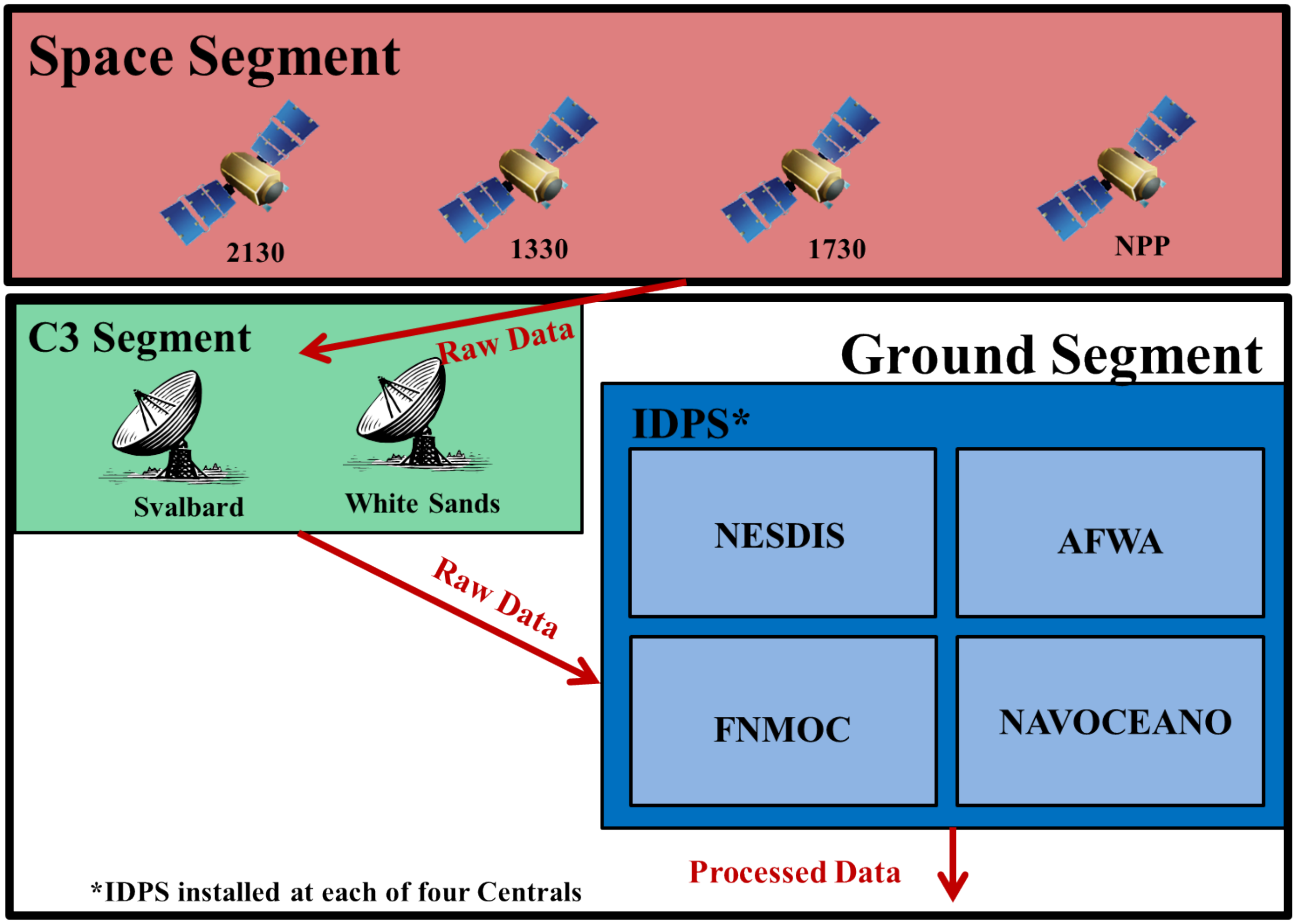



**Figure 16: Simplified Schematic of NPOESS Technical Architecture**

The functions and performance of the NPOESS technical architecture were specified by the Integrated Operational Requirements Document (IORD), which was a performance-based specification that was written in terms of the system's final data products: its EDRs. For each EDR, the IORD defined a set of system-level performance parameters; for example, the IORD specified its soil moisture data product in terms of sensing depth, horizontal resolution, vertical sampling interval, mapping accuracy, and measurement accuracy [D87]. To achieve the desired performance for each data product, performance requirements were derived and levied on each component of the system. Importantly, the task of deriving component performance requirements and of defining component design specifications was not executed by the NPOESS program office itself. Instead, in accordance with the DoD's the Total System Performance Responsibility (TSPR) acquisition strategy, the program's prime and subcontractors were authorized to design and develop the system's components with limited government oversight and according to their more cost-effective commercial best practices [D78]. Although the risks associated with TSPR have since been realized and its use discontinued, many DoD programs used TSPR in the late 1980s and early 1990s, just prior to the start of the NPOESS program. In an attempt to correct for the known flaws in its planned TSPR acquisition strategy, the program utilized a slightly modified Shared

System Performance Responsibility (SSPR) contracting structure. Although SSPR intended to increase the government's oversight and insight into the system development process, in practice, there was little difference between SSPR and other programs that used a TSPR contract structure [D78, D195, I13, I19, I22, I46]. In contrast, although both JPSS and DWSS were established using the IORD's requirements, neither program used a TSPR or SSPR acquisition strategy. Instead, NASA assumed the role of the system integrator on JPSS [I69, I59] and DWSS program management stressed a "back to basics" acquisition strategy that emphasized increased government oversight of the program's contractors [D51].

**Table 2: NPOESS Instruments and Their Relationship to Heritage**

| NPOESS Instrument | Heritage Instruments | Agency | Program | Primary Mission |
|---|---|---|---|---|
| Visible Infrared Imager Radiometer Suite (VIIRS) | AVHRR | NOAA | POES | Operational Weather, Climate |
| | OLS | DoD | DMSP | Operational Weather |
| | MODIS | NASA | EOS | Climate Science |
| Cross-Track Infrared Sounder (CrIS) | AIRS | NASA | EOS | Climate Science |
| | HIRS | NOAA | POES | Operational Weather, Climate |
| Advanced Technology Microwave Sounder (ATMS) | AMSU | NOAA | POES | Operational Weather, Climate |
| Conical Microwave Imager Sounder (CMIS) | SSMIS | DoD | DMSP | Operational Weather |
| | AMSR-E | NASA | EOS | Climate Science |
| Ozone Mapping and Profiler Suite (OMPS) | SBUV | NOAA | POES | Operational Climate |
| | TOMS | NASA | TOMS Earth Probe | Climate Science |
| Space Environmental Sensor Suite (SESS) | SEM | NOAA | POES | Operational Weather |
| | SES | DoD | DMSP | Operational Weather |
| Earth Radiation Budget Sensor (ERBS) | CERES | NASA | EOS | Climate Science |
| Total Solar Irradiance Sensor (TSIS) | TIM | NASA | SORCE | Climate Science |
| | SIM | NASA | SORCE | Climate Science |
| Aerosol Polarimetry Sensor (APS) | N/A | N/A | N/A | Climate Science |
| Radar Altimeter | Radar Altimeter | NASA | TOPEX | Climate Science |
| | Radar Altimeter | DoD | Geosat | Operational Weather |

### 4.1.2 Organizational Architecture for Environmental Monitoring in Low Earth Orbit

Although many components of the NPOESS, JPSS, and DWSS technical architectures were common, their organizational architectures differed. The NPOESS organizational architecture contained representatives from each of the agency collaborators and from the user groups that they supported. The first component was the Executive Committee (EXCOM), which was composed of leaders from all three partnering agencies. The EXCOM held budget responsibility for the program and the authority to make any decision that affected the system's baseline missions [D124]. For all technical decisions that did not directly impact the system's baseline, the EXCOM delegated decision authority to the Integrated Program Office (IPO) [D124]. The IPO, which was staffed with representatives from all three agencies, was responsible for mission execution [D124]. The third component, the user community, was composed of a hierarchy of users; both the IPO and EXCOM were responsible for executing a mission that met the needs of these users. Finally, when NPOESS was cancelled in 2010, the DoD and NOAA were assigned authority for the separate DWSS and JPSS programs and NASA continued as NOAA's partner on JPSS and helped the agency implement its requirements.

In subsequent sections, I will expand upon the organizational architecture described above in order to include the NPOESS Preparatory Project (NPP) and the program's prime and subcontractors. For clarity, in subsequent sections, when I use the terms "IPO" or "NPP program office," I refer to the distinct components in the program's organizational architecture. However, when I use the term "the program" or "the NPOESS program," I refer to all elements of the organizational architecture, including both the IPO and the NPP program office.

# 4.2 Epoch A

The NPOESS program was officially established by Presidential Decision Directive NSTC-2, "Convergence of U.S. Polar-Orbiting Operational Environmental Satellite Systems" in May 1994 [D43]. In this directive, President Clinton ordered the DoD and NOAA to converge DMSP and POES and to satisfy their operational missions jointly using a single shared system that would be developed and operated by an integrated program office [D43]. Clinton's decision directive emphasized that the primary motivation for convergence was cost savings; in particular, Clinton's reinventing government initiative found that by converging the two programs, $1.3 billion would be saved over the course of ten years [D75]. Clinton's cost estimate was supported by technical studies that explored the cost savings that would be enabled by convergence [D44]; several of these government studies are discussed below.

Following Clinton's directive, the NPOESS IPO was established in October 1994 [D195] and soon afterwards, the program began Phase 0 studies of potential technical architectures and joint requirements [I11, I15, D61]. The results from these studies were used to generate the program's IORD-I requirements document and the release of this document in 1996 marks the end of Epoch A. Also during this epoch, NASA, NOAA, and the DoD signed a Memorandum of Agreement (MOA) to formalize their roles and responsibilities within the program; the contents of this document are described in detail in Section 4.2.3.

## 4.2.1 Transition to Epoch A

The similarities between the technologies employed by DMSP and POES motivated many government studies of their convergence. Specifically, just prior to Clinton's decision directive, the GAO reported that over 70% of the bus components and 50% of the sensor components were common across the two programs [D229]. Furthermore, in addition to these hardware commonalities, the programs shared their raw and processed data through the NOAA/DoD Shared Processing Program [D162]. Despite these similarities, each time that the agencies studied convergence prior to 1994, their concerns over data control and dissemination overwhelmed their interest in cost savings; specifically, while the DoD's national security mission required the ability to selectively deny data to users, international partnerships and data sharing were central to NOAA's civilian mission [D83, I3, I33, I36]. Secondarily, agency representatives argued that convergence did not properly align with their plans to deploy existing operational assets that were either in storage or already under development [D44]. Finally, agency officials also questioned the true alignment of the DMSP and POES missions and the ability of a converged program to actually reduce agency costs [D230].

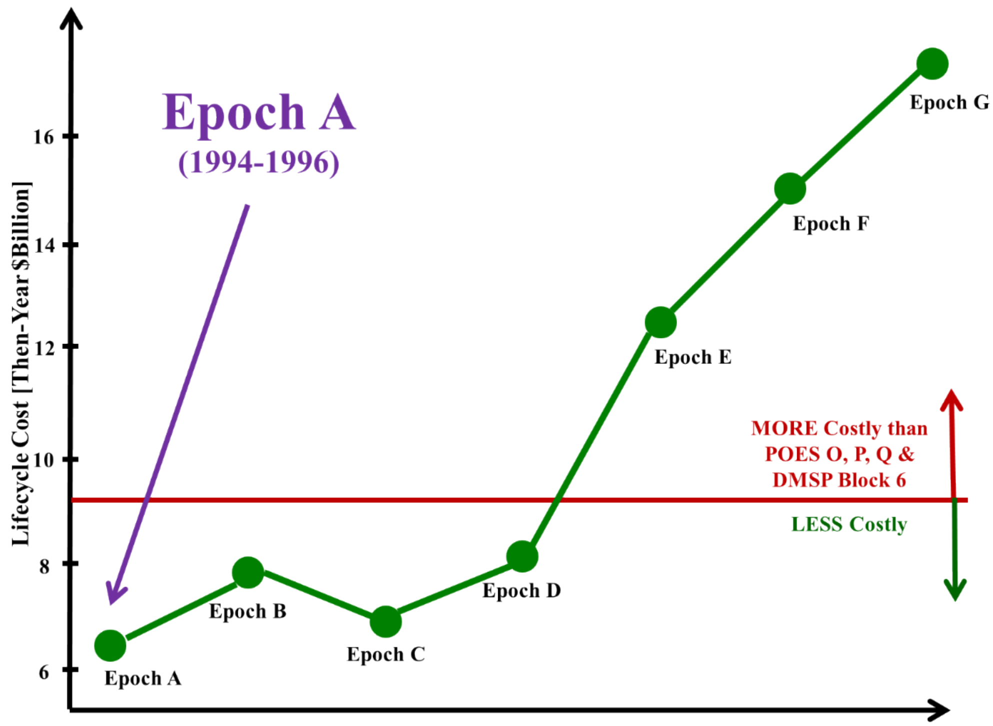



**Figure 17: Cost Growth in Epoch A**

Just prior to the presidential mandate that formed the NPOESS program, several critical factors aligned to overwhelm the agencies' previous hesitation to converge. First, advances in encryption technology allowed data to be selectively denied in an otherwise open environment [I3, I36]. Second, both agencies were in the process of studying concepts and technologies for follow-on systems; as a result, for the first time in twenty years, the agencies' plans to fly out and to upgrade their existing assets appeared to be aligned [D44, I37]. Third, despite ongoing studies, both programs faced budget reductions that threatened their ability to execute system upgrades independently [I3, D195]. Finally, because convergence was well-aligned with Clinton's reinventing government initiative, it garnered political interest from Congressional and executive leadership [D195]. With this confluence of factors, after the agencies completed their eighth study in March 1993, convergence seemed nearly inevitable; indeed, Clinton issued his decision direction shortly afterwards in May of the following year.

### 4.2.2 Epoch A Technical Architecture

The technical architecture that enabled $1.3 billion in lifecycle cost savings was defined in a Convergence Study by the White House Office of Science and Technology Policy (OSTP); the recommended architecture contained three spacecraft per constellation, five sensors per spacecraft (not including SARSAT and DCS), and a total of seven spacecraft throughout the program's lifetime [D44]. Three of the instruments, SESS, CrIS, and OMPS can be directly linked to heritage instruments that were planned to fly on either POES O, P, Q or DMSP Block 6.[5] Specifically, both SESS and CrIS had the same performance, functionality, and design parameters as the heritage SESS and HIRS instruments, respectively [D44]. OMPS included a slight modification to NOAA's heritage SBUV instrument, which added TOMS, an ozone mapper that had previously flown on a dedicated NASA mission [D44].

Unlike SESS, CrIS, and OMPS, the convergence VIIRS differed from NOAA's heritage AVHRR and DoD's heritage OLS because it combined each instrument's unique functionality and performance requirements in a single integrated sensor. During Epoch A, VIIRS contained six channels that had centers and bandwidths approximately equal to those on NOAA's AVHRR and one additional new channel at 8.55 μm [D44]. VIIRS used a final eighth channel to meet the DoD's need for low light imaging; all channels performed according to the DoD's more stringent requirement for horizontal resolution and its met unique need for the imagery channels to maintain constant resolution across a cross-track scan [D44]. Finally, VIIRS narrowed two heritage AVHRR bands centered at 6.15 μm and 8.7 μm to improve vegetation index and aerosol measurements [D44].

The Epoch A CMIS had the same channels as DoD's heritage SSMIS, but with slightly higher NETD performance requirements for each channel [D44]. Importantly, although there were key differences between NOAA and the DoD's heritage microwave instruments, including imaging capabilities and a conical scan pattern on the DoD's SSMIS, the cross-track scanning ATMS instrument was not included in Epoch A's architecture. Instead, the program assumed that NOAA's heritage temperature and humidity sounding functions could be executed by the higher performing DoD instrument, even though it scanned the Earth differently than NOAA's heritage AMSU [D44].

### 4.2.3 Epoch A Organizational Architecture

The organization tasked with developing the technical architecture discussed above was formally specified by the 1994 tri-agency MOA. The MOA assigned NOAA lead agency responsibility for the converged program's development and subsequent operation; as lead agency, NOAA was responsible for the program's execution both to the tri-agency EXCOM and to the program's various user communities [D124]. NOAA implemented these responsibilities by appointing the IPO's System Program Director (SPD) to be directly responsible for the "financial, programmatic, technical, and operational performance" of the *baseline* NPOESS system [D124]. NOAA was also responsible for hosting the IPO within its NESDIS organization [D124]. The MOA assigned the DoD responsibility for executing the system acquisition process; to implement this responsibility, the DoD appointed an Associate Director for Acquisition who was tasked with "developing, acquiring, and fielding the NPOESS components" according to established DoD processes [D124]. Finally, the MOA assigned NASA responsibility for "facilitating the development and insertion of new cost-effective and enabling technologies" to enhance the system's ability to meet its operational requirements [D124]. The MOA also required NASA to

[5] Before forming the joint NPOESS prorgam, both NOAA and the DoD were preparing to independently develop new systems. These systems—DMSP Block 6 and NOAA O, P, Q—were block upgrades to the heritage systems that proceeded them. In this dissertation, all analysis that compares the cost or the complexity of NPOESS to POES and DMSP uses the proposed block upgrades (i.e. NOAA O, P, Q and DMSP Block 6) as the reference systems.

perform periodic reviews of its research programs and identify new technologies that could be leveraged operationally in the NPOESS system [D124]. However, despite this requirement, the MOA emphasized that the NPOESS program's primary mission was operational; despite the organization's operational focus, the MOA requested that NASA provide technical support to the IPO and appoint an Associate Director for Technology Transition [D124].

As specified by the MOA, each agency delegated its individual authority to be shared on the tri-agency EXCOM; as a result, all major programmatic decisions had to be made collaboratively [D220, D147, I1, I3, I22, I26, I32]. Despite the tri-agency nature of the EXCOM, only the DoD and NOAA held budget responsibility for the program's decisions: NASA provided no funding for the operational program [D124]. In contrast, only the DoD and NASA had the institutional capabilities required to effectively manage the development and acquisition of a large technical system [I6, I26, I39, I46], since prior to the NPOESS program, NASA managed all of NOAA's satellite development programs. Importantly, although the DoD had significant experience with system development and acquisition, when the MOA was signed, the DoD's preferred acquisition strategy was TSPR; by using this acquisition strategy, the DoD delegated a significant portion of its authority and responsibility to its prime contractor.

**Table 3: NPOESS User Community [D124]**

**NPOESS User Community**

- **Joint Agency Requirements Council (JARC)**
  - Vice Chairman of the Joint Chiefs of Staff for DoD
  - Deputy Under Secretary of Commerce for Oceans and Atmosphere
  - Associate Administrator for Mission to Planet Earth for NASA
- **Senior User Advisory Group (SUAG)**
  - NOAA Assistant Administrator for Weather Services
  - NOAA Assistant Administrator for Satellite and Information Services
  - Air Force Director of Weather
  - Oceanographer of the Navy
  - Air Force Space Command Director of Operations
  - NASA Office for Mission to Planet Earth Science Division Director
- **Joint Agency Requirements Group (JARG)**
  - Air Force Space Command (DoD)
  - Office of Oceanographer of the Navy (DoD)
  - Air Force Directorate of Weather (DoD)
  - National Environmental Satellite, Data, and Information Service (NOAA)
  - Goddard Spaceflight Center (NASA)
  - Office of Oceanic & Atmospheric Research (NOAA)
  - National Marine Fisheries (NOAA)
  - Office for Mission to Planet Earth (NASA)

Finally, another key element of the NPOESS organizational architecture was its user community—the Joint Agency Requirements Council (JARC), the Senior User Advisory Group (SUAG), and the Joint Agency Requirements Group (JARG); the members of these user groups, which levied requirements on the joint system, are listed in Table 3. The JARG was responsible for collecting, harmonizing, and documenting agency operational requirements in the IORD, which was ultimately approved both by the JARC and by the individual agencies [D155]. Once the initial baseline IORD was established and the

IPO's execution responsibilities defined, all changes to the baseline had to be approved by these organizational components [D39]. Specifically, if IPO engineers explored trades that might impact system's ability to meet baseline IORD requirements, the SPD's decisions had to be vetted by the SUAG and JARG, the organizational components responsible for insuring that the program executed the mission required by its users [D39]. Ultimately, the authority to make major decisions on the system's baseline capabilities or on the program's baseline cost and schedule rested with the tri-agency EXCOM [D39, D124, I46]. Composed of three high-ranking representatives from each agency (the Under Secretary of Commerce for Oceans and Atmosphere, the Under Secretary of Defense for Acquisition, Technology, and Logistics and the NASA Deputy Administrator), the EXCOM was tasked to make major decisions baseline cost, schedule, and performance that would be suggested by the IPO's SPD [D39, D124]. During later epochs, agencies' different interpretations of the system's performance baseline required the EXCOM to become increasingly involved in programmatic decision making [D147, D195].

### 4.2.4 Summary: Epoch A's Architectural Changes and Policy Themes

Importantly, although the Epoch A technical architecture utilized DMSP and POES but not NASA EOS heritage, NASA was formally a partner in the NPOESS collaboration. Given NASA's prior role as the acquisition agent for NOAA's POES systems, NASA's inclusion in the joint program office was logical. However, the historic NOAA-NASA POES partnership had several critical implications for the subsequent NPOESS collaboration. First, because NASA was the agency responsible for POES system acquisition, as an agency, NOAA lacked the experience and knowledge necessary to manage the system acquisition process [I6, I26, I39, I46].

Second, through the Operational Satellite Improvement Program (OSIP), NASA developed and funded new sensor and spacecraft technologies that were later infused into NOAA's operational POES program; although OSIP was cancelled in 1981, many critical POES technologies, including AVHRR, were originally developed by NASA under this program [D38]. Furthermore, even after OSIP's cancellation, NASA continued investing in sensor technology and was developing multiple sensors with future operational potential under its EOS program. Given NASA's responsibilities and experience both with OSIP and EOS, as an agency, NASA housed the technical expertise necessary to manage technology development; by contrast, NOAA did not.

Yet, when the Clinton administration mandated convergence, it failed to specify a formal mechanism to transfer NASA's EOS technology to the program's technical architecture and its institutional capabilities to NOAA in the program's organizational architecture. Instead, the directive awarded NOAA with lead agency responsibility, the DoD with acquisition responsibility, and NASA with the responsibility for technology transition. Furthermore, the implementation plan that supported the presidential directive clearly separated the NPOESS operational and the EOS research missions and stated that the converged program should utilize EOS technology *only* if it was capable of meeting the agencies' jointly-specified operational requirements [D83]. In this way, the presidentially mandated convergence was incomplete: although it ordered the convergence of the DMSP and POES organizational and technical architectures, it neither accounted for the role that NASA had previously served in both nor anticipated the role that NASA would continue to play as it developed and operated its EOS program.

## 4.3 Epoch B

Epoch B spanned three years: from the release of the IORD-I in 1996 through the formation of the NPP program in 1999. Shortly after the IORD-I's release, the program developed a government reference architecture and issued requests for proposals to industry for five risk reduction contracts for the OMPS, CrIS, VIIRS, and CMIS sensors and for the space and ground segment. After the evaluation process, the program selected two companies for each instrument and these contractors began their early sensor development work. Industry studies of the space ground system also continued during this time, although their interaction with instruments contractors was limited. Finally, although the IORD-I required several new instruments to be added to the technical architecture, their development was postponed until Epoch D. Overall, activities in Epoch B focused on defining the government's reference architecture and identifying industry teams to begin early design work.

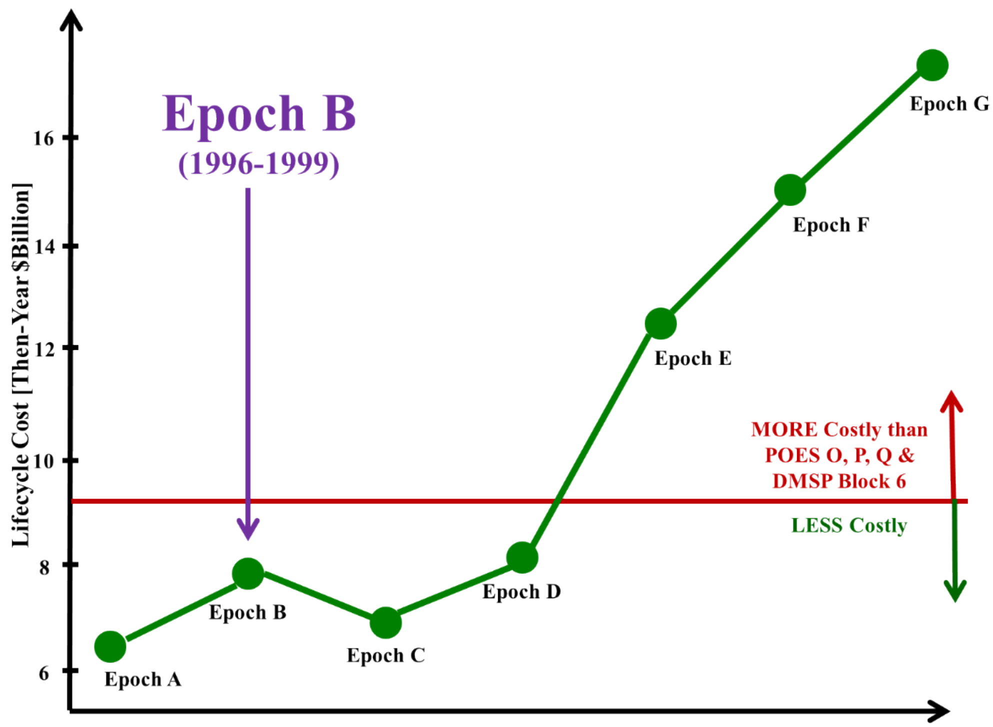



**Figure 18: Cost Growth in Epoch B**

### 4.3.1 Transition to Epoch B

Shortly after the presidential directive that formed the NPOESS program, NOAA and the DoD began to generate and validate the program's joint IORD-I requirements. In accordance with DoD Instruction 5000.2, the system's users generated the IORD-I separate from the program office and unconstrained by the technical solution that had been assumed during Epoch A [D83]. Instead, each agency collected and reported their validated requirements to the JARG, which identified requirements as being shared or unique, prioritized amongst the EDRs, and established objective and threshold performance criteria for each EDR [I15, D83, D87]. The resulting IORD-I was then sent to the JARC and to individual agency leaders for review and approval. The IPO participated in the process by supplying cost and technical analysis to support the JARG's decisions on EDR inclusion, prioritization, and performance specification [I4, I15]. The IPO's analysis was largely completed by Martin Marietta and Lockheed, the two companies that had been selected to complete Phase 0 concept studies of the converged system [I15, I23]. Once the IORD-I was approved, the IPO used contractor input to generate the government reference architecture that is discussed below [D61].

The final IORD-I contained 61 EDRs: 37 that were shared by NOAA and the DoD, 13 that were DoD-unique, and that 11 were NOAA-unique [D87].[6] Importantly, although NASA's Associate Administrator to Planet Earth signed off on the IORD-I, because the document contained only operational requirements, none of the EDRs were *formally* assigned or attributed to NASA [D87]. Finally, six EDRs were prioritized as being Key EDRs, since each contained one or more Key Performance Parameters (KPPs); the remaining 55 EDRs were officially equal [D87, D148, I15]. One of the most critical but tacit assumptions made during the development of the IORD-I was that all user needs for atmosphere, climate, ocean, land, and space environment data were to be contained in the document, even if the heritage DMSP and POES systems had not previously collected it [D61, I26]. As a result, instead of containing only the converged set of requirements from DMSP and POES, the IORD-I documented *all* NOAA and DoD user needs for related data in low Earth orbit [I26, D87, D61]. Since Epoch A's technical architecture was not capable of meeting all of the IORD-I's requirements, the program defined a new one during this epoch.

To commence the development of its new technical architecture, the program proposed an "Optimized Convergence" acquisition strategy which delayed awarding a prime contract for the system's integrator for five years [D166, D195]. In a typical TSPR program, the government awards a prime contract to a company which then extends subcontracts for the system's components or develops those components in-house. However, in the "Optimized Convergence" strategy, the government awarded multiple risk reduction contracts for key instruments but did not initially select a prime contractor; instead, the IPO managed the development of two options for VIIRS, CMIS, OMPS, and CrIS through their critical design review (CDR) and then selected these instrument to be included in the program's technical architecture. After the IPO selected its final instruments, it selected a prime contractor to manage their continued development and to integrate them into the larger system. Despite having valid reasons for utilizing the strategy—including concerns over detrimental prime-instrument contractor partnering, increased budget pressures, and a relaxed need date for the first NPOESS satellite [D166]—"Optimized Convergence" had several critical implications for the program's organizational architecture that are discussed below.

### 4.3.2 Epoch B Technical Architecture

The IORD-I expanded the NPOESS technical architecture's capability and performance by adding four new instruments (the altimeter, ERBS, TSIS, and ATMS), adding new functions to VIIRS, SESS, and CMIS, and enhancing the performance of CrIS and ATMS. Epoch B's architecture had three spacecraft per constellation and six spacecraft throughout the program's lifetime; however, the program assumed that a European EUMETSAT satellite that could be populated with NPOESS instruments and flown in the mid-morning orbit [D61]. All satellites were also assumed to launch on a Delta-II class launch vehicle [D61].

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[6] The IORD-I also contained nine additional Pre-Planned Product Improvement EDRs (P3I). These EDRs were not met by the technical architecture that was defined during Epoch B.

Epoch B's radar altimeter and SESS produced EDRs that had previously been collected by separate DoD or international programs. The altimeter was primarily responsible for ocean current, ocean wave characteristics, and sea surface height and topography data that had previously been collected by related instruments in the Navy's Geosat Follow-on and the international TOPEX/POSEIDON programs [D61]. While the functions and performance of the NPOESS altimeter were equivalent to the instrument's heritage, the NPOESS instrument differed because it was placed on a multi-sensor platform in a polar-orbit: the Geosat altimeter was the single payload on a free-flying spacecraft and both Geosat and TOPEX flew in non-sun synchronous orbits [D167]. The sensors contained in the SESS sensor suite also included additional sensors that had previously flown on DMSP 5D-3 but were not included in the Epoch A architecture: one sensor that had previously flown on TOPEX, and one which was a new ionospheric scintillation sensor [D61].

Like the altimeter and SESS, ERBS and TSIS did not have DMSP or POES heritage and instead were a part of NASA's EOS and ACRIMSAT programs. Although neither instrument was required by DMSP or POES's traditional weather users, both contributed to NOAA's operational climate mission. Importantly, both instruments were of great value to NASA, which had concurrently begun to advocate for several EOS Aqua measurements to be included in the NPOESS operational requirements set [D137]. The ERBS's addition was just one of several decisions which increased the program's resemblance to the NASA EOS: in particular, in order to meet the requirements levied by the IORD-I, VIIRS, CMIS, ATMS, CrIS, and OMPS's performance and functional capabilities had to more closely resemble NASA's EOS heritage instruments than they did the instruments that were previously flown on DMSP or POES.

Compared to Epoch A's architecture, Epoch B's VIIRS had an additional six optical ocean color bands that were similar to those on NASA's MODIS instrument [D61, D167]. Interestingly, in this epoch, VIIRS was defined as a suite of two instruments: one containing the low light channel and one containing the remaining channels that met higher horizontal resolution requirements. Although the primary motivation for separating the two instruments minimizing the low light sensor's sun-shield and improving its sensitivity [D61], the program was also willing to accept proposals for an equally capable, but integrated instrument during the subsequent source selection competition [D236].

Several changes and additions to CMIS and ATMS also increased these instruments' resemblance to NASA's EOS sensors. First, the capabilities of CMIS were expanded from Epoch A's architecture to include capabilities similar to EOS's AMSR-E. Specifically, in addition to including channels near 19 GHz, 37 GHz, and 90 GHz, Epoch B's CMIS also included channels near AMSR-E's 6 GHz, 10 GHz, and 22 GHz channels [D61, D167]. Although the temperature and humidity sounding components of CMIS remained similar to Epoch A's architecture, the program added ATMS, a cross-track microwave temperature sounder that was similar to NOAA's heritage AMSU-A, albeit with slightly less functionality [D61]. The addition of ATMS recovered the one heritage NOAA capability, cross-track microwave sounding, which was absent from the initial Epoch A architecture; this capability allowed NOAA to retain the coincident cross-track microwave and infrared sounding data that was critical for its numerical weather prediction models.[7] Finally, CrIS's performance was enhanced to a level commensurate with EOS's AIRS instrument [D61].

[7] ATMS was not included in Epoch A because initial analysis suggested that NOAA might be able to use microwave data from CMIS. However, when the issue was studied further, the program determined that NOAA required cross-track data to execute its mission [I15, I37].

The technical architecture necessary to meet the IORD-I's requirements produced more data products with higher performance than the previous epoch. Importantly, despite this increased capability, like all programs, performance and functionality ultimately had to be traded against cost and schedule constraints. Because the NPOESS program was established to reduce cost and was intended to replace two agencies' systems, NPOESS had a particularly stringent set of cost and schedule constraints that would ultimately had to be traded against the multiple, high-performance EDRs that were specified in the IORD-I.

### 4.3.3 Epoch B Organizational Architecture

The purpose of the NPOESS organization was to make decisions regarding those trades. Any trades to the IORD-I's functional and performance requirements had to be reviewed by the JARG and the IPO and approved by the SUAG [D39]. To implement changes that affected the system's baseline, the IPO would inform the EXCOM of the deviation request's cost, schedule, and performance impacts and would request final approval [D124]. Once the EXCOM granted approval, the IPO and the prime contractor were responsible for implementing the prescribed change [D39]. Importantly, a weak authority structure existed within the program's hierarchy of users; as a result, any change to the program's baseline performance had to be approved by *all* members of program's user groups and changes could also be vetoed by any single member [I26, I48, D240, D148].

The EXCOM was the only organizational component with decision authority that interfaced with the NPOESS user community and the IPO; however, throughout the program, the EXCOM often failed to execute its authority. After the IORD-I had been approved, EXCOM meetings were infrequent and often failed to result in a decision; for example, the GAO reported that over a two year period, the EXCOM met only five times and usually deferred decisions by requesting additional information [D216]. When EXCOM meetings did occur, they were poorly staffed by the DoD; instead of attending himself, the DoD's representative (the Under Secretary of Defense for Acquisition, Technology, and Logistics (AT&L)) delegated his responsibility to attend the meetings to the Under Secretary of the Air Force [D220]. Outside of their infrequent or poorly attended meetings, the EXCOM members generally assumed that the IPO would use the authority that had been delegated to it and would not require significant EXCOM guidance [I46, I50]. Unfortunately, three factors—the IPO's staffing, the program's TSPR-like contract, and the "Optimized Convergence" strategy—complicated and ultimately reduced the IPO's ability to adequately manage the program's technical development after the IORD-I was released.

While the EXCOM met infrequently during this period, the IPO managed its multiple risk reduction contracts: two risk reduction contracts each were awarded for OMPS, VIIRS, CrIS, and CMIS and for the eventual SSPR prime contract. Instrument risk reduction contracts provided funding for both hardware and algorithm development; as a result, single contracts were awarded to sensor vendors that partnered with an algorithm subcontractor [I20, I39]. Risk reduction contracts for the system were also issued to prospective prime contractors and their ground system subcontractor teams. Importantly, risk reduction contracts were managed directly by the IPO during Epochs B and C and interactions between the instrument and prime contractors and the algorithm and ground system subcontractors were limited [I46, I47].

### 4.3.4 Summary: Epoch B's Architectural Changes and Policy Themes

After the release of the IORD-I, the program's technical architecture increasingly resembled NASA's more capable EOS system; compared to the previous epoch, its instruments had significantly higher performance and functionality—two qualities that do not come without increased cost. Although specific cost inducing mechanisms will be discussed in detail later, in terms of the program's history, it is important to note two factors that enabled these additional EDRs and performance increases to be included in the IORD-I. First, the historic relationship between NOAA and NASA intertwined the two agencies' user communities and provided a mechanism for NASA scientists and engineers who were familiar with the EOS program's capabilities to educate NOAA users on their operational benefits [I5, I15, D148]. Second, during the IORD-I's development, the JARG generally accepted all requests for agency unique EDRs and set EDR performance at the most stringent level that had been requested by the agencies' multiple user groups [I2, I4, I10, I11, I15, I19, I27, I32, I33, I35, I47, I48].

The NOAA-NASA relationship that emerged during the IORD-I's development was reminiscent of the agencies' partnership during the OSIP-era. For example, the agencies ran Operational Satellite Simulation Experiments to simulate the impact that future satellite systems could have on NOAA's weather forecasting capabilities. When NASA and NOAA included the EOS satellites in these experiments, they observed the dramatically valuable impact that EOS data could have on NOAA's operational missions [I5, I15]. Since the EOS satellites were scheduled to be deployed before NPOESS and NOAA users expected to use much of their data operationally, it was illogical to set IORD-I requirements below the EOS baseline that NOAA users had observed during these jointly conducted experiments: as a result, many of the IORD-I's requirements for performance and functionality were set to EOS's more stringent requirements, which in most cases exceeded DMSP and POES's heritage capabilities [D61].

## 4.4 Epoch C

Epoch C began with the formation of the NPP program in 1999 and concluded with the selection of the SSPR prime contractor in 2002. During this epoch, the IPO held eight instrument preliminary design reviews (PDR), one for each risk reduction contractor for its OMPS, VIIRS, CrIS, and CMIS sensors. After PDR, the IPO initiated the source selection process and down-selected to a single vendor for each instrument. Afterwards, the selected vendors completed instrument CDRs.

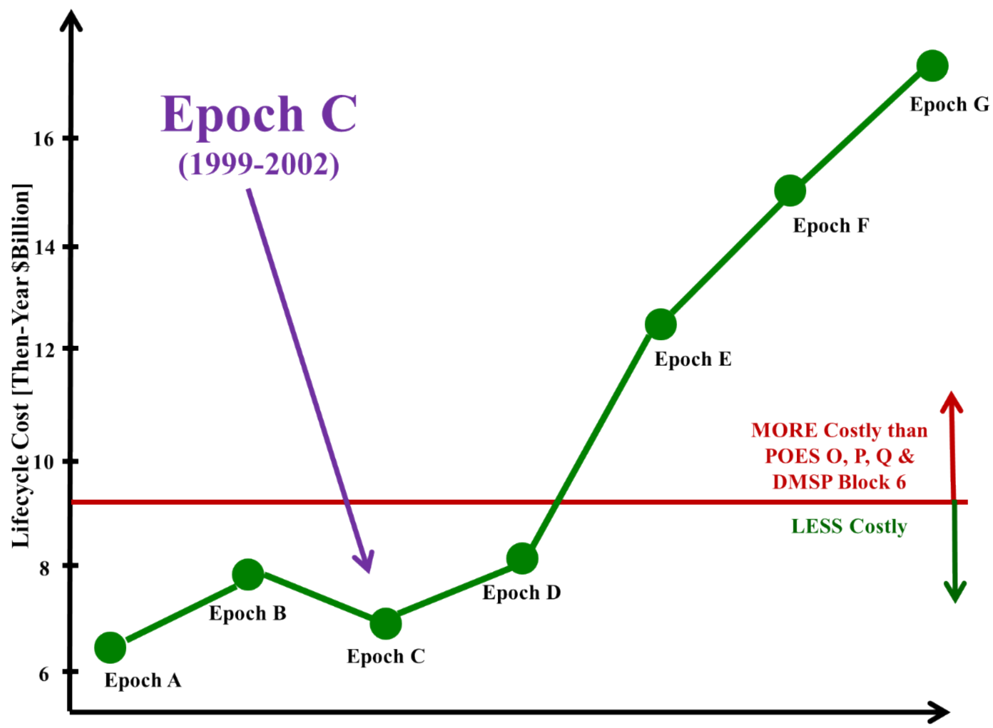


**Figure 19: Cost Growth in Epoch C**

Also during this epoch, the IPO approved several key changes to its organizational and technical architectures. First, the MOA that established the NPP program and critically altered the program's organizational architecture was signed in 1999 [D84]. Next, several changes to the program's technical architecture that were motivated by NPP were formalized by an update to the VIIRS Sensor Requirements Document in 1999 and by a revision to the IORD in 2001 [D127, D235]. These activities induced some of the most significant changes to the program's organizational and technical architectures that not only altered both but also critically affected the evolution that took place during subsequent epochs.

## 4.4.1 Transition to Epoch C

As part of the "Optimized Convergence" strategy, the IPO selected two risk reduction vendors for each sensor to develop instrument concepts through PDR. To further reduce instrument risk, the IPO expected to fly prototypes of each new instrument on a demonstration mission that would fly before the instruments were used operationally [I37, D195]. Although the IPO originally planned to retro-fit NOAA POES satellites with first copies of their new sensors, the program's engineers soon realized that the cost to modify a heritage POES bus was prohibitively expensive, particularly in the budget environment that had already necessitated their use of "Optimized Convergence" strategy [I37, D195].

Concurrently, the NASA Earth Science Division was continuing to endure budget reductions that made the future of its EOS program appear increasingly uncertain. Specifically, although EOS Aqua, Terra, and Aura were all scheduled to launch between 1999 and 2004, it appeared unlikely that funding would be allocated to produce additional copies of each satellite to continue the EOS climate mission [D118, I37, I39]. Although the IORD-I technical architecture had similar capabilities to these satellites, the first

NPOESS satellite was not scheduled to launch until 2008: after Terra and Aqua's predicted 6-year lifespans [D141]. Furthermore, in addition to requiring its climate records to be long term and continuous, NASA also needed to carefully calibrate measurements that would be taken across multiple platforms; however, since the first NPOESS satellite was not scheduled to launch until after the end of Terra and Aqua's missions, NASA not only faced a potential data gap, but it also lost the opportunity to perform real-time, on-orbit calibrations between NPOESS and EOS [D35, D141].

To address the impending cancellation of EOS, the requirement for continuous and calibrated climate data, and the IPO's need for a risk reduction mission, NPP was proposed as a joint NASA-IPO program that would simultaneously bridge the gap between EOS and NPOESS measurements and provide risk reduction for the IPO's key sensors. In the proposed program, the IPO would continue funding and managing the development of its high risk sensors; however, instead of demonstrating sensor prototypes on a retro-fitted POES bus, sensors would fly on a new NPP spacecraft. The development of the spacecraft, sensor integration, and the final system's launch would be managed and funded by NASA [D60, D84]. Once on-orbit, the NPP system would interface with the rest of the NPOESS technical architecture, including its C3 and IDPS segments, which would continue to be developed and managed by the IPO. Finally, the IPO would fund and manage NPP mission operations and NASA would provide additional support to insure that NPP's data products were of appropriate quality to contribute to their climate science mission [D60, D84].

As proposed, the NPP program was essentially all things to all agencies: it both reduced the risk of incorporating new technology into an operational system and it bridged a potential continuity and calibration gap in the climate science data record. But the NPP program also provided an additional opportunity for NASA: specifically, by volunteering to manage the NPP program, NASA formalized its technology development role within the IPO and in doing so, greatly influenced the subsequent evolution of the program's organizational and technical architectures.

## 4.4.2 Epoch C Technical Architecture

The formation of the NPP program affected the NPOESS technical architecture in three critical ways: it introduced a new emphasis on climate science, it further increased the similarities between VIIRS and NASA's MODIS instrument, and it enhanced the capabilities of ATMS. The most obvious technical edition to the NPOESS program was the NPP satellite bus and the four instruments that were assigned to its mid-morning orbit—VIIRS, CrIS, OMPS, and ATMS. To meet its risk reduction mission, NPP's instruments were identical to those selected for the NPOESS mission and the NPP spacecraft was designed to interface with components of the NPOESS ground system, including the IDPS and portions of the C3 segment.[8] By collecting data using the NPOESS operational instruments and exercising NPOESS's new IDPS and C3 systems to transform raw data into final data products, the NPP mission demonstrated some of the most essential and high risk components of the NPOESS technical architecture. Only the design of the NPP spacecraft differed from NPOESS operational system: instead of procuring a copy of the operational spacecraft from the SSPR contractor, NASA opted to procure a spacecraft bus independently and to directly manage the NPP system's integration through its Goddard Space Flight Center (GSFC).

[8] NPP did not plan to use the SafetyNet™ portion of the ground system.

Although the NPP program only required copies of NPOESS operational instruments and an interface with its IDPS and C3 systems to execute its risk reduction mission, it required several modifications to each of those components in order to execute its climate science mission. First, as discussed above, the NPP program provided data continuity for the EOS program and bridged the gap between EOS and NPOESS. To successfully execute these responsibilities, the NPP mission required a one year overlap with NASA's EOS mission so that instrument precision and bias could be thoroughly characterized [D35]. Similarly, in order to maintain data continuity toward the end of NPP's lifetime, the first NPOESS satellite had to be launched before the conclusion of the NPP mission. These schedule requirements placed additional constraints on the operational system's development: in addition to synchronizing NPOESS development to POES and DMSP's predicted end-of-life, the NPOESS program also needed to accommodate need dates from NASA's climate science community. Since appropriate execution of a risk reduction mission required the NPOESS and NPP instruments to be developed sequentially, the climate science mission's schedule constraints further complicated the NPOESS program's already budget constrained technical development process.

Second, proper execution of NPP's climate science mission required new performance, design, and verification/validation specifications. Several performance attributes, such as instrument stability, which that critical to developing and maintaining long term climate data records were not specified in the IORD-I [D87, D88]; therefore, in the IORD-II, long term stability requirements were added to 18 EDRs and additional requirements for measurement uncertainty, accuracy, and precision were added to 21 others.[9] Performance requirements, particularly for horizontal resolution, were also tightened in order to provide climate quality measurements [D87, D88]. Finally, three new climate-centric EDRs were added to the IORD [D87, D88]. One of these EDRs prompted the addition of a tenth and final sensor to the NPOESS technical architecture: the Aerosol Polarimetry Sensor (APS).

Finally, although the IORD specified performance and not design requirements, to successfully implement its climate science mission, NPP required instrument designs to be backwards compatible with EOS [D34]; as a result, design requirements were levied both on VIIRS and on ATMS. NASA began driving the VIIRS design process in 1997 when it funded both VIIRS contractors to explore the technical and cost impacts of accommodating MODIS design requirements and adding additional MODIS-like capabilities [I39, D127, D235, D195]. At the conclusion of NASA's study, both prospective VIIRS contractors reported that most NASA requirements could be accommodated without significant cost or design impact [D235]; as a result, the IPO modified its VIIRS risk reduction contracts to include a new VIIRS Sensor Requirements Document that levied additional performance and design specifications on the VIIRS instrument [D127, D235]. The resulting VIIRS had more capability than its predecessor in the Epoch B architecture; in particular, nine channels, each of which can be directly traced to MODIS, were added during this epoch [D159, D167, D128].

The implementation challenges associated with the proposed VIIRS designs began surfacing after the IPO selected Santa Barbara Research Center to continue the instrument's development; in fact, shortly after winning the VIIRS contract, Santa Barbara redesigned their instrument's optical system and as a result, increased the mass and volume that it required [I10, D61, D167, D178]. But even prior to this, the IPO's decision to select Santa Barbara's design over its competitor's (ITT) substantially different proposal, also affected the program's technical architecture. Specifically, ITT proposed a suite of three instruments that

[9] For reference, the IORD-II contained 55 EDRs [D87, D88].

separated the ocean color channels and the low light channel from the suites' remaining 16 channels, whereas the Santa Barbara design integrated all 23 channels into a single box that utilized one telescope [D195]. Although the program preferred Santa Barbara's design because it capitalized on the team's MODIS heritage, the sensor's highly integrated design introduced unanticipated complexity into the development process that ultimately overwhelmed the cost savings that Santa Barbara assumed could be achieved using its heritage MODIS design [I15, I21, I39, I54].

Unlike the VIIRS requirements changes that were levied prior to contractor down-selection, changes to the program's microwave sounder requirements did not affect risk reduction activities for CMIS; instead, they motivated NASA to sponsor the development of a new, more capable sensor to replace the prior epoch's ATMS. The new ATMS instrument performed *both* temperature and microwave soundings and as a result, fully recovered the POES capabilities that had been lost in the initial Epoch A architecture. ATMS's 12 temperature sounding channels were identical to heritage AMSU-A and its seven humidity sounding channels mapped directly to AMSU-B, albeit with two additional channels clustered around the 183 GHz water vapor line [D167]. The critical difference between ATMS and AMSU-A and B was the mass, power, and volume utilized by each instrument: ATMS consumed approximately 1/3 of the resources that were required by both AMSU instruments [D131].

Also unlike the VIIRS requirements changes, which had been requested by NASA but were ultimately the responsibility of the IPO, NASA proposed to fund and manage the development of the first ATMS instrument that would fly on NPP. During the ATMS development process, NASA defined instrument performance and design requirements, managed instrument source selection, and oversaw contractor activity [D141]. Once the first ATMS unit was demonstrated on NPP, the subsequent copies that would be flown on the NPOESS operational satellites would be funded by the IPO; importantly, the cost of a second ATMS was not included in initial program estimates and thus increased the cost of the program. Despite this additional cost, ATMS provided direct operational benefit not only to NOAA, which had utilized AMSU-A and B on POES, but also to NASA, which had also used those instruments to execute its EOS climate mission. By replicating its EOS cross-track microwave sounder capabilities on NPOESS, NASA obtained additional backwards compatibility to its EOS system that would not have been possible if the NPOESS technical architecture included only the conically scanning CMIS instrument.

Although the formation of the NPP program motivated significant changes to VIIRS and ATMS, CMIS and OMPS were largely unaffected by program activities during this period. Since both prospective contractors had relatively similar designs, the IPO's selection of Ball as the OMPS contractor and Boeing as the CMIS contractor had minor impacts on the program's technical architecture. However, Epoch C's OMPS included slightly more functionality and performance than NASA's heritage instruments; in addition to carrying a nadir mapper and profiler, the suite also included a limb profiler which extended the nadir profiler's range and vertical resolution [D54].

### 4.4.3 Epoch C Organizational Architecture

To develop the NPP and NPOESS systems, the MOA defined a new organizational architecture that assigned NASA the responsibility for executing NPP's climate science mission and budget responsibility for developing the NPP spacecraft and the ATMS instrument, and for integatring VIIRS, OMPS, and CrIS onto the NPP bus [D60, D84]. The IPO retained budget and mission responsibility for the NPP instruments and algorithms, as well as for the NPOESS ground system, which included both the IDPS and C3 segments [D84, D127]. Importantly, despite the addition of the NPP risk reduction mission, the IPO retained mission and budget responsibility for the operational NPOESS program, which at the time, also included six other instruments and two spacecraft that were not a part of the NPP program.

An important characteristic of Epoch C's organizational architecture was the bifurcation of budget responsibility and authority between the NPP program office and the IPO. The NPP MOA explicitly stated that no funds could be exchanged between NASA and the IPO and assigned authority over the NPP spacecraft, the ATMS instrument, and the system's integration to the NPP program office [D84]. By holding and financing their contracts, the IPO retained authority on the remaining instruments, the ground segment, and the NPOESS spacecraft [D84]. As a result, although the NPP program office was responsible for executing its climate mission, it had no formal mechanism to affect the IPO's management of the sensors that would ultimately execute that mission [I17, I24, I33, I39, D84]. To further complicate the NPOESS organization, although the program's technical architecture evolved to more closely resemble NASA's EOS system, NASA's engineers, who had experience developing EOS, resided in the NPP program office and not the IPO [I21, I24, I28]. Importantly, since the IPO managed the contracts for the program's instruments, the organization provided an ineffective mechanism for NPP engineers to direct the instrument development process.

### 4.4.4 Summary: Epoch C's Architectural Changes and Key Policy Themes

The program's organizational and technical architectures changed more drastically during Epoch C than during any other time on the program. But perhaps more important than changes to the architectures themselves was the significant change to how the program planned to execute its future development, integration, and test processes. As detailed by multiple government studies [D34, D35, D37], the processes used to develop, integrate, and test a research mission are fundamentally different from those used in support of an operational mission. Therefore, from its very beginning, NPP's two missions—reducing risk for an operational system and supplementing a research system—were fundamentally incompatible.

Furthermore, in addition to altering the program's technical architecture, NPP transformed the program's organizational architecture and enhanced NASA's role. Although specific impacts of these organizational changes will be discussed in detail in later chapters, at this point, it is important to note that the NPP program office and the IPO occupied comparable levels in the program's organizational hierarchy and that both components reported to agency leadership but did not interface with one another. As a result, all formal interactions between the IPO and NPP had to occur within the EXCOM, where the NASA administrator served both the needs of the NPP program office and those of the IPO [I29, I46]. This arrangement equated NPP and NPOESS's contradictory research and operational missions and forced the trade-offs between their requirements, cost, and schedule to be adjudicated by the agencies' representatives to the EXCOM.

## 4.5 Epoch D

Epoch D spanned from prime contractor selection in 2002 to the program's Nunn-McCurdy breach in 2005. The first major event of the epoch was the selection of Northrop Grumman[10] as the system prime contractor and the transfer of the IPO's contracts for VIIRS, OMPS, CrIS, and CMIS to the integration house in 2002. Shortly afterwards, development challenges, schedule slips, and cost growth were reported on each instrument and on NASA's ATMS; for example, only a year after the prime contract award, development costs for ATMS, CrIS, VIIRS, and CMIS grew by 75%, 272%, 43%, and 29% respectively [D214]. VIIRS was most severely impacted by cost and schedule delays during this epoch: in 2004, Northrop reported that development challenges on the instrument would delay the NPP launch date [D148]. As a result in 2005, the EXCOM ordered an independent review team to assess the instrument's development progress and to propose a corrective action [D240, D216].

In response to the rapid cost growth that occurred during this epoch, the both the IPO and the prime contractor explored options to modify the program's organizational and technical architectures to reduce cost. In 2002, the IPO began studying options to reduce the capability and cost of its SESS instrument [D195] and in 2005, the IPO explored options to remove CMIS from several spacecraft, to cancel the NPP program entirely, and to reduce the number of spacecraft in the operational constellation [D216, D240]. Paradoxically, during this era, the IPO also accepted a costly addition to its technical architecture: the Landsat program's Operational Land Imager (OLI) instrument [D108, D90]. Finally, in addition to considering architectural changes, during this epoch, the IPO also explored schedule modifications and requested additional funding from its sponsors that would enable it to develop its baseline technical architecture using additional financial resources [D195, I16, I46]. Ultimately, a confluence of organizational, technical, and political factors impeded the IPO's ability to change any aspect of its cost, schedule, or performance baseline until program management declared a critical Nunn-McCurdy breach in 2005.

### 4.5.1 Transition to Epoch D

The transition to Epoch D had been planned as part of the IPO's "Optimized Convergence" strategy and the transition occurred on schedule when the IPO selected Northrop Grumman in 2002. Prior to this selection, as it did with its instrument contractors, the IPO funded two prospective system integrators, Lockheed Martin and Northrop Grumman, to execute system-level risk reduction activities. As part of this effort, Lockheed and Northrop were granted limited access to the technical and programmatic data produced by the IPO's instrument contractors so that they could include appropriate technical, cost, and schedule estimates in their final proposals to the IPO. Importantly, neither prime was able to perform detailed assessments of the instrument contractors' performance nor were they able to exercise any authority over the instruments during this time [I2, I15, I46, I47, I49].

[10] The contract was originally awarded to TRW which was acquired by Northrop Grumman shortly thereafter.

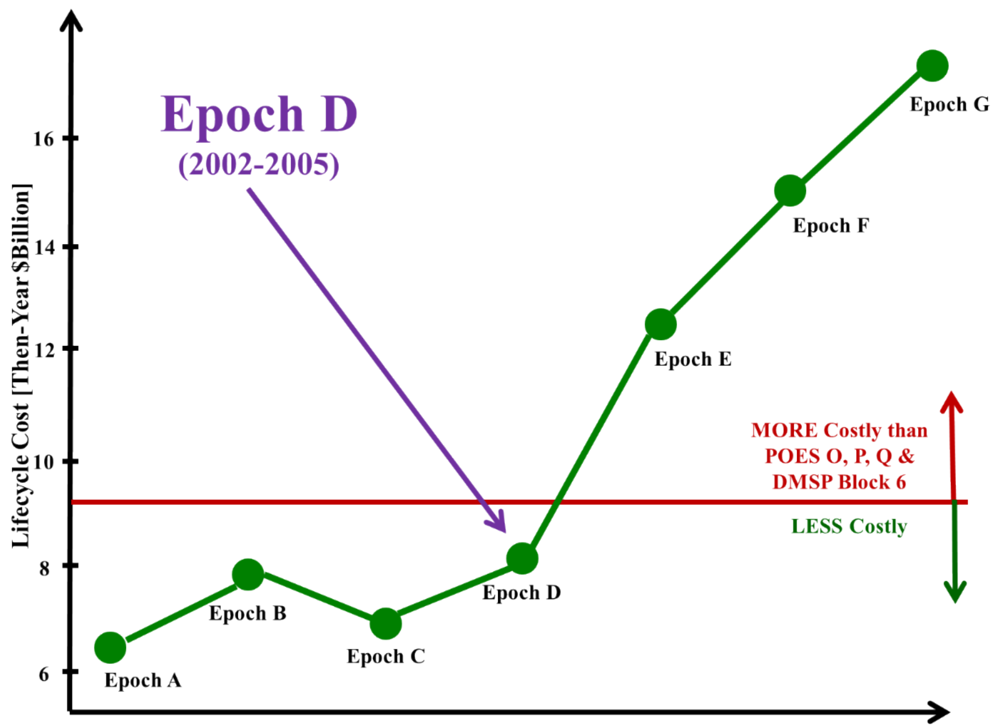


**Figure 20: Cost Growth in Epoch D**

### 4.5.2 Epoch D Technical Architecture

Several components were added to the NPOESS technical architecture during Epoch D. First, although the Epoch B architecture assumed that a EUMETSAT satellite would fly NPOESS instruments in the mid-morning orbit, the program decided to procure its own mid-morning satellite when EUMETSAT made a block buy of common satellite buses that were incapable of hosting NPOESS's high performing instruments [D195]. Besides the addition of this satellite, the primary differences from prior epochs were the addition of ATMS and CrIS to the early morning orbit [D17, D139] and the decision to launch the operational NPOESS satellites (i.e. not NPP) using the Evolved Expendable Launch Vehicle (EELV), rather than a Delta-II [D39] . Shortly after Northrop was selected, the contractor began reporting cost growth; in response, the contractor and the IPO explored options to reduce the number of SESS instruments in the constellation or to reduce the suite's functionality. Even though both options would have saved the program money and the IORD did not specify how many space environment EDRs had to be collected on each operational satellite, no trades or reductions in capability were made [I26, I44, D195, D88]. Instead, the fully functional SESS instrument remained on all three operational satellites throughout this epoch.

Despite the cost growth that motivated the IPO to consider trades to reduce SESS's capabilities, the organization incurred an additional cost when the DoD, NOAA, and NASA signed an MOA that added the OLI instrument to its mid-morning satellite; the OLI had previously flown on dedicated satellites that were developed by the NASA-USGS Landsat program. To accommodate OLI on the NPOESS mid-morning spacecraft, both Northrop and the IPO engaged in a series of studies to assess the cost and technical impacts of their decision and to derive OLI instrument and spacecraft interface requirements

[D90]. A second MOA, issued a year later, recognized the significant cost impact that OLI had on the NPOESS technical architecture and ultimately removed the instrument [D108].

The program's inability to manage its cost growth was a function of the organizational architecture during this epoch, which hindered the decision making authority of all components below the program's EXCOM. Faced with the inability to internally manage its own cost growth, the IPO had no choice but to request that the EXCOM approve changes to the program's technical, cost, and schedule baseline. After an early 2005 request for additional funding was denied, but program costs continued to grow, the IPO presented the EXCOM with a set of options to reduce the technical architecture's capabilities and to decelerate the program's cost growth; prominent options included removing CMIS from the mid-morning satellite, cancelling the NPP program, and deleting the mid-morning satellite altogether [D240, D216]. Although many of these options simply returned the technical architecture to a configuration that it held in previous epochs, when the options were presented to the EXCOM in the middle of 2005, the decision making body deferred its final selection and instead, requested that the IPO perform additional analyses [D216]. Shortly afterwards, with its technical architecture largely unchanged from the time it signed its prime contract, IPO management declared a Nunn-McCurdy breach.

### 4.5.3 Epoch D Organizational Architecture

Several key changes to the program's organizational architecture occurred during Epoch D. First, once the IPO selected its prime contractor, it formally delegated authority and responsibility for the instruments, the ground system, and the NPOESS spacecraft to Northrop. Northrop also assumed responsibility and authority for the sensors that were not developed during the program's risk reduction activities: this included APS, the altimeter, TSIS, ERBS, and SESS.

The transfer of the IPO's four risk reduction sensor contracts for VIIRS, CrIS, CMIS, and OMPS occurred within six months of prime contract award. However, even though Northrop assumed budget and mission responsibility for these instruments, until its relationship with their vendors was contractually defined, Northrop could not execute its authority or manage instrument development. After winning the contract and gaining the ability to more closely inspect its new subcontracts, Northrop discovered that the instruments, which had previously been the responsibility of the IPO, were not developed to industry-standard CDR-levels of maturity [I46, I47, D149]. Instead, several of the instruments' designs remained fluid even after their CDRs and their vendors encountered challenges translating their CDR-approved paper designs into engineering development units [I23, I24, D178]. After a similar assessment period, the subcontractor for the ground system, Raytheon, reported that each instrument's CDR-certified algorithm was analogously immature [I22, I30, I46].

Since Northrop's execution plans had assumed that each of the IPO-developed instruments and algorithms would be at CDR-levels of technical maturity, its post-contract award revelations—coupled with a cut to the program's budget—necessitated a program re-plan in 2003 [D134, D195]. When Northrop completed this exercise, the program's lifecycle cost grew from $6.5 billion at contract award to $8.1 billion less than a year later [D217]. As Northrop focused on assessing the status of its new instrument contracts, evaluating the systematic impacts of their unexpected immaturity, and developing a program-wide strategy for managing their future development, the prime was slow to begin actively managing the development challenges that persisted on the program's instruments. Meanwhile, the NPP engineers that had been engaged in instrument development prior to prime contract award mobilized to provide additional support to the program's struggling sensor vendors [I9, I24, I28, I39]. Despite its lack of contractual authority or budget responsibility for instrument development, the NPP program office encouraged its engineers to play a greater role in subcontractor activities in the hopes that increased technical support would mitigate the impending schedule delays that could compromise their climate mission [I24, I28].

After the program re-plan revealed cost growth and subcontractor performance remained poor, both the IPO and Northrop explored a variety of technical and management options for reform. Despite these efforts, two components of the program's organizational architecture—its user hierarchy and its new Tri-Agency Steering Committee—hindered both the IPO and Northrop's ability to affect positive change. As discussed previously, since there was no delegation of authority within the user hierarchy, the program office required unanimous approval from each user representative before it could change any aspect of the system's performance, even if changes did not affect the system's ability to meet its IORD requirements. Many technical trades to reduce cost, including those for the SESS instrument, failed to obtain unanimous user approval and as a result, could not be implemented by the IPO [I26, I48, D195, D240].

Without the ability to reduce the system's technical capability to save cost, the IPO was left with no other option than to request additional funding from its parent agencies. However, during this epoch, agency leaders delegated program oversight to the Tri-Agency Steering Committee (TSC) that was formed below the EXCOM. Although the EXCOM delegated the mission responsibility to oversee the program to this committee, it retained authority over the program's baseline. As a result, the TSC functioned primarily as an intermediary between the IPO and the EXCOM; although TSC members could request program reviews and status reports from the IPO, they often filtered the IPO's requests for additional funding before they could be heard by the EXCOM [I16, I46], which continued to meet infrequently during this epoch [D216].

### 4.5.4 Summary: Epoch D's Architectural Changes and Key Policy Themes

Epoch D was the first time that the program reported cost growth and that it considered trades to reduce system capability and cost. However, as discussed above, the program's user community hindered its ability to make trades and requests for additional funding were either filtered by the TSC or were denied by the EXCOM. As a result, the program's activities were constrained by its near-term funding profile, which forced management to prioritize the system's development according to need-date; as a result, all elements of the NPOESS technical architecture that were utilized by the NPP mission received the funding that was available, while other elements' budgets were reduced. This decision primarily affected Northrop's subcontract to Boeing for CMIS, which experienced such significant funding reductions that little development was accomplished during this period [I1, I11,I13, I16, I26, D240]. Northrop similarly delayed work on the NPOESS spacecraft bus so that it could allocate the remainder of its yearly funds to the joint NPP-NPOESS ground system and to the four instruments that would fly first on NPP [I11, I16, I25]. Although reducing the budget allocated to NPOESS-only development activities enabled the program to increase the support it provided to joint NPP-NPOESS projects, it ultimately compromised the operational program's schedule and increased its operational cost per unit so significantly that program managers were forced to declare a Nunn-McCurdy breach.

## 4.6 Epoch E

Epoch E began in December 2005, when the NPOESS SPD notified Congress that the program's per unit cost had increased at least 25% over its current baseline. The SPD's actions were legally mandated by the Nunn-McCurdy Act, which requires that the DoD notify Congress any time one of its major acquisition programs exceeds a specified threshold. The Nunn-McCurdy Act calculates these thresholds in terms of Program Acquisition Unit Cost, or the total cost of a program's development, integration, and test activities divided by the number of units that it produces [179]. There are two Nunn-McCurdy breach thresholds: the significant threshold and the critical threshold. When a program breaches the significant threshold, its unit cost has grown over 15% since its last baseline estimate. When a program breaches the critical threshold, its unit cost has grown over 25% since its last estimate; programs that breach the critical threshold are required to undergo a certification process to verify that the program is essential for national security, to examine root-causes for the program's cost growth, and to explore alternative organizational and technical architectures that can be utilized to reduce program costs and to prevent additional growth in the future [179].

The NPOESS program breached both Nunn-McCurdy thresholds and underwent a six month certification process that began in 2006. After this process, during which representatives from all three agencies proposed and analyzed over 40 alternative technical architectures [D150, D151, D152, D153, D157], the program emerged with a less capable technical architecture and an altered organization to execute its development. While agency and IPO leadership supported these certification activities, Northrop continued managing the program's key sensors, whose development remained troubled throughout this period; for example, one of the most critical test failures, which involved breaking the CrIS engineering development unit during a vibration test, occurred in October 2006 [D195]. Despite such these failures, the program's first instrument, ATMS, was delivered for integration to the NPP spacecraft in November of that same year [D161]. Finally, less than two years later in the spring of 2007, Epoch E drew to a close, when many of the changes mandated by the certification process came undone.

### 4.6.1 Transition to Epoch E

Although Northrop reported cost growth on all of its instruments, it was the severe challenges facing the VIIRS development team which drove the Nunn-McCurdy certification process to start in 2006. Specifically, in late 2004, the IPO announced a delay in the VIIRS delivery date that threatened NPP's planned launch in late 2006 [D148]. The VIIRS schedule continued slipping throughout 2005, when it not only impacted the launch of NPP, but it also delayed the launch of the first operational satellite which had been previously planned for 2009 [D217]. In response to these baseline changes, the EXCOM established an independent program assessment team to review the program's status and to assess its costs [D240, D216]. It was this team's initial findings which forced the program to notify Congress that it had breached Nunn-McCurdy's 15% cost growth threshold in September 2005 and the release of their final report, which found greater than 25% cost growth, that triggered the certification process to begin that December [D240, D216]. The resulting process affected the program's organizational and technical architectures and caused its lifecycle cost estimate to increase from $8.4 billion just prior to restructure to $12.5 billion afterwards [D218].

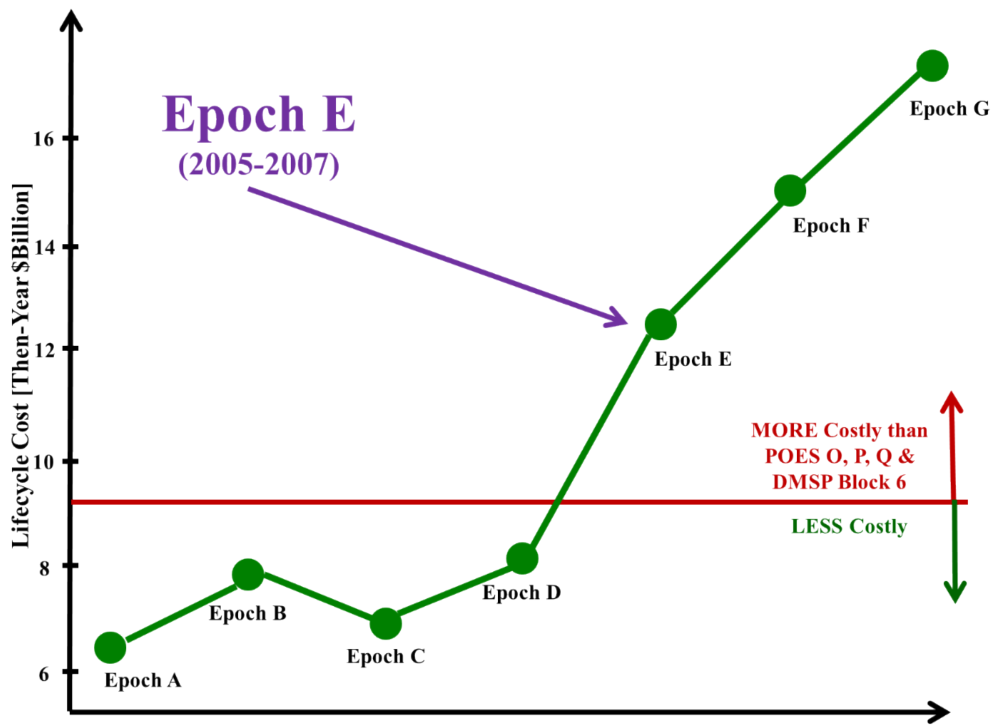


**Figure 21: Cost Growth in Epoch E**

## 4.6.2 Epoch E Technical Architecture

In support of the certification process, representatives from the DoD, NASA, and Northrop generated over 40 options that de-scoped the program's technical architecture by reducing the number, functionality, and performance of the program's spacecraft, instruments, and ground system [D150, D151, D152, D153, D157]. After the generation process, each architecture was evaluated to determine its near-term and lifecycle cost, its schedule, and the risk that it posed to data continuity for POES, DMSP, and EOS, and its ability to meet the program's EDRs. Options were immediately eliminated if they failed to meet the highest priority KPPs, but as in the IORD, all other EDRs were officially equal [I15, D148]. Within the initial set of architectures, many options were similar: they proposed removing sensors from one or more of the constellation's three platforms, moving the altimeter to its own dedicated spacecraft, or removing the sensors that did not contribute to the operational weather mission (TSIS, APS, OMPS, and ERBS) from the program altogether [D150, D151]. Other options suggested replacing Northrop's unique NPOESS bus with its heritage EOS design or replacing CMIS with operational copies of the free-flying Windsat satellite [D157]; Windsat was a joint IPO-Navy research mission that demonstrated several of the key technologies that were to be used in the operational CMIS sensor. Other proposals suggested replacing VIIRS with NOAA's heritage AVHRR, or with a modified AVHRR with performance and functionality similar to VIIRS during Epoch A [D157]. Finally, more drastic proposals considered options that cancelled NPP or that diverged NOAA and the DoD's systems [D240].

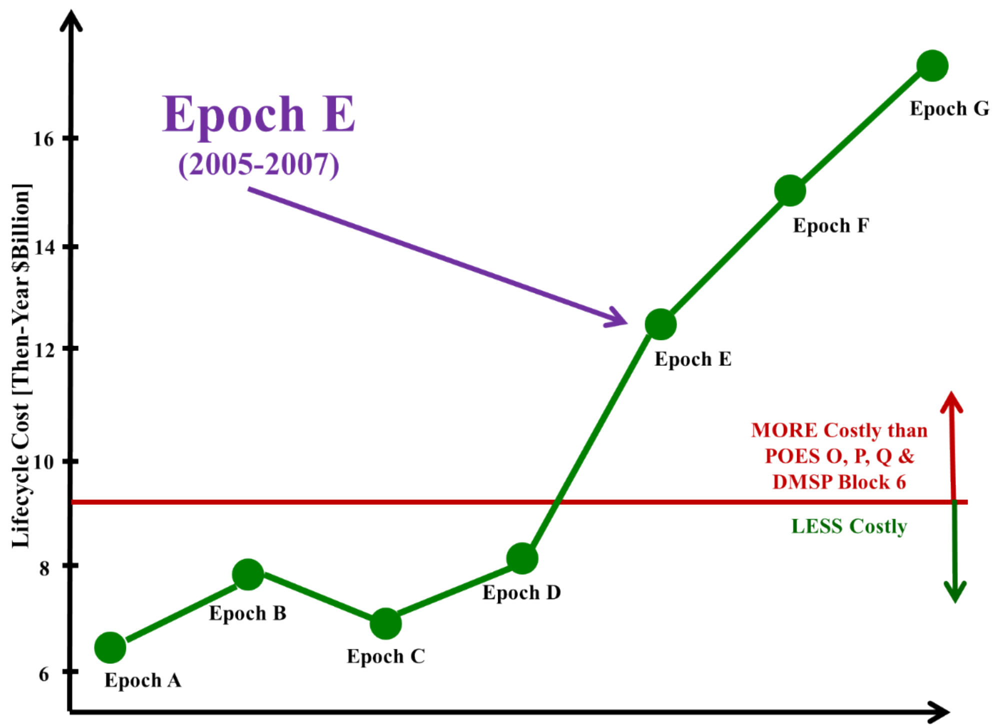


**Figure 22: Cost Growth in Epoch E**

After option generation, an integrated tri-agency team consolidated similar options, eliminated low-performers, and recommended a final set of four options [D150]. The first was to maintain the program of record by developing technical architecture that had previously been defined and by supporting the existing industry teams with the funding that was necessary to develop it [D150]. The independent team that had reviewed the program just prior to certification suggested a second option, which reduced the system to a two-orbit constellation, with one orbit in the early morning and one in the afternoon [D150]. This option maintained the baseline sensor complement with the exception of the altimeter, which it eliminated to achieve additional savings. Plans for NASA's NPP mission were also preserved.

NASA proposed a third option that expanded NPP's role. Specifically, although NASA also proposed reducing the operational constellation to two spacecraft and relying on METOP in the mid-morning, it also proposed using a copy of its NPP spacecraft in at least one of the operational orbits [D150]. NASA suggested that using this approach, the program could retain the option of cancelling the other NPOESS-unique buses and could continue using NPP clone spacecraft in the future [D150]. The first NPP clone would fly in the afternoon orbit and would not carry CMIS; again, with the exception of the altimeter, the baseline instrument complements for the remaining spacecraft were preserved. Finally, the DoD proposed a forth option that reduced the NPOESS operational constellation to a single spacecraft in the afternoon orbit and utilized DMSP and METOP in the early and mid-morning orbits, respectively [D150]. The sensors planned for the afternoon NPOESS spacecraft remained the same as in the baseline program.

Despite the effort that was expended to generate, evaluate, and identify top options, divergent preferences prevented agency leaders from making a final selection amongst the candidates. Faced with this apparent impasse, the newly created Program Executive Officer (PEO) made a unilateral decision to define a new architecture that was absent from the collaboratively developed set of options [D150, D218, I7]. Like the previously considered options, the final Epoch E technical architecture consisted of only two spacecraft, in the early morning and afternoon orbits, and relied on METOP for mid-morning data; the NPP program was also preserved [D218]. Unlike previous options, multiple sensors were de-manifested, or stripped of their program funding; in case interested agencies later decided to fund these sensors, Northrop preserved the spacecraft resources necessary to enable their reintegration [D218]. Affected instruments included APS, the radar altimeter, the survivability sensor, and TSIS; additionally, ATMS and CrIS were removed from the early morning orbit [D218]. Finally, the number of spacecraft was reduced from six to four over the program's lifecycle [D218].

Several other sensors had their functionality or performance reduced to levels commensurate with heritage. The SESS instrument was replaced by the less capable NOAA heritage SEM instrument [D218]. The ERBS instrument was cancelled and replaced only on the first afternoon satellite with CERES, an already built sensor spare from NASA's EOS program [D218]. Although CERES provided slightly less spatial resolution than was planned for ERBS [D54], it saved the program development costs since it could immediately be furnished by NASA. Finally, the OMPS instrument suite had its limb profiler removed; the nadir profiler and mapper stayed intact [D218].

The certification process also impacted the CMIS instrument by cancelling the contract for its development and ordering the IPO to re-define the sensor's requirements and to procure it from a new vendor [D54]. The replacement instrument produced the same EDRs using analogous channels and frequency ranges; however, the new microwave imager sounder (MIS) reduced the dish diameter from 2.2 meters to 1.8 meters [D92, D167]. With this reduction, the new MIS had less horizontal resolution but offered mass savings and the opportunity to relax the attitude and jitter control requirements that were derived from the larger conically spinning dish [I27, D157].

### 4.6.3 Epoch E Organizational Architecture

The major change to the organizational architecture that occurred during the epoch—the addition of the PEO role—was also intended to enable greater prioritization of the program's operational missions. Prior to Nunn-McCurdy, programmatic decisions that affected both NPP and NPOESS had to be adjudicated at amongst agency leaders at the EXCOM level [I5, I6, I9]. In previous epochs, NPP derived its authority and its budget and mission responsibility directly from NASA leadership—not from the IPO or the TSC—which only interfaced with NPP indirectly through the EXCOM. Since the EXCOM met rarely and thus failed to provide direction on how to allocate the program's limited budget between NPOESS and NPP, the program was forced to prioritize NPP because it had the earliest launch date [D195, I46].

By adding a PEO, the program placed both the NPP program office and the IPO beneath a single decision maker and as a result, eliminated the default prioritization that NPP had enjoyed during prior epochs. The addition of the PEO also eliminated the ineffective TSC and provided a more streamlined management structure between the IPO, NPP, and tri-agency EXCOM. Since NOAA held lead agency responsibility for the program, the PEO, like the SPD beneath him, directly reported to management in NOAA-NESDIS [I18, I33, I46, D145].

### 4.6.4 Summary: Epoch E's Architectural Changes and Policy Themes

As a result of the Nunn-McCurdy certification process, the program's technical architecture assumed a configuration that it had not held since Epoch A. While key sensors like VIIRS and CrIS still provided greater performance and functionality than they did at convergence, the climate instruments were eliminated. This change suggests an attempt to prioritize the program's operational weather mission above the climate missions that were added later. Importantly, these changes were not collaboratively developed and were essentially mandated by a DoD-appointed PEO and implemented through the DoD's certification process. Although the PEO also reduced or eliminated several critical DoD technologies—including SESS, the altimeter, CMIS, and the survivability sensor—the DoD-centric nature of the process and the PEO's final unilateral decision incensed the NOAA-NASA climate community, which saw its missions threatened by this new prioritization [I46, D54]. Since the PEO position was formally added to the program's organizational architecture during this epoch, NOAA-NASA leaders had reason to be concerned that their climate missions would continue to be marginalized in the future. As a result, once the program emerged from Nunn-McCurdy certification, leaders from both agencies mobilized to gain administrative support and funding to return the de-manifested climate sensors back to the NPOESS technical architecture and to restore the program's focus on its climate missions [D54, D39].

## 4.7 Epoch F

Epoch F began shortly after the program completed its Nunn-McCurdy certification and continued until the formal divergence of the program, which was mandated in February 2010. The epoch began in the spring of 2007 when NOAA named a new Assistant Administrator for Satellite and Information Services and created a new deputy position to provide the administrator with additional support [D122, D80]. Also in the spring of 2007, NOAA and NASA announced plans to restore funding for the OMPS Limb Profiler that had been de-manifested during Nunn-McCurdy [D102]. Similarly, in the following year, both TSIS and ERBS were re-manifested on the program [D102].

Other key events included an updated MOA and the formation of the Tri-Agency Joint Assessment Team (TJAT) in 2008. The key change in the MOA altered the interaction between the DoD's milestone decision authority—the individual tasked with executing the DoD's acquisition responsibilities—and the EXCOM; specifically, prior to 2008, the DoD's milestone decision authority was required to obtain concurrence from the EXCOM prior to making decisions that impacted the acquisition process [D220]. After the 2008 update, the DoD's milestone acquisition authority was required only to *consider* the EXCOM's input when making acquisition decisions [D220]. This change, coupled with the Under Secretary of Defense for AT&L's absence at EXCOM meetings hindered program governance when he overturned several decisions made at the EXCOM [D220]. Simultaneously, the TJAT was formed to provide additional guidance to the EXCOM and to consider alternative procurement strategies. For example, the TJAT considered cancelling NPP, replacing VIIRS with AVHRR, and using the NPP satellite operationally [D64, D207, D208].

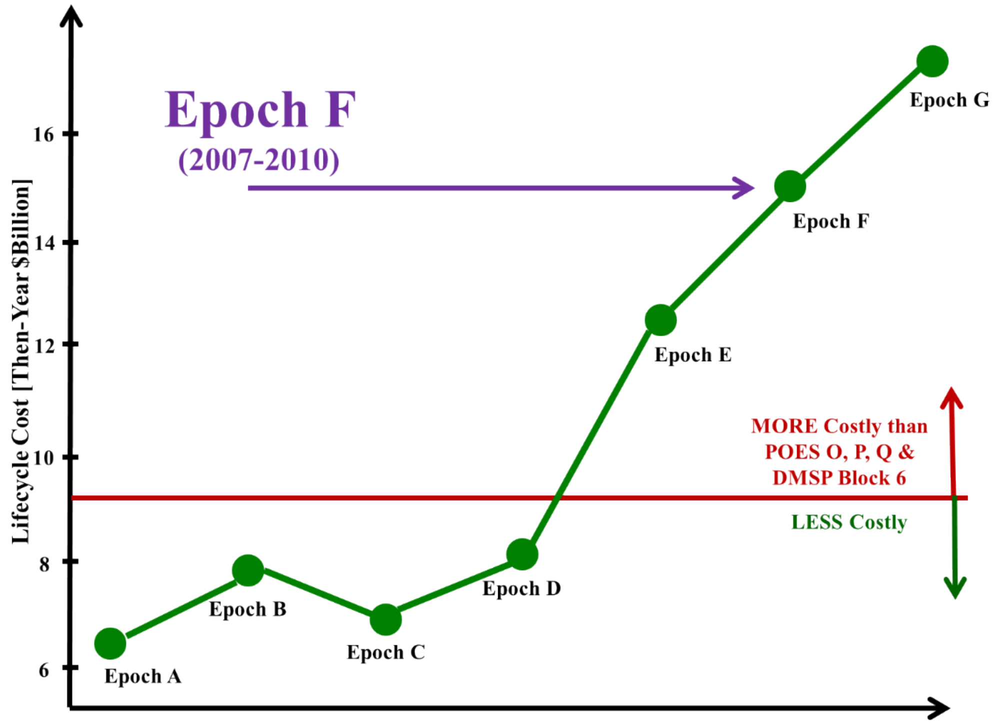


**Figure 23: Cost Growth in Epoch F**

Meanwhile, development challenges, primarily on the VIIRS sensor, continued to plague the program with cost growth and schedule delays. Key VIIRS issues that occurred during this epoch included: the discovery of cross-talk and its threat to ocean color EDR performance, an accidental EMI over-test, and the discovery that the instrument's launch locks were at risk for disengaging during launch [D195]. Of course, these and other less severe technical issues contributed to cost growth during this epoch; just prior to divergence, the program's cost estimates grew to $15 billion, over double the amount predicted at convergence [D221].

In response to continued cost growth and delays to both the NPP and NPOESS launches, the NPOESS EXCOM ordered several independent review teams to assess the program and to make recommendations to improve its performance. The separate teams reached approximately same conclusions: that the program's organizational architecture and weak staffing support from its parent agencies continued to hinder its performance, that the program was inadequately funded, that the program's technical architecture should be preserved, and that the certified technical architecture would be developed at the lowest cost and schedule by the converged program using its existing contractor team [D147, D241]. The White House OSTP review, which ultimately cancelled the program, began after the independent review teams' results were announced, in the fall of 2009.

While independent review teams, agency leaders, and representatives from the White House considered the program's future, sensor and system development continued. Northrop delivered OMPS, VIIRS, and CrIS to NPP between November 2008 and June 2010 [D161] and successfully completed its mission CDR in August of 2009 [D158]. Interestingly, Northrop's technical progress occurred despite significant leadership turnover at the IPO: during this epoch alone, the IPO saw three separate PEOs and SPDs assume and then quickly depart their assigned roles [D161]. Despite this fluid management structure, the IPO and contractors' performance steadily increased throughout this period. The program's sensor vendors overcame the challenges that they had encountered while developing first units and subsequent units were entering production [D241]. Additionally, Northrop's spacecraft development was steadily progressing and unlike prior epochs, independent review teams certified that the prime's development, integration, and test plans for the first operational NPOESS satellite were realistic and executable [D241]. Despite this progress and contrary to recommendations of multiple independent review teams, the White House cancelled the NPOESS program in February 2010.

### 4.7.1 Transition to Epoch F

The organizational and technical architectures established during Nunn-McCurdy threatened the program's ability to carry out the NOAA-NASA operational climate and climate science research missions. First, the addition of the PEO eliminated the default prioritization that NASA's NPP program had enjoyed during prior epochs and authorized a single point of contact to adjudicate issues and to allocate scarce resources between the NPP program office and the IPO. Without the guarantee of dedicated program resources and prioritization, NASA's NPP climate science mission was at risk: not only was the PEO authorized to make decisions that could adversely affect NPP instrument performance, but he could also further delay NPP's launch if doing so benefited the development of the operational system. The threat that the PEO would make either decision was very real given the prioritization that the Nunn-McCurdy certification process had placed on the NOAA-NASA climate missions: with TSIS, ERBS, APS, and OMPS Limb now absent from the technical architecture, the program's ability to contribute to its scientific mission was reduced and its renewed focus on its operational weather mission was reinforced.

The changes to the program's organizational and technical architectures during this period reacted to the changes mandated by Nunn-McCurdy and restored the priority that NPP and the NOAA-NASA climate missions had enjoyed during prior epochs. These changes were instituted primarily by NOAA-NASA leaders whose actions were enabled by a shared and vocal climate user community that opposed the Nunn-McCurdy-mandated changes to the program. For example, almost immediately after the program completed its certification, leaders from World Climate Research Programme and the Global Climate Observing Program sent formal letters to the Committee on Earth Observation Satellites to express their concern for climate data continuity and its role in the future NPOESS program [D54]. The White House OSTP responded to international concern by meeting with NOAA and NASA leaders to review the impact that Nunn-McCurdy had on the program's climate missions, to prioritize climate measurements and instrument re-manifestation, and to identify alternative systems capable of contributing to the international climate record [D54]. After issuing a joint report in December 2006, the agencies solicited help from the NRC which facilitated a workshop for over 100 academics, scientists, and engineers to contemplate opportunities to contribute to the climate record using assets from the NPOESS program; in 2007 and 2008, the NRC was also tasked to produce two reports on the same topic [D54]. At the same time, the NRC completed its Decadal Survey and made specific recommendations for re-manifesting climate instruments on both the NPP and the operational NPOESS systems [D31]. Bolstered by this out-pouring of user support and institutional backing by the OSTP and NRC, NOAA and NASA were able to institute the two final changes to the program's organizational and technical architectures before the program was formally cancelled in 2010.

### 4.7.2 Epoch F Technical Architecture

During this epoch, the program heeded recommendations by the NRC and re-manifested several of the climate sensors that had been removed during Nunn-McCurdy. Specifically, TSIS and OMPS-Limb were both restored to their previous assignments on the NPP and NPOESS satellites and ERBS was re-assigned to the NPP satellite and plans were made to produce copies of the existing ERBS instrument for use in the operational system [D102]. Additionally, although the TJAT considered options that would reduce the technical architecture's climate science capabilities (particularly if VIIRS was replaced by AVHRR or NPP was cancelled), NOAA and NASA's participation ensured that capabilities critical to climate science were preserved [D64, D207, D208].

### 4.7.3 Epoch F Organizational Architecture

With the instruments necessary to execute the NASA-NOAA climate missions re-manifested in the technical architecture, the only Nunn-McCurdy mandated change left to be undone was the addition of the PEO position. Although the PEO position was occupied until the program's cancellation, the PEO's authority to adjudicate issues and to allocate scarce resources between the operational NPOESS and NPP systems was eroded after former NASA civil servants transferred into leadership positions at NOAA NESDIS. Specifically, in 2007, NOAA replaced its head of NESDIS, the NOAA Administrator for Satellite and Information Services and created a new deputy position to support the administrator [D122, D80]. Both positions were filled by NASA career civil servants who had spent their previous careers working at NASA Headquarters or at GSFC, NASA's home for NPP [D122, D80].

Like all other NOAA employees supporting NOAA's satellite development and operations, the NPOESS PEO position was formally assigned to the NESDIS organization. The relationship between NESDIS and the program resembled a matrix organization: NESDIS assigned staff to work in the IPO but managed them as NESDIS employees. Throughout this epoch, NESDIS management utilized the performance evaluation of the PEO to subvert the authority that the position had been granted by the EXCOM; in doing so, NESDIS was able to restore NPP and the NOAA-NASA climate missions to the priority that they enjoyed prior to Nunn-McCurdy. If the PEO made a decision contrary to NESDIS's preferred outcome, the individual would find himself penalized in his performance evaluation [I18, I33, I46, I50]; as previously noted, the program cycled through multiple PEOs and SPDs while NESDIS leaders used their performance evaluations as a mechanism for manipulating management decisions to support continued prioritization of NPP and its associated missions [D161].

### 4.7.4 Summary: Epoch F's Architectural Changes and Policy Themes

The changes mandated by the Nunn-McCurdy certification process reduced the technical architecture's similarly to NASA's EOS system by eliminating functions that contributed only to NOAA and NASA's climate missions. By de-manifesting climate instruments, Nunn-McCurdy made a clear statement to agency leaders that in order to control its costs, the program needed to resume its convergence role: as low-cost means for executing the DMSP and POES systems' operational weather missions. The partial return to Epoch A's architectures not only resulted in a reduction of the system's climate monitoring capabilities, but it also implied a reduced role for NASA, since technology infusion and climate science were outside the scope of the newly prioritized operational weather mission.

The NASA-NOAA alliance that emerged during this epoch to both restore the de-manifested sensors and to manage the NOAA NESDIS office, had been cultivated for years—from the OSIP-program prior to convergence to the agencies' jointly run Operational Satellite Simulation Experiments which drove many of the IORD-I's requirements. However, the alliance's actions during Epoch F differed from previous epochs because they were opposed by the agencies' DoD collaborators: specifically, after Nunn-McCurdy, the DoD was willing to accept performance comparable to heritage POES and DMSP in order to reduce the program's cost [D147, D195]. Therefore, by restoring the technical architecture to the configuration that it held prior to Nunn-McCurdy, NOAA and NASA prioritized their climate missions over the DoD's attempts at cost control. NOAA and NASA's relationship with the DoD further deteriorated when the DoD's Under Secretary of Defense for AT&L delegated his responsibility for attending EXCOM meetings to a representative who was not authorized to make decisions and then later overturned decisions that had been made by NOAA and NASA in his absence [D220].

Additionally, NASA resumed and expanded the role it held prior to Nunn-McCurdy by restoring the program's focus on climate and staffing former NASA personnel in NESDIS management positions. By transferring former NASA employees—who were better aligned with NPP's mission than the IPO's—the PEO's authority was eroded and his ability to adjudicate issues that affected both NPOESS and NPP was compromised. With NASA's role in the operational program increased, the collaboration during this epoch was essentially composed of two partners, NASA and the DoD, whose interpretation of the system's core mission fundamentally differed. While the Nunn-McCurdy process signaled the DoD's desire to return to the limited operational weather mission and the lower cost technical architecture that existed at convergence, NASA viewed NPOESS, and particularly its NPP program, as an extension of EOS, a system which was so expensive and exquisite, that it was cancelled with only one third of its planned capabilities completed. Of course, NASA's desire to utilize the NPOESS program as a follow-on to EOS was not unique to this epoch; indeed, throughout the program's lifecycle, its organizational and technical architectures evolved to support of NASA's climate science goals.

## 4.8 Epoch G

Epoch G began with the cancellation of the NPOESS program in February 2010 and continued until the formal cancellation of the DWSS program in January of 2012. With the cancellation of NPOESS, the White House dissolved the IPO and assigned the DoD responsibility for developing a system to collect data from the early morning orbit. NOAA and NASA were assigned responsibility for the afternoon orbit and for fielding a Common Ground System (CGS) that would be used by both systems for command and control and for data processing [D175]. NOAA and NASA's program, JPSS, was established immediately and both agencies were directed to ensure that NPOESS requirements could be met "on the most rapid practicable schedule and without reducing system capabilities" [D175]. By establishing JPSS quickly, the Administration's hoped to minimize the possibility of a data gap in the afternoon orbit, which could occur if the final POES satellite (which had launched in 2009) failed before its replacement was launched. DWSS's activities, on the other hand, were delayed until the fourth quarter of fiscal year 2011; unlike NOAA, the DoD had two more heritage DMSP satellites to launch before it risked a data gap in the early morning orbit [D175].

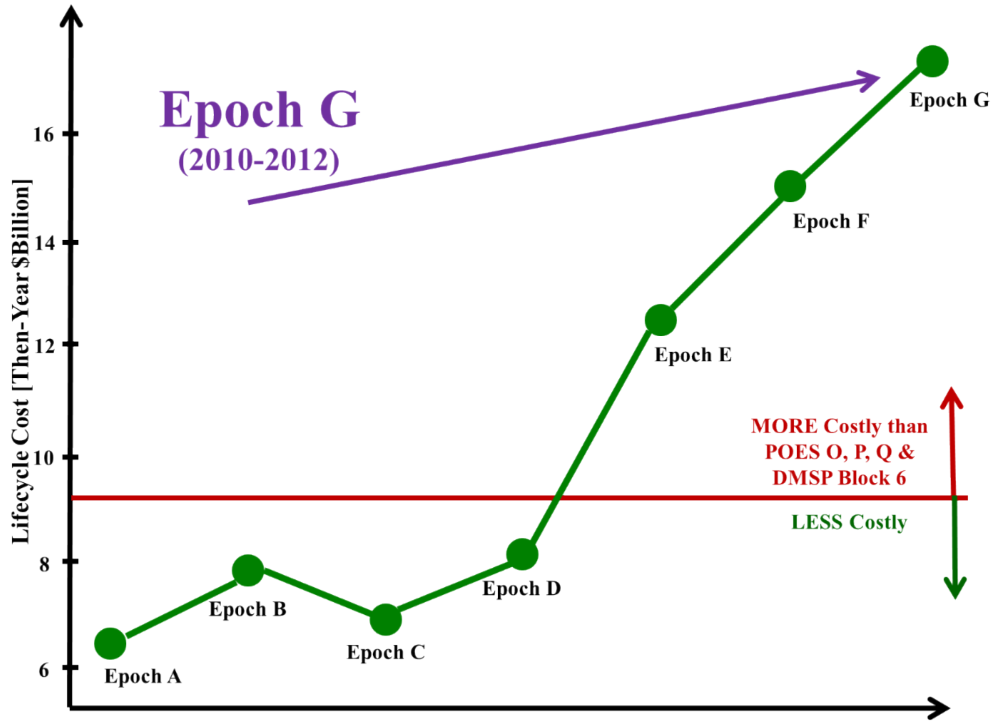


**Figure 24: Cost Growth in Epoch G**

Despite the need to mitigate the potential for a data gap, the majority of both the JPSS and DWSS programs' activities during this epoch focused on a lengthy, costly, and complicated transition process that involved de-staffing the IPO, forming two new program offices, transitioning contracts, defining agency unique requirements, and establishing new program baselines. Even though the JPSS program planned to leverage capabilities that were developed during NPOESS and NPP, it took several months to establish formal relationships between the JPSS program office and NPOESS and NPP's contractors; for example, it was not until September 2010 that Raytheon's contract for the ground system was transferred to NASA [D232] and that a contract for the JPSS-1 spacecraft bus was awarded to Ball Aerospace [D65]. In addition to the time it took to transition contracts to the JPSS program, NPOESS contract termination liabilities alone cost the government $84 million [D232].

Furthermore, despite Presidential direction that the JPSS system should "consist of platforms based on the NPP satellite," numerous system requirements were changed and technical capabilities were also enhanced during this period. Specifically, the JPSS program embarked on a "NASA-ficiation" process, that identified and corrected residual risks from NPP and applied new NASA standards to the program's contracts [D135, I63]. During this epoch, the program also conducted numerous trades that changed or enhanced the heritage NPP system's capabilities [D100, I56, I59, I63] and finalized its Level 1 requirements document—the NOAA-specific replacement to the IORD [D65].

Even more important than defining the systems that would replace POES, during this epoch, the JPSS program also focused on preparing the NPP satellite for launch. In fact, when the program was under-funded by a continuing resolution in fiscal year 2011, it had to prioritize NPP development and launch preparation over staffing up the JPSS program office or ordering long lead items for JPSS-1 [D232]. The

NPP ground system development was a particular focus during this epoch, since it had not been prioritized as highly as the NPP instruments and thus, was the least mature component in the NPP system architecture [D226]. Despite the challenge of readying the NPP ground system, the NPP satellite launched in October 2011 and continues to operate successfully today.

Concurrent with these technical activities, the JPSS program also worked to define and stabilize the roles that each agency played in the JPSS organizational architecture. During this epoch, those roles remained fluid and an independent review of the program concluded that JPSS's management structure was "dysfunctional," that there was "confusion as to the responsibility, accountability, and authority of senior managers," and that NOAA senior management was too involved in program execution [D142]. In addition to these findings, the ground system organizational architecture remained unstable during this period, as both NASA and NOAA's Center for Satellite Applications and Research (STAR) attempted to exert control over its development [I69, I60, I66].

Activities on the DWSS program were similar, as the DoD worked to de-scope its NPOESS contracts and to transition them for use on its new program. In parallel, the DWSS program office also examined system capability trades and explored opportunities to reduce the program's cost [I62, I68, I65]. Ultimately, because the program was unable to significantly reduce its $6.1 billion lifecycle costs [D20] and DoD leadership expressed an interest in formally re-visiting their requirements [I62, I68, I65], the program was cancelled in January 2012. Prior to DWSS's cancellation, the DoD continued to work with its former NPOESS partners to define an MOA for the CGS [D100] and to coordinate VIIRS testing activities, since both programs planned to procure VIIRS using Raytheon, the heritage NPOESS vendor [D51].

### 4.8.1 Transition to Epoch G

As discussed above, the OSTP's review of the NPOESS program—which began in fall of 2009—played a critical role in the transition from NPOESS to the diverged JPSS and DWSS programs. During this review, the OSTP staff studied four strategies for restructuring the program, three of which were recommended during an independent review that preceded their analysis [D147]. In particular, they considered enhancing the IPO's funding and staffing support while maintaining the program's organizational and technical architectures [D147, I42]. They also considered options that altered the program's organizational architecture by eliminating the EXCOM's authority and by assigning either NASA GSFC or the Air Force Space and Missile Center responsibility for the program [D147, I42].

The forth option that was considered—to cancel the program and its prime contract—went against the advice of an independent review team, which recommended that the government maintain the NPOESS technical architecture and its contracts in order to minimize the risk of a data gap [D147]. Despite this and related review team recommendations [D241], the OSTP team was also communicating with NASA management, which had developed a plan to execute a follow-on program for NOAA using clones of NASA's NPP system [I28, D175]. These proposals ultimately formed the basis of the JPSS program that was established at NPOESS's cancellation [D175, D99].

## 4.8.2 Epoch G Technical Architecture

As noted above, the JPSS technical architecture was based on NPP. The primary JPSS constellation was composed of only one satellite in the afternoon orbit and one replacement for that satellite. The first satellite, JPSS-1, hosted VIIRS, CrIS, ATMS, OMPS-Nadir, and CERES while the second, JPSS-2, hosted VIIRS, CrIS, ATMS, and both OMPS-Limb and OMPS-Nadir, but no CERES [D99]. Despite the changes that were motivated by the "NASA-ification" process, contracts for the JPSS-1 instruments and spacecraft bus were all awarded to their heritage NPOESS vendors [D29, D21]. In addition to the primary satellite, the JPSS technical architecture also included a "free-flyer" satellite and one replacement free-flyer. NOAA and NASA planned to use this satellite to host the instruments that were not flown on NPP but were still required by NOAA; these instruments included TSIS, DCS, and SARSAT [D225].

Although the JPSS spacecraft architecture changed significantly from the NPOESS program, the ground architecture did not; in fact, the JPSS program inherited Northrop's subcontract to Raytheon for the ground system and maintained its IDPS and C3 segments during this epoch. Although the NOAA-NASA JPSS team managed the ground system, they intended for the CGS to interface with the DWSS satellite and provide both the C3 and IDPS functions to its users [D100]. As such, during this epoch, the agencies began working together to jointly define CGS interfaces and to establish the MOA that would govern the how the agencies would continue to work together to develop and utilize the CGS [D100]; however, the DWSS program was cancelled before these details were completed [I68, I70].

Finally, the DWSS technical architecture contained the NPOESS instruments that were absent on JPSS, MIS and SEM, and one shared instrument, VIIRS [D51]. Like JPSS, these instruments were all hosted on the same spacecraft bus and the constellation was composed of a single satellite, this time in the DoD's preferred early morning orbit. Also like JPSS, the DWSS program planned to develop one replacement satellite for its constellation; however, unlike JPSS, the DWSS program maintained its contracts with Northrop for the spacecraft bus and Northrop's subcontract with Raytheon for VIIRS. Like VIIRS, MIS and SEM were also directly derived from NPOESS [D51]. While development on each of these components proceeded, the DWSS program concurrently examined opportunities to reduce the functionality, performance, and cost of the DWSS architecture. Although the program analyzed numerous options that included less capable instruments and a smaller spacecraft bus, no official changes were incorporated into the program's technical architecture prior to its cancellation [I62, I68, I65].

## 4.8.3 Epoch G Organizational Architecture

While the DWSS program office studied changes to its technical architecture, its organizational architecture remained stable during this epoch. Specifically, mission responsibility was transferred from the IPO to the Air Force Space and Missile Center (SMC). Within SMC, the DWSS program office was assigned to the Defense Weather Systems Directorate, which also housed the separate DMSP program [D51]. In addition to shifting responsibility from the IPO to SMC, the government's relationship with its NPOESS heritage contractors also changed during this epoch. Specifically, instead of delegating a significant amount of responsibility to the program's contractors, plans for the program emphasized its "back to basics approach" which, unlike the TSPR-like model that existed on NPOESS, was described as "intensive and active oversight of the contractor and subcontractor" [D51].

Like the DWSS program, the JPSS program's relationship with the NPOESS contractors also strengthened during this period, since NASA directly managed the contracts for each instrument, for the spacecraft bus, and for the ground system; as such, NASA assumed responsibility for end-to-end JPSS system integration, a role that Northrop held previously on the NPOESS program [D99, I69, I59]. NASA's end-to-end responsibility on JPSS was different than the role that it held previously on POES and that it concurrently played on the related GOES program; in POES and GOES, NASA was responsible for only the space segment, while NOAA was responsible for developing the ground system and for managing the complete system's integration [I55, I63, I66]. In the new JPSS organization, NASA established two projects to manage the JPSS ground and space segments and one project to continue managing NPP and then managed those projects in a NASA program office located at the GSFC [D225]. Through GSFC center management, NASA's JPSS program office received funding and Level 1 requirements direction from the newly formed Joint Agency Satellite Division (JASD) located at NASA Headquarters [D143]. JASD, in turn, received funding and Level 1 requirements direction from NOAA NESDIS, which also managed a separate NOAA JPSS Office (NJO) [D143]. Finally, during this epoch, the relationship between the NJO and NASA's program office was described as being one of "collaboration and consultation" [D94].

As noted in above, the JPSS Level 1 requirements document was essentially the NOAA-specific replacement to the NPOESS IORD. However, unlike the shared authority that it for the NPOESS IORD, NOAA held unilateral authority over JPSS's Level 1 requirements; it also had the sole responsibility to fund them and to insure their successful implementation. NOAA delegated its implementation responsibility for deriving requirements below Level 1 to NASA, which had the authority implement those requirements as long as they did not exceed NOAA's budget [I56, I63]. NASA's financial relationship with NOAA was cost-reimbursable: Congress allocated NOAA money, which it then transferred to NASA [D65, D99, D29]. NASA did not contribute any of its own money to the JPSS program.

Although the responsibilities of each element in the JPSS organizational architecture stabilized by the end of Epoch E, the relationships between components were adversarial for some time [D142]. In particular, the NJO and senior NOAA / Department of Commerce (DoC) management played such an active role in the NASA program office that they ultimately eroded the responsibility and authority that had been officially delegated to NASA's managers [D142]. In addition, NOAA's Center for Satellite Applications and Research (STAR) organization sought to play a more significant—if not complete—role in managing the JPSS ground system [I69, I60, I66].

Despite these early challenges, by the end of the epoch, the roles of the NASA and NOAA program offices evolved to be more distinctly defined. Specifically, the NJO emerged as the office responsible for integrating the NASA produced data products with those that were actually consumed by the larger NOAA user community, which included organizations like STAR [I60, I63, I66]. Alternatively, NASA was responsible for developing the ground and space segments that were inherited after the cancellation of the NPOESS program [D65,I66]. With these roles more clearly defined, another Tom Young independent review team in 2014 praised the program for its successful organizational reform [D143].

### 4.8.4 Summary: Epoch G's Architectural Changes and Policy Themes

The White House decision memo that cancelled the NPOESS program cited the fact that the program was over budget, behind schedule, and underperforming [D175] as the primary incentives for its termination. Despite this motivation, the programs that were established in NPOESS's wake suffered from many of the same technical and organizational challenges that plagued their predecessor. Furthermore, even before the newly separate NOAA and DoD program offices could begin executing their missions, both agencies had to invest a significant amount of time and money simply terminating the NPOESS contract, re-defining new contracts and agency unique requirements, and establishing new program offices. Despite these transition costs, the Administration intended for the DWSS and JPSS programs to return to the acquisition strategies that had been successful prior to Epoch A, when NOAA and the DoD acquired systems separately and NASA served as NOAA's acquisition agent [D175].

Despite this intention, the JPSS and DWSS's technical architectures differed significantly from the pre-Epoch A POES and DMSP architectures. Specifically, the total operational constellation (including both JPSS and DWSS satellites) contained two fewer satellites than POES and DMSP and one fewer ground system. The primary JPSS satellites no longer hosted DCS, SARSAT, or SEM but continued to host the operational climate and climate science instruments, CERES and OMPS-Limb, that were added during the NPOESS program. Furthermore, each of the heritage POES or DMSP instruments—VIIRS, CrIS, ATMS, OMPS, and MIS—had significantly more performance and functionality than the instruments flown prior to Epoch A. Despite these differences and the Administration's intent in cancelling the NPOESS program, the JPSS program's predicted lifecycle costs reached $11.9 billion [D225] during this epoch and DWSS's costs were reported to be $6.1 billion [D20] just prior to its cancellation.

Perhaps more significant than the persistent lifecycle cost growth, was the increasing risk of a data gap, which could occur if the on-orbit POES satellite failed before a replacement was launched. While independent review teams warned of this risk prior to NPOESS's cancellation [D147] and the risk was acknowledged in the White House decision memo [D175], the probability that a gap would occur increased during this epoch [D142], when the JPSS launch dates slipped to 2015 and 2018 [D225]: eight years after the launch of the final POES satellite. One of the reasons cited for this launch slip was a continuing resolution that under-funded the JPSS program and forced it to prioritize the completion and launch of NPP over the development of the operational JPSS satellites [D232]. This persistent prioritization of NPP highlights the key difference between the JPSS and POES organizational architectures: while the DWSS organizational architecture returned to the form that it held during the heritage DMSP program, JPSS did not. Instead, the JPSS program essentially merged with NASA's existing NPP program office. As noted above, the agency's role in the JPSS organization was enhanced from the role it held on POES: instead of managing only the space segment's development, on JPSS, NASA was also responsible for the ground system and for end-to-end system integration. Today, the probability that there will be a gap in satellite data in NOAA's traditional afternoon orbit has been described as "unacceptably high" [D143].

## 4.9 Conclusion and Motivation for Upcoming Chapters

Although this chapter focused on technical and organizational architectures of the past, as of this writing, the NOAA-NASA JPSS program continues to develop satellites and a ground system. Additionally, even though the DoD has yet to establish a formal program to replace DWSS, the Air Force's Weather System

Follow-on (WSF) project continues to study options for collecting environmental monitoring data in low Earth orbit. Importantly, since 2012, many of the policy decisions and directives concerning WSF and JPSS address the cost growth that occurred in prior epochs and attempt to alter both programs' organizational and technical architectures to reduce their costs in the future.

As noted in Chapter 1, a current movement in the space acquisition community espouses a new strategy—disaggregation—for architecting technical systems; formally defined, disaggregation refers to the separation of missions, functions, and sensors across systems [46]. One of WSF's primary focuses was studying the potential for disaggregating DMSP's heritage sensors—an optical-infrared imager-radiometer, a microwave imager-sounder, and a space weather sensor—across multiple small spacecraft [D25]. In parallel with this study, the Air Force also completed an Analysis of Alternatives to formally update the requirements it established for NPOESS [D25]. At the conclusion of this work, the Air Force reduced the number of requirements that it intended to independently meet, increased its dependence on domestic and international partners, and recommended establishing a formal DMSP follow-on program that would employ a disaggregated technical architecture [D62]. As recently May 2014, Congress denied the Air Force's budget request for a follow-on program in the House mark-up of the 2015 Defense Authorization Act [D69]. As a result, the future of the DoD's technical architecture remains uncertain.

Although NOAA and NASA do not specifically use the term disaggregation, recent changes to the JPSS technical architecture can be described as such. In particular, the CERES and OMPS-Limb instruments were removed—or disaggregated—from the JPSS spacecraft and the free-flyer spacecraft that hosted TSIS, DCS, and SARSAT were disaggregated from the JPSS program and moved into as a separate program office within NESDIS [D227]. These decisions were motivated by an independent review team's report that recommended that JPSS eliminate all sensors that did not directly contribute to its operational weather mission [D142]; put another way, the report suggested disaggregating NOAA's operational weather mission from its operational climate and climate science missions. As the risk for a data gap increased, the same independent review team later suggested that JPSS disaggregate its two most critical weather instruments, CrIS and ATMS, from the larger JPSS spacecraft and develop an ATMS-CrIS "free-flyer"[11] spacecraft that could be launched sooner than JPSS-1 [D143]. As recently as May 2014, the House Appropriations Committee denied funding for the newly established TSIS-SARSAT-DCS free-flyer program and expressed reservations over NOAA's plans to fly CERES on JPSS-2 [D117]; the future of the ATMS-CrIS free-flyer and the technical architecture for JPSS-3 or 4 remains uncertain.

Like their technical architectures, JPSS and DWSS's organizational architectures also became increasingly disaggregated after 2012. As noted above, the Air Force's most recent plan required the DoD to coordinate more closely with partners that were operating program offices housed in different domestic and international government agencies. As also discussed, management of the JPSS free-flyer that hosted TSIS, DCS, and SARSAT was disaggregated from the central JPSS program office and into its own office that was housed within NESDIS. Budget responsibility for two climate centric sensors, CERES and OMPS-Limb, was transferred from NOAA to NASA for JPSS-2 [D227] and a recent proposal even suggested that NOAA itself should be disaggregated from the JPSS program, which instead could be managed entirely by NASA [D9].

[11] "Free-flyer" is an industry term that refers to a small spacecraft that host only a few instruments.

The agencies' recent interest in disaggregation was at least partially motivated by the cost growth that was experienced during NPOESS, JPSS, and DWSS. Since aggregation fundamentally alters a program's organizational or technical architecture, to study the cost impacts that aggregation had on environmental monitoring programs, I focused on their architectures and investigated how aggregation increased their complexity and cost. In the upcoming chapters, I apply Chapter 3's research approach to make sense of the 20-year history that was relayed above and to better understand exactly how cost growth was related to complexity induced by aggregation.

Since the NPOESS program spanned six of the seven epochs discussed above, Chapters 5 and 6 focus specifically on this program: Chapter 5 discusses NPOESS technical complexity and Chapter 6 discusses NPOESS organizational complexity. Chapter 7 reviews the complexity contained in the JPSS and DWSS programs and compares it to the NPOESS program that they replaced. Finally, Chapter 9 applies the lessons learned from the case studies to analyze the disaggregation trades that were noted above. In this way, I am able to use an improved understanding of the historic impacts of aggregation to inform future decisions to aggregate or disaggregate environmental monitoring programs in the future.

# 5 NPOESS Technical Complexity

*Once you start getting down to the nuts and bolts of it, the customers for the two different systems had noticeably different priorities. Once they started trying to put together the technical requirements document for NPOESS, that is the sort of thing that was coming up. Part of the way that they solved this was that whoever had the more stringent requirement was what got put into the document. If you start doing that, you quickly work your way up to a very expensive system.*

–Interviewee 2

This chapter presents an analytic history of the NPOESS program's technical architecture. Using the quantitative framework defined in Chapter 3, I first represent the NPOESS technical architectures, quantify their complexity, and observe the evolution of complexity over time. Aided by the framework's global perspective on complexity, I then identify five decisions that affected complexity on the NPOESS program and notice a lag between the decisions that increased complexity and a corresponding increase in the program's cost estimates. Next, I review the qualitative data within each epoch that was used to identify complexity mechanisms, to create the DSMs, and to calculate the metric. I also present qualitative data that explains why the program made costly decisions. Then, I continue by using VIIRS's development history as a concentrated case study that illustrates how the program's decisions induced complexity while its cost estimates remained low. Finally, I conclude by summarizing the mechanisms that increased NPOESS's technical complexity and by noting the important relationship between technical and organizational complexity that is the subject of Chapter 6.

## 5.1 Evolution of Complexity

Qualitative data revealed that eight different mechanisms induced technical complexity on the NPOESS program. These mechanisms were classified according to the type of complexity that they induced: design, process, or architectural. Design complexity, or low technical maturity, was observed in the program's instruments, its spacecraft, and its ground system. Process complexity was observed in stringent oversight requirements and in requirements conflict. Finally, three types of architectural complexity were observed: mission relationships, programmatic relationships, and interferences. Mission relationships included physical, data, and reliability relationships between components and also design relationships, when components were designed to be common across different environments and systems. Finally, components were also observed to interfere mechanically, optically, and electromagnetically.

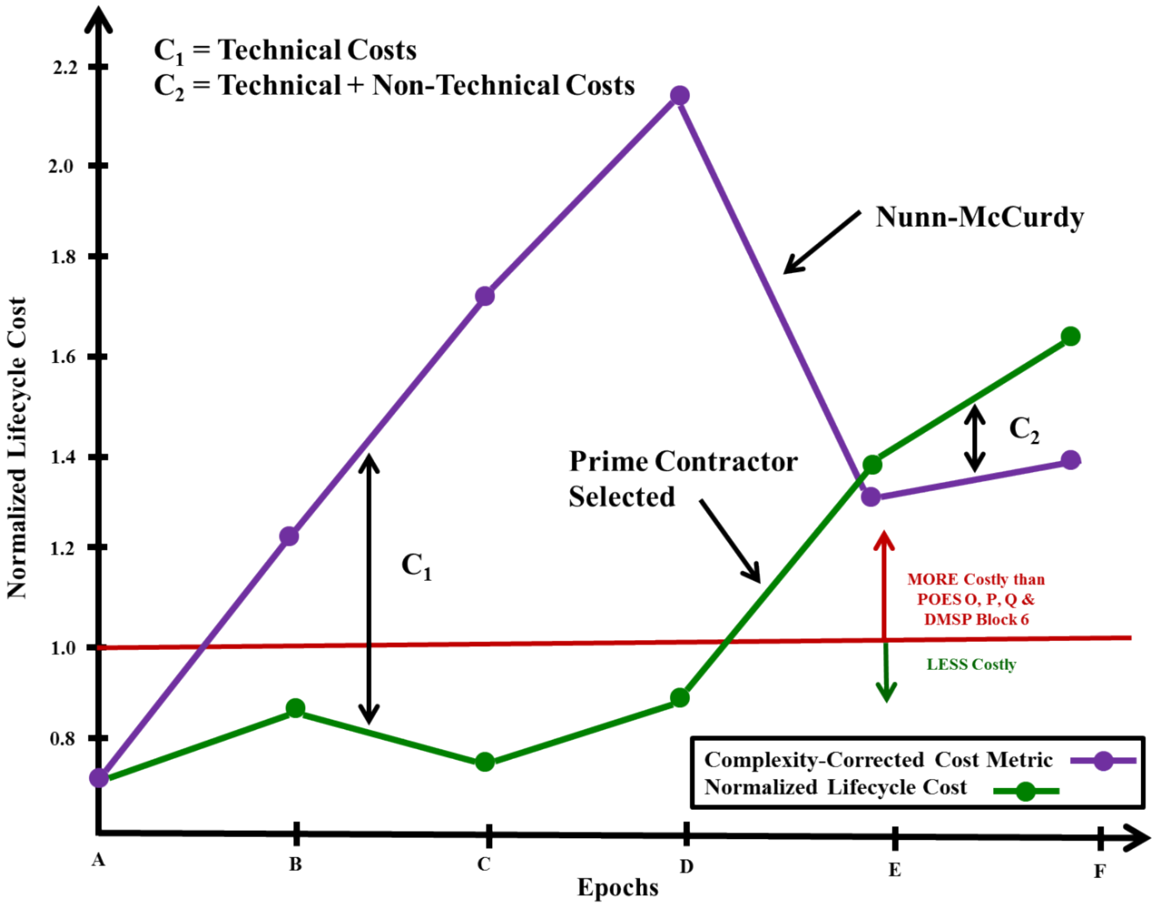


**Figure 25: Program Cost Estimates Compared to Complexity-Corrected Cost Estimate (Technical Complexity Metric)**

### 5.1.1 Applying the Framework

Each complexity mechanism was represented in the DSMs that were created for each epoch. These DSMs contained three component types: spacecraft, instruments, and ground processing systems. First, the DSMs contained the constellation of all three NPOESS spacecraft, plus the NPP spacecraft. Next, they contained 12 instruments and captured how those instruments interfaced with the spacecraft and data processing algorithms and also how they interfered with one another. The DSMs also captured interfaces between the ground processing algorithms and the ground system and between the ground system and the spacecraft. Finally, a design and process complexity score was assigned to each component by adding +1 for every complexity mechanism that was present; for the instruments, design complexity was assessed according to a process described in the Appendix.

While the DSMs contained information on both the ground and space segments, for several reasons, the complexity metric that I used focused solely on the space segment. The first reason was noted in Chapter 1: that the original goal of this research was to understand how jointness affects space segment costs. Second, the ground segment architecture remained relatively constant throughout the NPOESS program while the space segment evolved considerably. And third, there is little quantitative understanding of how aggregation or disaggregation affects ground system costs [47] but cost estimating relationships for spacecraft of various sizes are readily available. Importantly, although my analysis and metric do not specifically focus on the ground system, in sections that follow, I do provide a qualitative description of how complexity affected its costs. Finally, the complexity metric captures cost and not benefit; therefore, it does not track how the system's capabilities and performance increased alongside its complexity. My focus on cost is intentional; however, it should be noted that the NPOESS system's performance and capabilities exceeded those of the predecessor POES and DMSP systems.

Following the process described in Chapter 3 and further detailed in the Appendix, I calculated the complexity metric for each epoch and normalized it by the complexity of the pre-convergence POES and DSMP systems.[12] Each metric included the launch, recurring, and complexity-corrected non-recurring costs for the space segment; however, operations and ground system costs were not included. By defining the metric in this way, I intentionally focused on non-recurring cost since the NPOESS program's costs grew during development rather than during production or operation. To apply Chapter 3's approach for studying cost growth to other types of joint systems where recurring or operations costs may dominate, the metric should be adjusted accordingly.[13]

### 5.1.2 Observing the Dynamic Nature of Complexity

Figure 25 illustrates the evolution of technical complexity on the NPOESS program and compares it to the program's estimated costs during each epoch; like the complexity metric, the costs were normalized by the cost of the pre-convergence POES and DMSP systems. From this comparison, one can draw several conclusions:

- Complexity was injected into the NPOESS technical architecture during the program's earliest epochs.
- Despite this increase in complexity, the program's costs estimates continued to remain low until after its prime contractor was selected in Epoch D.
- After the prime was selected, the program's cost estimates increased substantially while the complexity present in its system simply continued on the trajectory that it had followed during previous epochs.
- The Nunn-McCurdy certification substantially reduced technical complexity by de-manifesting several sensors and cancelling multiple replacement spacecraft.
- Despite the Nunn-McCurdy processes' successful reduction in technical complexity, the program's cost estimates continued to grow.

The relationship between the technical complexity metric and the program's cost estimates motivates several conclusions about cost growth on the NPOESS program:

- During the early epochs, the NPOESS program underestimated and under managed the complexity contained within its technical architecture.

[12] DMSP Block 6 and POES O, P, Q

[13] For example, if Chapter 3's approach is applied to study cost growth on the Joint Strike Fighter, then recurring and operations costs should be a critical component of the technical complexity metric. Complexity mechanisms that cause these cost types to grow should be identified and accounted for in the metric.

- When the program began to more actively manage its technical complexity, its cost estimates began to grow.
- During the program's final epochs, its cost had both a technical and a non-technical component, since the program's cost estimates exceeded the costs predicted by my technical complexity metric.

These conclusions are consistent with the qualitative data that was used to support the DSMs' construction and the metric's calculation.

### 5.1.3 Complexity-Inducing Decisions

Five decisions were identified to affect the complexity of the NPOESS technical architecture. These decisions were:

- **Decision 1:** Defining the agencies' requirements jointly in the IORD-I.
- **Decision 2:** Adding the NPP program to execute dual risk reduction and climate science missions.
- **Decision 3:** Retaining the technical baseline while the program's costs were increasing and no additional funding was available.
- **Decision 4:** Reducing the technical baseline by de-manifesting climate instruments and by cancelling follow-on spacecraft during the Nunn-McCurdy re-certification process.
- **Decision 5:** Enforcing NASA process requirements even though NPOESS components were developed to DoD standards.

Table 4 maps each of these decisions to the complexity that it injected into the NPOESS technical architecture. Since my analysis focuses on cost and complexity *growth*, Decision 4—which reduced technical complexity rather than increased it—is not included.

**Table 4: Complexity Mechanisms Induced by Each Decision**

| Complexity Type | Complexity Mechanism | Decision 1 | Decision 2 | Decision 3 | Decision 5 |
|---|---|---|---|---|---|
| Design | Instrument Design Maturity | X | X | | |
| Design | Spacecraft Design Maturity | X | | | |
| Design | Ground Design Maturity | X | | | |
| Process | Oversight Requirements | | X | | |
| Process | Requirements Conflict | | X | | X |
| Architectural | Mission Relationships | X | X | | |
| Architectural | Interferences | X | | | |
| Architectural | Programmatic Relationships | | | X | |

In the remainder of this chapter, I review qualitative evidence that supported each DSM's construction and each metric's calculation. Unlike Chapter 4, where I noted every time an instrument was added or subtracted from the system, in this chapter, my discussion focuses specifically on the *mechanisms* that increased complexity; of course, although my qualitative discussion will focus on complexity mechanisms, the metric that I used accounted both for changes to the architecture's content and to its complexity.

By focusing on complexity, the sections that follow provide evidence that allows the reader to *zoom-in* to the complexity mechanisms that affected program costs *within* each of the epochs that are shown in Figure 25. Using this perspective, one can gain a detailed process-centric understanding of complexity and its impacts at any point in time on the program, while simultaneously appreciating how that complexity evolved over time. This is one of the important benefits of the research approach that was proposed in Chapter 3.

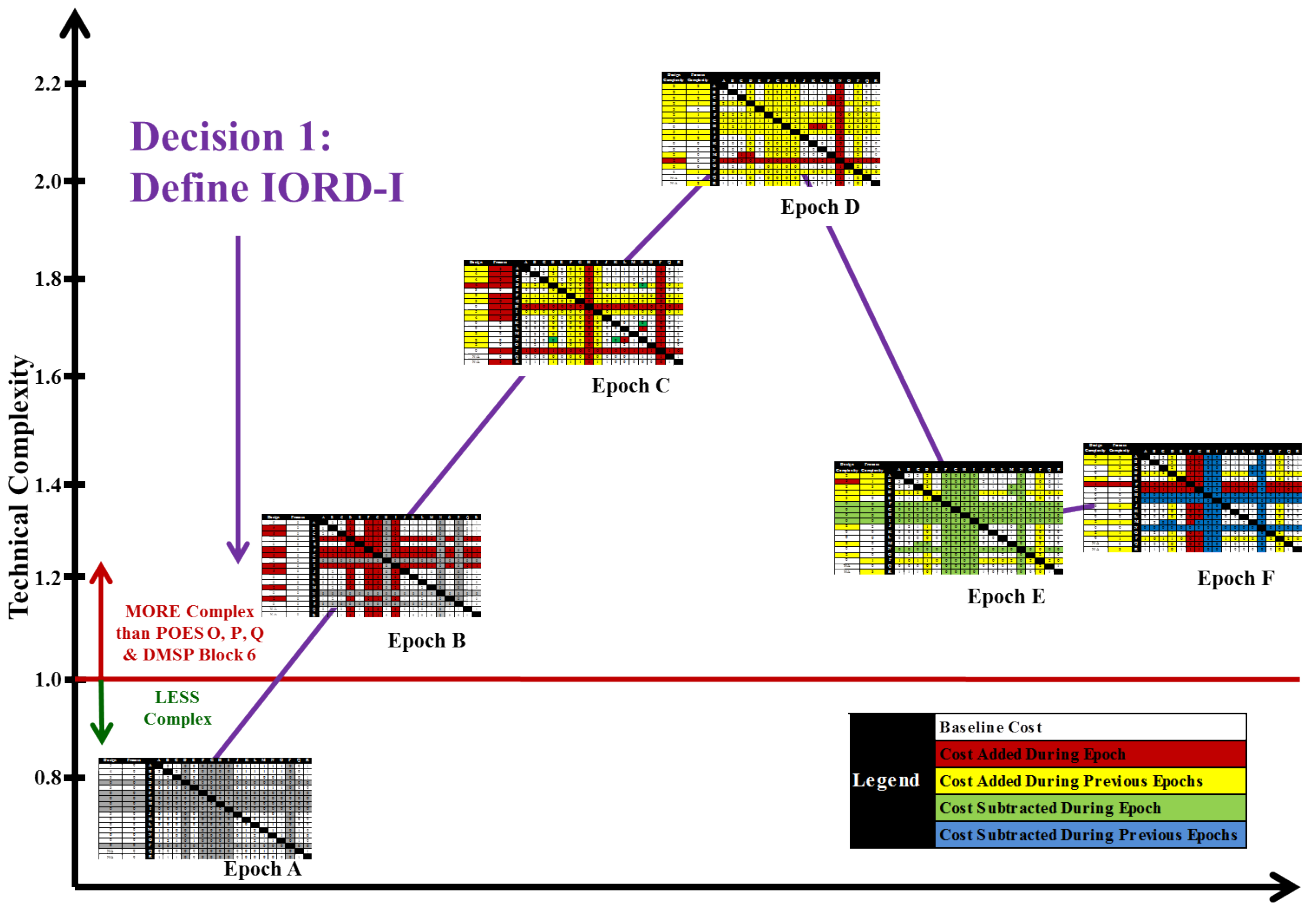


**Figure 26: Complexity Impacts of Decision 1**

## 5.2 Decision 1: Define the IORD-I

The first complexity inducing decision was to define the system's requirements in the IORD-I; as shown in Figure 26, this decision caused the system's complexity to exceed the complexity of the pre-convergence POES and DSMP systems. Interviewees described the IORD-I as a concatenation of each agency's unique or driving requirements; as such, the IORD-I induced both architectural and design complexity. First, the IORD-I induced architectural complexity by requiring that four new instruments be added to the technical architecture so that several agency unique requirements could be met. Second, induced architectural complexity was also induced in the following ways:

- Instruments interfered electromagnetically,

- Instruments interfered mechanically,
- Instruments interfered optically,
- Instruments interacted with one another through the system's reliability budget,
- And the instruments and spacecraft were designed to be common across the constellation.

In addition to architectural complexity, the IORD-I induced design complexity by levying each agency's unique or driving requirements on single instruments; the primary impact of this decision was the agencies' heritage instruments were capable of meeting the IORD's joint requirements and that a significant amount of new design effort was required. Like the instruments, Northrop also had to modify its heritage bus design so that it could host all of the program's increasingly capable instruments. Finally, the ground system's design complexity also increased because—even though the system's users required data products in different forms and formats—the IORD only specified requirements in terms of EDRs. The remainder of this section provides additional description of each of the architectural and design complexity mechanisms that were induced when the agencies defined their requirements jointly in the IORD-I.

## 5.2.1 Architectural Complexity

To meet the IORD-I's requirements, the program used an aggregated spacecraft architecture: rather than distributing instruments across multiple spacecraft in a train, on NPOESS, all instruments in the same orbit shared a common spacecraft bus. To enable instruments to be co-manifested on the same bus without compromising their performance, adverse interactions between the instruments had to be mitigated. Instrument interferences were controlled by altering instrument designs, altering the spacecraft bus design, or in many cases, by doing both. Therefore, mitigation strategies required an additional non-recurring design effort for both the spacecraft and the instruments.

### 5.2.1.1 Interferences

Two types of electromagnetic interference (EMI) interactions resulted from the decision to use an aggregated spacecraft architecture. The first interaction was induced by assigning an active radar altimeter to share the same bus as multiple passive instruments. The active altimeter affected the passive instruments in two ways: by interfering or jamming their tracking, telemetry, and command equipment or by inducing currents in their electronics [41]. Although the program planned to mitigate both unwanted effects at the system-level by adding additional shielding on its instruments [I9, I15, I46], the total cost impact of this EMI interaction was not fully realized since the altimeter was de-manifested during the Nunn-McCurdy process. The second EMI interaction was induced by NOAA's highly sensitive SARSAT and DCS payloads. Since both instruments were extremely sensitive to EMI noise, SARSAT had to be mounted on a large boom and separated from the spacecraft bus [I15] and the program had to levy stringent EMI requirements on each of its instruments and on the spacecraft structure [I8, I9, I15].

The aggregated spacecraft architecture also induced mechanical interactions since CMIS's large conically spinning microwave antenna mechanically perturbed the spacecraft structure and disturbed nearby instruments like VIIRS which had tight pointing requirements. Prior to the program's Nunn-McCurdy restructure, CMIS was a 2.2-meter diameter, 257 kg spinning dish [D92] which drove the design of the spacecraft's attitude determination and control (ADCS) and structure subsystems [I15, I27, I46]. In order to compensate for the momentum and jitter induced by CMIS, the common spacecraft included additional momentum wheels, a reinforced structure, and additional mechanical isolation systems for particularly sensitive instruments like CrIS [I21, I24, D149]. The impact that CMIS had on Northrop's common spacecraft design was so significant that NASA opted to independently procure a separate spacecraft to reduce the costs of its NPP program [I10]. Additionally, during Nunn-McCurdy certification, the program reduced CMIS's size and capabilities so that it would have a less significant impact on the spacecraft's overall design and cost.

In contrast to CMIS, which induced mechanical perturbations into the system, during Epoch D, the temporary addition of the Landsat OLI instrument drove the design of the spacecraft bus by levying even more stringent stability requirements on it. Unlike the other NPOESS instruments which had spatial resolutions on the order of several kilometers and were therefore more tolerant of spacecraft jitter, to achieve its 30-meter spatial resolution requirement, the OLI needed an extremely stable platform [D90]. Once the program performed a more detailed analysis of the accommodations necessary to support the OLI instrument and realized the significant cost that it would add to the common spacecraft design, the OLI was removed from the program. As a result, the only real cost incurred by the program was in the time that its engineers devoted to studying OLI's impacts when their efforts could have been focused elsewhere.

Complexity was also induced by instruments' interactions in the system's reliability budget. Several studies noted that when a spacecraft hosts multiple payloads, different instruments or components of the spacecraft bus can fail at different times. If a mission critical payload fails, then the entire spacecraft may have to be replaced; this can result in an over-lap of capabilities while two duplicate spacecraft populate the same orbit [D2]. Alternatively, if a non-mission critical payload fails and the spacecraft is not immediately replaced, several system users will suffer a data gap while they wait for a mission critical payload to fail and to necessitate the system's replacement [D2]. The NPOESS program had four mission critical payloads: VIIRS, CMIS, CrIS, and ATMS [D1].

Given those considerations and assuming constant instrument reliability, the studies concluded that a system using an aggregated spacecraft architecture required more instruments over the program's lifetime than one which disaggregated its mission critical payloads across multiple spacecraft [D1, D2]. Therefore, to maintain a constellation with four mission critical instruments per spacecraft, the program would either need to develop additional spare instruments or to increase the reliability of each instrument. Importantly, the studies also noted that the overall cost impact of their conclusions were unclear, since they depended highly on the uncertain relationship between instrument cost and reliability [D1, D2]. Furthermore, since the NPOESS program was cancelled before any of the operational satellites were launched, this particular cost impact was not realized on the program. Regardless, the analysis by the Aerospace Corporation and related work by the Johns Hopkins Applied Physics Lab and TRW [D36] illustrated an important technical cost that *can* affect multi-instrument, multi-satellite space systems like NPOESS.

Finally, although less significant than the EMI, mechanical, and reliability interactions, the instruments also interfered optically since most instruments competed for space on the bus's Earth-observing nadir face [41]. While most instruments needed to be oriented towards the Earth, TSIS needed to point towards the sun; as a result, program had to develop a new pointing platform to enable TSIS to view the sun while the other instruments faced the Earth [I43, D86].

### 5.2.1.2 Mission Relationships

The key complexity-inducing mission relationships between components were design relationships, since instruments and spacecraft were designed to be common across all three NPOESS orbits. Although every instrument was not assigned to every orbit, the program planned to use a common bus across the constellation; therefore, the bus was designed to accommodate every instrument even if ultimately flew without them [I07, I15]. The motivation for using a common bus was cost savings and flexibility: the program only had to pay one set of bus non-recurring costs and could use any bus as a spare if a satellite was lost during launch or if it failed on-orbit [I13, I15]. However, using a common bus also *induced* complexity: instead of tailoring each bus to meet the reduced requirements of a single orbit's payload, the common NPOESS bus had to be designed to simultaneously meet the requirements of *all* of the constellation's payloads. As a result, each of the bus's subsystems had to be designed to meet the instruments' most stressing requirements.

Furthermore, in order to fly common instruments and buses across the constellation, both components had to be designed and demonstrated to be compatible with multiple orbital environments [I9, I49]. Although the resulting system was common across orbits, it was *over-designed* for any particular orbit and the complexity that was induced by adapting instrument and spacecraft designs to be common ultimately increased their non-recurring costs. Although these complexity costs may not have overwhelmed the cost savings gained by using commonality, they highlight an important cost to consider when architecting a system to use common or specialized components. As summarized by one interviewee: "We go to commonality at all costs because there was no analysis done to determine what the cost of that commonality was" [I13].

## 5.2.2 Design Complexity

The IORD-I's requirements also induced design complexity in the instruments, spacecraft, and ground system by levying more stringent requirements than those on the pre-convergence POES and DMSP systems. According to a program assessment in 1997, the heritage DSMP and POES systems met none of the IORD-I's threshold requirements [D61]. Instead, heritage DMSP lacked the capability to meet 22 EDRs, was judged to perform below the threshold requirements for 10 EDRs, and significantly below threshold for the IORD-I's remaining 29 EDRs. The results for heritage POES were similar, as it was incapable of meeting 22 EDRs and performed below threshold or significantly below threshold on 31 and 8 EDRs, respectively. Even DMSP Block 6 and NOAA-O, P, Q, whose cost estimates and technical architectures formed the basis of the original convergence analysis, failed to meet many of the IORD's requirements: DMSP Block 6 only met 17 of the IORD-I's 61 EDRs and NOAA-O,P,Q only exceeded threshold requirements for two EDRs and met threshold requirements for only 20 of the remaining 59 EDRs. By comparison, the same assessment judged Epoch B's technical architecture to meet threshold requirements on 59 of the IORD-I's EDRs and to exceed threshold for the remaining two [D61].

Interviewees acknowledged that, in retrospect, the IORD-I's requirements contributed to the program's cost growth [I2, I7, I10, I35, I48] by levying each agency's most stringent requirements [I2, I3, I7, I32, I35, I48]. As a result, the IORD-I hindered the program's ability to capitalize on the agencies' heritage technology and increased the amount of technology development that was necessary to meet the joint requirements set [D61, D148, D195].One interviewee summarized the cost impact of the IORD-I's requirements as: "Whoever had the more stringent requirement was what got put in the document. If you start doing that, you quickly work your way up to a very expensive system" [I2]. Another interviewee echoed this sentiment and particularly noted the impact that the IORD-I had on the program's instruments: "When you go look to combine the most stringent requirements of DoD with the most stringent requirements of NOAA and put them into single instruments….it's a difficult environment to function in [I7]."

### 5.2.2.1 Instrument Design Complexity

The IORD-I induced instrument design complexity by adding new functions to Epoch A's instruments or by increasing the performance of their heritage functions. As discussed in Chapter 4, to meet the IORD-I's requirements, the program's instruments grew increasingly similar to instruments from NASA's EOS program. However, despite their increased similarity to EOS, because the NPOESS instruments still had to meet DoD-specific requirements, their design complexity increased. The three requirements that were particularly impactful to instrument designs were:

- Requirements for EOS quality data,
- Requirements for a Fourier transform infrared sounder,
- And requirements for both cross-track and conical microwave sounding.

In this section, I focus only on the requirements listed above and reserve additional discussion of VIIRS' requirements for Section 5.7.

One of the IORD-I's most significant requirements was for EOS quality data. In order to meet NOAA's requirements, VIIRS, CrIS, and CMIS changed significantly from the instruments that were included in Epoch A's architecture [D61, D44]. The program's original cost estimate assumed that only VIIRS would require a significant non-recurring investment [D44]; however, in order to satisfy the requirements levied by the IORD-I, both CMIS and CrIS also required significant changes to their heritage designs. Specifically, the IORD-I added new functions to the DoD's heritage microwave sounder and enhanced its performance compared to heritage DMSP and EOS microwave sounding capabilities [D61, D44, D103, D167]. The technical evolution required to meet the program's requirements for CMIS was so significant that in addition to funding two risk reduction contracts during Epoch B, the program sponsored an additional risk reduction mission, Windsat, to demonstrate the instrument's immature technologies [I26, I45]. Obviously, the program's requirements for CMIS increased significantly after Epoch A, since Epoch A's architecture utilized a microwave sounder that was similar to the DoD's heritage SSMIS [D44].

Unlike CMIS, which combined separate functions from two heritage instruments and required enhanced performance, the IORD-I's requirements for infrared sounding could be fully satisfied using the EOS program's AIRS instrument [D61]. As a result, NOAA's requirements alone did not necessarily induce additional non-recurring costs, since the program could leverage NASA's AIRS instrument and avoid a non-recurring investment. Despite this opportunity for cost savings, the program did not leverage NASA's AIRS instrument and instead required that CrIS be a Fourier transform instrument [D45]; of the two types of infrared sounders, AIRS was grating spectrometer. Interviewees speculated that the motivation for requiring a Fourier transform instrument derived from the DoD's aversion to actively cooled technology [I15]: while all components of the NPOESS system were passively cooled [I15, I33, D103], NASA's AIRS instrument used active cooling [D103]. Regardless, by requiring CrIS to be a

Fourier transform instrument and to meet EOS quality requirements, the program had to develop a completely new instrument, which was ultimately delivered to the NPP program a full 74 months behind its original schedule [D163].

As noted in Chapter 4, ATMS was not included in Epoch A's technical architecture because analysts assumed that NOAA's users would be able to use similar data from a conically scanning instrument. Despite this assumption, NOAA maintained its agency unique requirement for coincident infrared and microwave soundings; since CrIS (its infrared sounder) was a cross-track scanner, NOAA needed a cross-track microwave sounder, even though many of the channels on the resulting ATMS and the conically scanning CMIS instrument were similar [I15, I27]. Another important characteristic of the program's final ATMS instrument was that it contained the functionality of all three of NOAA's heritage microwave sensors: AMSU-A, AMSU-B, and MHS. ATMS gained this full functionality during Epoch C, when NASA offered to develop a new instrument that would more efficiently use spacecraft resources by occupying a third of the volume, mass, and power of the three heritage instruments [I15, D130].

The decision to combine NOAA's heritage instruments was motivated primarily by the program's aggregated spacecraft architecture, since there were limited resources to accommodate all three cross-track instruments on the multi-sensor spacecraft [I15]. Had NOAA explored opportunities to utilize CMIS's conical microwave data or accepted a reduced cross-track microwave sounding capability with only one or two of its heritage instruments, the government could have saved the non-recurring costs that NASA invested in developing ATMS. Ultimately, ATMS was delivered to NPP 21 months late and at a cost of $195.18 million; this represented a 75% cost growth from NASA's original estimate at the instrument's Mission Confirmation Review in 2003 [D163].

#### 5.2.2.2 Spacecraft Design Complexity

The program's aggregated architecture also increased the design complexity of the spacecraft bus, since Northrop had to redesign several of its standard T430 bus's subsystems so that they would be capable of supporting NPOESS's instruments. Although Northrop assumed a bus design derived from EOS's Aqua and Aura [D17], several instrument masses continued to grow after the prime contract was awarded; as a result, some of the T430 design had to be modified to accommodate instruments' new resource requirements [I23, I44, D149]. Separate from this unanticipated mass growth, Northrop also had to space qualify FireWire, a new IEEE1394 data bus that was capable of supporting the large data-rate and volume that would be produced by the aggregated NPOESS spacecraft [D172]. The data bus most commonly used by space systems at the time, IEEE1553, was incapable of supporting the demanding data-rate requirements of the multiple instruments on the NPOESS spacecraft [D172].

#### 5.2.2.3 Ground System Design Complexity

The IORD-I's requirements also drove complexity into the ground system by:

- Levying the DoD's requirement for data latency across all components of the ground system,
- And by specifying performance requirements in terms of EDRs rather than in terms SDRs or instrument performance.

Data latency refers to the amount of time between data collection and its availability to the system's users in processed form. Low data latency was critically important to the DoD's operational weather mission since military forces use satellite weather predictions to make real-time decisions regarding troop activity [D61]. Although low data latency was a driving requirement for the DoD's operational weather mission, it was comparatively unimportant to the program's climate missions [I15, I39, I47]; one interviewee described these differences as "The climate EDRs….are based on weekly averages and everything else. If you got those a day after observation, no one would have noticed" [I47]. Despite the agencies' differing timeliness requirements, the IORD-I levied a single data latency requirement on all of its EDRs, even if they only contributed to the program's climate missions.

Levying the DoD's driving requirement for latency on all of the system's EDRs impacted the cost of the ground system because it conflicted with requirements for processing climate data [I39, I47]; one interviewee described this conflict as "There are deeply conflicting purposes…an operational algorithm has to be robust and rapid…they had time pressure, the minimum delivery time, latency. The latency requirement was stacked up against all of the performance things [I39]." In order to produce high quality data products according to the DoD's driving latency requirement, the ground system utilized a complex and costly parallel processing system [I47]. Although Raytheon, the ground system subcontractor, performed trade studies which demonstrated that cost could be reduced if latency requirements for non-time sensitive EDRs were loosened, the latency requirement was never changed [I47,I48]. As a result, Northrop's proposed SafetyNet™ ground system delivered 77% of all EDRs within 15 minutes of observation and 95% of EDRs in 28 minutes [D192]. By comparison, the heritage DMSP, POES, and EOS systems met data latency requirements on the order of 100-180 minutes [D154].

Another key characteristic of the IORD-I was that it specified performance attributes only for the system's EDRs and allowed the program's contractors to independently manage SDR and instrument performance. An unanticipated outcome of this decision was that many of the program's users did not use EDRs or if they did, the common EDR produced by the ground system did not meet their specialized needs. Interviewees reported that some operational users' preferred to receive SDRs since that level of data processing could be better assimilated into their models [I35, I45]. However, since the IORD did not levy performance requirements on the SDRs, the government's subsequent attempts to manage SDR performance increased cost by both officially and unofficially adding new requirements to the ground system [I22, I45, I70].

NPOESS's common EDRs were also incapable of meeting the diverse needs of all NPOESS's many operational users. As a result, NOAA independently developed a separate system, the NPOESS Data Exploitation System (NDE), which interfaced with the NPOESS IDPS and NOAA's users. As shown in Figure 27, the NDE was a component of the NOAA Environmental Satellite Processing Center (ESPC) and it interfaced with NOAA users like the National Weather Service and the Comprehensive Large Array-data Stewardship System (CLASS), NOAA's data-archiving program [D186]. NDE's purpose was to convert generic EDRs into NOAA users' preferred formats and to generate NOAA-unique data products through additional processing [I35, I66, D186, D179]. As indicated in Figure 27, although NDE was developed outside of the NPOESS program and did not directly contribute to its costs, it created an additional cost for one of NPOESS's partners and therefore, is an important cost of jointness.

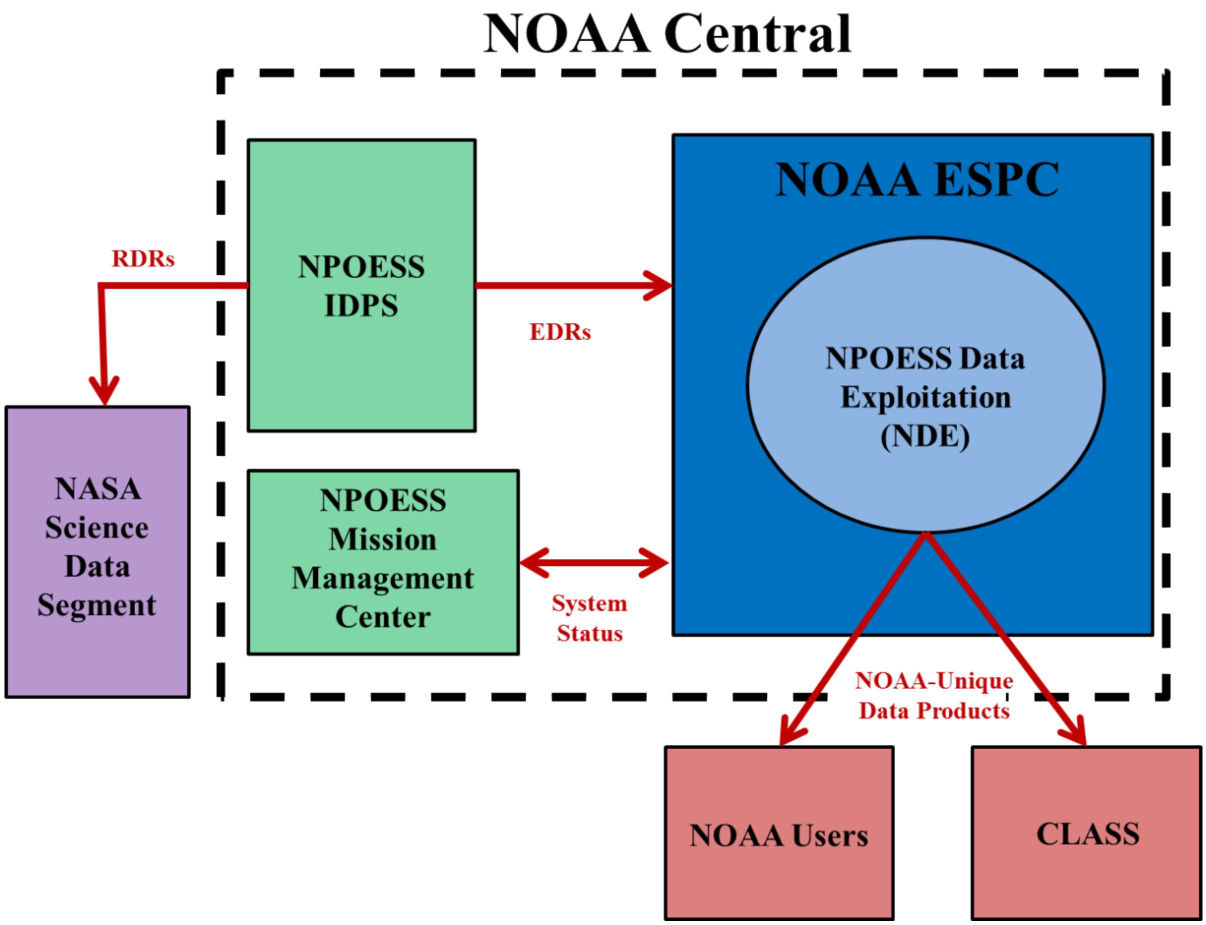


**Figure 27: Schematic of Ground System Illustrating Additional Components That Were Added to Process Data (based on [D186])**

## 5.3 Decision 2: Add NPP

The decision to add the NPP program further increased the system's cost by injecting design, process, and architectural complexity into the NPOESS architecture. Specifically:

- Requirements that were added to the IORD-II and to instrument design specifications increased design complexity by requiring additional technology development.
- NASA's preferred management approach and NPP's climate science mission added process complexity by increasing the government's oversight of its contractors.
- NPP's dual risk reduction and climate science missions conflicted and induced process complexity because the missions were not prioritized.
- The NASA and DoD requirements that were levied on NPP components also conflicted and induced process complexity as program engineers were forced to reconcile and to work to both sets of requirements.
- The NPP spacecraft's interface to the NPOESS ground system and the NPP Science Data Segment's interface to the IDPS both induced architectural complexity.

Additional description of each of these complexity mechanisms is provided below.

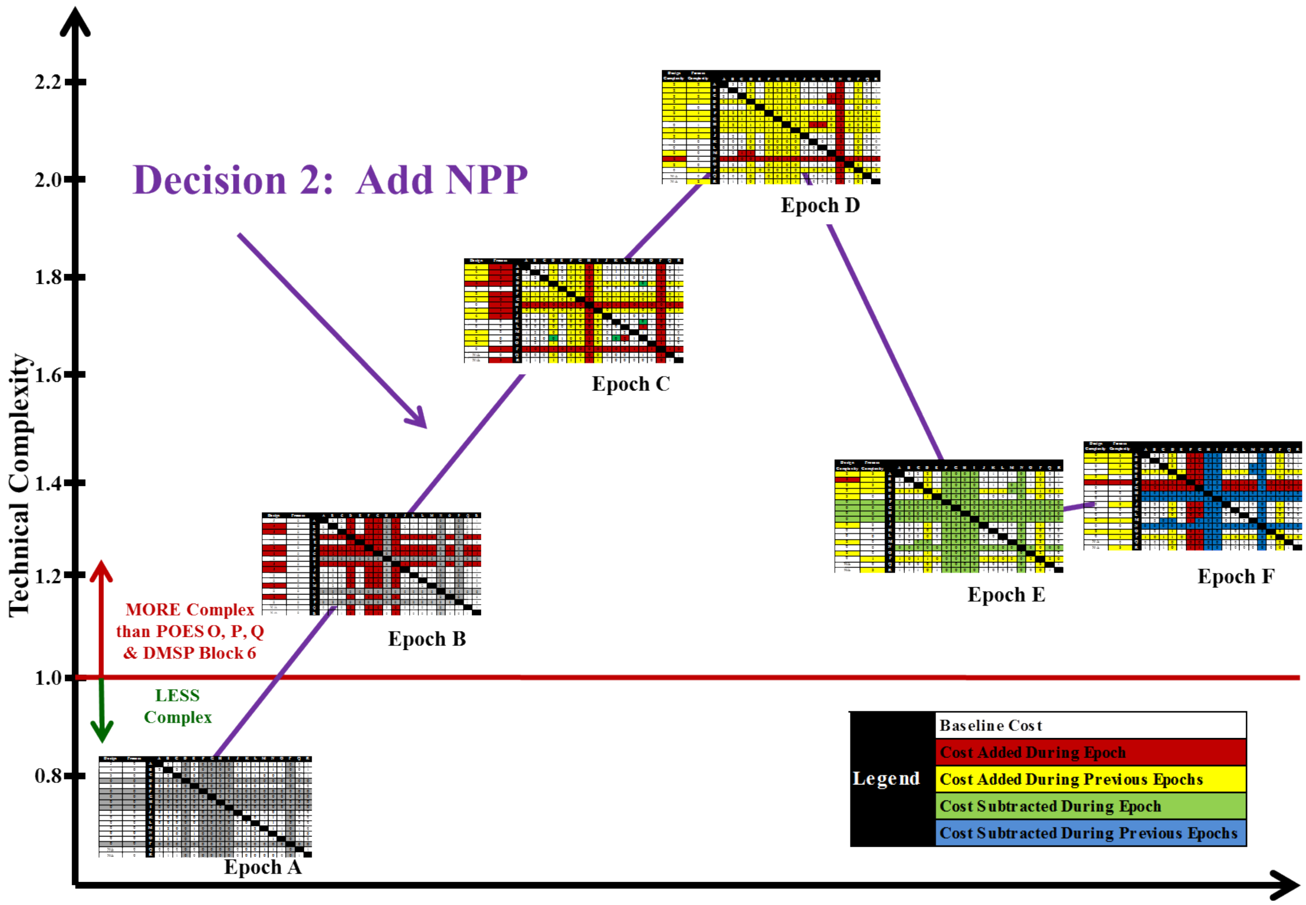


**Figure 28: Complexity Impacts of Decision 2**

### 5.3.1 Instrument Design Complexity

Key changes between the IORD-I and IORD-II included new requirements for long term stability and more stringent requirements for other performance attributes such as measurement uncertainty, accuracy, and precision. Specifically, long term stability requirements were added to 18 EDRs and additional requirements such as measurement uncertainty, accuracy, or precision were added to 20 others [D87, D88]. As performance requirements for EDRs were increased, the design complexity of the instruments that produced those EDRs increased correspondingly.

New EDRs and other data products were also added both in the IORD-II and in individual sensor requirement documents. The primary addition to the IORD was a new EDR for Aerosol Refractive Index, which could only be satisfied once the new APS instrument was added to the program. Unlike this requirement which was specified as an EDR in the IORD, other data products were added to the VIIRS sensor requirements document but not to IORD. For example, NASA levied requirements for Cloud Mask, Snow Mask, Active Fires, Enhanced Vegetation Index, and aerosol collection over land through the VIIRS Sensor Requirements Document and these requirements were added to prospective vendors' contracts prior to down-selection [D235]. Each of the data products added to the VIIRS Sensor Requirements Document had antecedent products on MODIS; thus, by levying additional requirements on VIIRS, the program was able to maintain continuity for key climate variables that were collected by NASA's EOS program.

In addition to increasing VIIRS' functional similarity to MODIS, the VIIRS Sensor Requirements Document tightened previous performance specifications. For example, during this epoch, VIIRS was required to produce precipitable water and active fires data products: two capabilities that had previously existed on MODIS but were not required of previous epochs' VIIRS [D235]. VIIRS was also required to meet new polarization sensitivity requirements and to produce data products at dual levels of spatial resolution; in particular, the higher of the two spatial resolution requirements tightened the IORD-I threshold requirement by changing it from 4 km to 0.5-1.0 km [D235]. Most of these changes to VIIRS' horizontal resolution requirements were a direct result of NASA's 1997 design study [D235] and ultimately increased the instrument's design complexity by reducing its ability to capitalize on heritage designs and by increasing the amount of non-recurring design work that was necessary to meet new requirements.

### 5.3.1 Process Complexity

The process complexity induced by NPP had a significant impact on the overall NPOESS program's cost. First, the IPO's TSPR-like contract for NPP's instruments and ground system conflicted with NASA's preferred management approach, which utilizes closer government-contractor relationships and oversight [D148]. As a result, the government's involvement and direct management of its contractors increased after the formation of NPP.

Ultimately, the close government-contractor relationship was essential during the calibration and validation process, when the NPOESS and NPP program offices collaborated with their contractors to develop and implement calibration and validation (i.e. cal-val) plans. Importantly, these plans were largely based off of NASA's EOS program [I30, I37, I58, I60], which followed more stringent processes than operational missions and as a result, required more budget than originally anticipated [I45, I60]. Generally, calibrating and validating data for climate science requires a more substantial process than is necessary for operational weather prediction [I60, D140, D35]; therefore, the NPP's climate science mission contributed to the program's increased process complexity.

Second, in its post-cancellation assessment of NPOESS, the Aerospace Corporation found that NPP's dual missions had conflicting objectives that "created significant tension in program cost, schedule, and performance" [D195]. Interviewees echoed this finding and attributed the resulting cost growth to debates that arose when NPP instruments experienced test failures that would be resolved differently depending on the system's primary mission [I5, I18, I25,I26, I33]. One interviewee described the schism between NPP's risk reduction and climate science missions as: "In a risk reduction program you might have said, 'this instrument might not be perfect but let's see what we get out of it.' Now you have, 'this instrument *better* be perfect and you better spend the money that you need to spend to make that instrument perfect'" [I25].

The difference in mission philosophies affected the program's cost because the NPP system was priced as a risk reduction mission [I25, D195]. By definition, risk reduction missions are more likely to accept risk and the possibility of reduced system performance because the mission's purpose is not to provide operational data to users, but instead, is to demonstrate new technologies and to identify enhancements or corrections that can be incorporated into *future* operational systems. However, as one interviewee pointed out, to NASA, climate science *was* an operational mission [I26]: NASA interpreted NPP's mission as one which delivered operational data to its scientific users. The differences in the agencies' interpretation of NPP's missions primarily emerged when an anomaly was encountered during instrument test; whereas a risk reduction mission would be more willing to accept reduced performance in order to maintain cost and schedule, a climate science mission, particularly one attempting to maintain data continuity with an existing system, placed a higher emphasis on performance.

Therefore, process complexity costs emerged when the program's instruments, particularly VIIRS and CrIS, encountered test anomalies which would be resolved differently for climate science and risk reduction missions. Typically, when faced with test anomalies, the program defaulted to a resolution that would be acceptable to the program's climate science advocates or spent time debating the costs and benefits of the alternative approaches. In such cases, even when the program selected a less costly anomaly resolution, cost was incurred as the program's standing army waited for management's decision and delays rippled through disparate parts of the program [I12, I13, I23, I28]. Had NPP's climate science and risk reduction missions been complementary or clearly prioritized, the program could have avoided this unnecessary process complexity.

A test failure experienced on NPP's VIIRS vividly illustrates the impact of NPP's conflicting requirements. After test data suggested that VIIRS would fail to meet its ocean color requirement, the subsequent investigation identified the failure's root cause to be the instrument's filters. Because the manufacturing process for the filters had not been specified by the government, they contained defects that hindered the instrument's performance; as a result, in order to fully resolve the problem, the program would need to manufacture new filters according to a more stringent quality-controlled process and replace the filters on the existing instrument [I4, I9, I21, I39]. According to VIIRS' risk reduction mission, once root cause had been identified, the anomaly was officially resolved, since it could be corrected during the production of subsequent units. However, since ocean color was a critical climate science measurement, according to NPP's climate science mission, the filters should have been re-manufactured and replaced on the NPP instrument.

Unable to compromise between the missions' two preferences or to agree on one of the multiple mitigation plans proposed by the instrument's contractor, program managers ultimately raised the ocean color issue to the EXCOM and requested that the committee resolve the problem. Although the EXCOM did not select the most costly option of re-manufacturing the filters and replacing them for NPP, their compromise decision, to use the existing filters but to rotate their position in the instrument, required re-work that would have been absent had NPP prioritized its risk reduction mission [I4, I9, I39]. Furthermore, the debate leading up to the EXCOM's decision was so contentious and extended, that the Aerospace Corporation dubbed this period in the program's history the "Ocean Color War" [D195]. Of course, during this time, the program also induced additional costs as its VIIRS team waited for a final decision and the impacts of the resulting delays rippled through the program.

Because the VIIRS "Ocean Color War" impacted NPP's ability to comply with IORD requirements, it represents one of the more drastic cost impacts that resulted from the conflict between NPP's dual missions. Unlike the ocean color anomaly, many issues were not adjudicated at the EXCOM level; instead, program managers defaulted to NPP's more stringent climate science mission requirements or resolved anomalies using an unnecessarily expensive process intended to satisfy each mission's stakeholders [I5, I9, I18, I25]. One interviewee described the situation that resulted from the government's conflicting mission requirements as: "When those folks didn't agree, the contractor had no idea who to listen to. They'd kind of throw up their hands. But what happened most of the time, I've been told, that when there was disagreements between the two government agencies involved…what often happened is that time was taken to reach consensus between the government. And often the only real way to reach consensus was to do the most conservative thing. If one person in the group wanted to do one test and another one wanted to do another test, typically the consensus was to do both tests [I9]."

Finally, another unanticipated cost that emerged during NPP's instrument tests was not a result of the system's conflicting missions but rather, was a function of the separate requirements that NASA levied on the NPP spacecraft. The development of the NPP instruments was managed for the IPO by the prime contractor, whose work was governed by an Air Force contract that was compliant with military standards. Once completed, instruments were to be delivered to the NPP spacecraft contractor, whose work was governed by a NASA contract that complied with NASA's unique standards. Although this delineation of responsibility was consistent with the MOA that formed the NPP program, it did not address a particular line in the MOA which required NASA to also "provide and manage overall mission system engineering [D84]." According to this directive, NASA developed its own set of NPP mission requirements which then had to be reconciled with the requirements that governed the instruments' development. Interviewees reported that the disconnect between the two requirement sets induced cost growth when engineers had to reconcile both baselines in order to insure that the instruments developed by the IPO were compliant with NASA's NPP requirements [I9, I23, I31]. Had NASA adopted the IPO's engineering standards instead of defaulting to NASA internal standards and processes, the program could have mitigated the situation that it ultimately found itself in, when it was forced to reconcile the two requirement baselines during instrument test.

## 5.3.2 Architectural Complexity

Adding the NPP program also increased architectural complexity by adding new interfaces between the NPP satellite and components of the NPOESS system. The first interface was between NPP's climate science users and the data products produced by the IDPS. Like the operational users who preferred data to be in formats other than EDRs, NPP's climate science users required raw data, intermediate data products, and the ability to reprocess data using unique algorithms. To meet these needs, NASA developed the Science Data Segment (SDS) to interface with the IDPS and to collect data for delivery to its climate scientists [D186]; this interface is shown in Figure 27. Again, since the government did not initially levy performance requirements below the EDR level, unanticipated effort was required to insure that the system's intermediate data products met the needs its scientific users [I5, I21, I22, I45, I39].

The NPP interface to the NPOESS ground system also provided a mechanism for other users to request alternate forms of data that were not included on the initial NPOESS contract. For example, climate scientists requested that the ground system save all intermediate data products, including those produced during the transition from RDRs to SDRs and from SDRs to EDRs [D32, I48]. Climate scientists made this request so that they could independently tweak the parameters or calculations that were used to create the system's final data products. Although this capability would enhance the scientific utility of the sensor data, it strained the ground system, which needed to be enlarged in order to store all of the data. Ultimately, program management reached a compromise and agreed to modify its contract with Northrop to require the ground system save all intermediate data products that scientists could not independently obtain through backwards calculations performed outside of the NPOESS ground system [I48, D39, D192]. While the compromise decision was less costly than the scientists' original request, it altered the program's original technical baseline and thus, increased it cost. Furthermore, even after this decision was made, scientific users continued to request that changes be made to Northrop's algorithms: science, they argued, did not work using a frozen requirements baseline [I39, I48, I61]. While this may be the case, the requirement instability that was enabled by NPP's interface with the NPOESS IDPS ultimately induced cost growth on the NPOESS program.

The second NPP-NPOESS interface that contributed to architectural complexity was between the NPP spacecraft and the NPOESS ground system: although the IPO funded the ground system's IDPS and C3 segments and NASA funded the NPP spacecraft, no funding was allocated to define the spacecraft-ground interface. Interviewees report that neither Ball's statement of work for the NPP spacecraft nor Northrop's contract for the NPOESS ground system contained a work item requiring that the contractors define and document the NPP-ground system interface [I29, I30, D127]. To insure that the systems' interfaces were complementary, the contractors worked informally to share necessary information; however, the program also had to invest additional time and money to formally define these interface requirements with NASA's NPP leadership, IPO leadership, and representatives from Ball Aerospace, Northrop, and the ground system subcontractor, Raytheon. The organizational impediments to this and other ground system interface issues will be discussed in further detail in Chapter 6.

## 5.4 Decision 3: Retain the Baseline

During Epoch D, the program was under-funded [D195] while its technical baseline was preserved and its cost estimates grew. The decision to under-fund the program without de-scoping its capabilities induced lifecycle cost growth when cost or schedule growth on one component affected the budget allocated to another. Although this type of programmatic interaction would never have occurred if the program had been fully funded, because program budgets can be unstable and are exogenous to a program's control, the risk of cost growth due to programmatic interactions between system components appears to be an important factor that should be considered when a system's architecture is defined and its budget is proposed. On the NPOESS program, three types of programmatic interactions induced cost growth:

- Interactions between developmental sensors,
- Interactions between developmental and leveraged sensors,
- And interactions between components of the NPOESS and NPP systems.

The program used the term "leveraged sensor" to denote a sensor with low non-recurring costs that essentially duplicated an existing sensor technology; leveraged sensors included SESS, TSIS, ERBS, APS, and the altimeter [I15, D86]. I classify the remaining sensors—VIIRS, CMIS, CrIS, OMPS, and ATMS—as developmental because they required significant design effort that began during Epoch B.

The costs induced by interactions between the program's developmental sensors resulted from the decision to reduce one sensor's funding so that the program's scare resources could be applied towards a

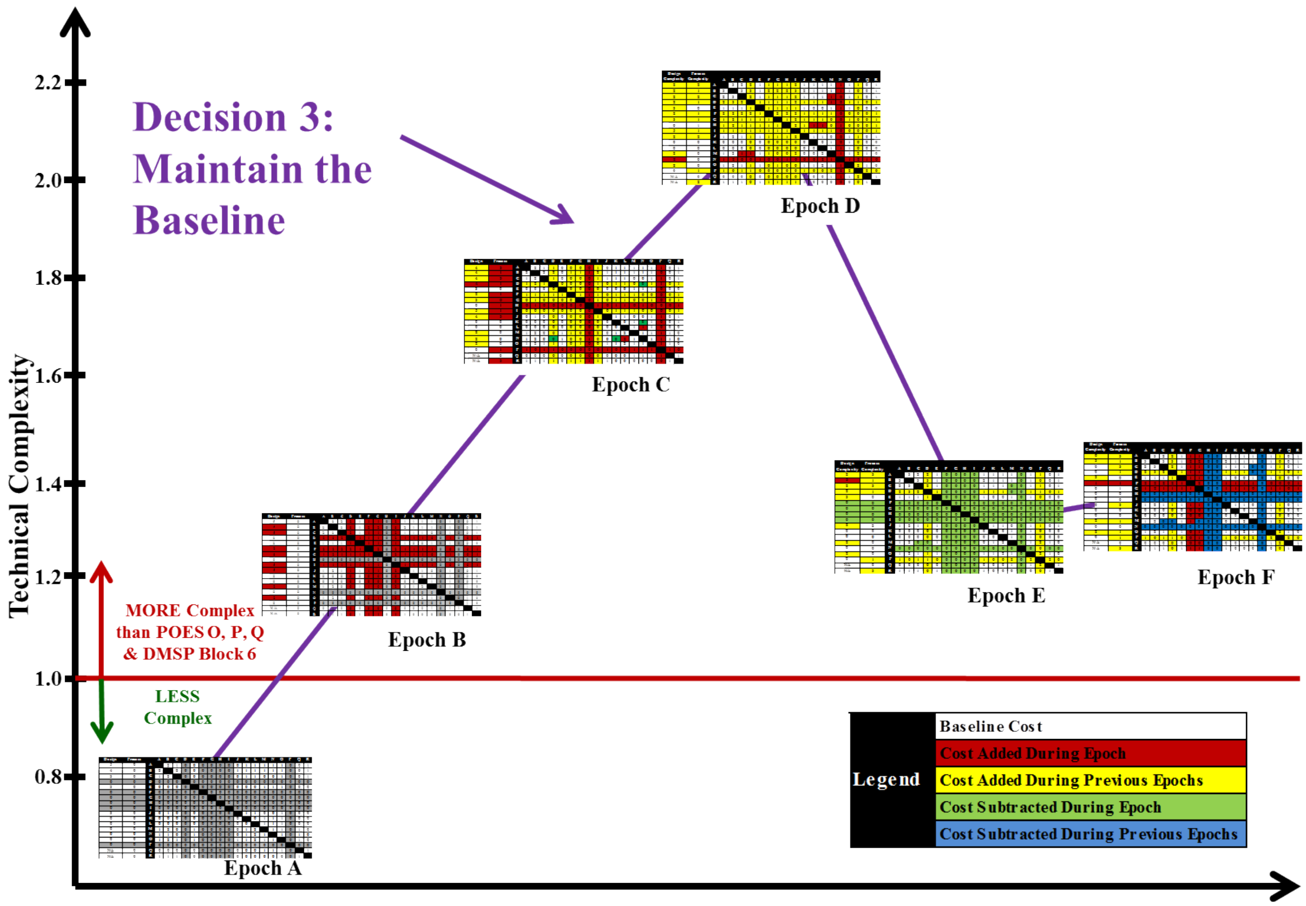


**Figure 29: Complexity Impacts of Decision 3**

higher priority sensor. This decision, which induced lifecycle cost growth by extending the development schedule of lower priority instruments, is vividly illustrated using CMIS as an example. Although two risk reduction contracts were issued for CMIS, compared to the other developmental sensors, CMIS was the last one scheduled for launch. As discussed in Chapter 4, when other instruments' cost and schedule grew significantly but the program was denied additional funding, IPO management was forced to prioritize its spending according to launch schedule [I11, I16, I25]; as a result, CMIS's funding was reduced and its schedule was extended. The IPO's changes to the CMIS development baseline were so significant that the down-selected CMIS subcontractor, Boeing, was unable to make substantial progress [I1, I11I13, I16, I26, D240]. As a result, the IPO essentially funded an ineffectively small contractor team in order to maintain its CMIS contract and to enable work to be quickly scaled up at some point in the future. Of course, until that future date when the contractor could begin developing the instrument in earnest, the instrument's schedule lengthened, its costs correspondingly grew, and its progress essentially stalled.

Before Boeing's contract was cancelled, its cost grew over 29% from the initial estimate in 2002 [D214] and while the quantitative data necessary to determine exactly how much of that growth can be attributed to the IPO-mandated funding cuts and schedule delays was unavailable, qualitative interview data suggests that this relationship was substantial [I1, I11, I13, I16, I26]. Thus, CMIS's programmatic relationship to higher priority developmental instruments represents an architectural complexity cost that was incurred on the NPOESS program: although CMIS was officially funded until the program's Nunn-McCurdy certification, given the budget and schedule restrictions that were necessitated by the cost growth on the program's higher priority instruments, the CMIS contractor was unable to produce a programmatic benefit commensurate with the cost spent keeping its contract open. Therefore, CMIS's cost growth illustrates how programmatic interactions between system components can induce additional cost whe cost growth on one instrument hinders the development of another.

In addition to inducing costs by impeding other instruments' development, delays on the program's developmental sensors also induced delays and cost growth on its leveraged sensors. At the beginning of the Epoch D, Northrop began developing its common bus to support the program's five development and five leveraged sensors; however, because the majority of the program's budget and human resources were focused on developmental sensors that were exhibiting s cost growth, little attention was paid to the leveraged sensors and to the schedule needs of their user communities. These delays were further exacerbated by Northrop's aggregated spacecraft architecture: had the program adopted a more disaggregated approach, it could have launched several of the leveraged sensors before the delayed developmental ones.

Instead, the leveraged sensors were essentially held hostage [41] by the aggregated program which simultaneously delayed their procurement but promised their eventual launch on an operational satellite. Of course, many leveraged sensors like APS, SESS, and the altimeter were eventually de-manifested during Nunn-McCurdy; however, it's possible that if these instruments never been included in the aggregated NPOESS program, their user communities would have garnered enough funding to support a dedicated program that was capable of launching the sensor more cost and schedule effectively. In fact, after its deletion from the NPOESS manifest in 2005, the APS user community funded its sensor's placement on another spacecraft which was launched before NPP [D167].[14] Thus, the leveraged sensors' programmatic relationship to higher priority technology development projects represents another cost that was incurred on the NPOESS program: although the program funded multiple leveraged sensors prior to Nunn-McCurdy, given the delays induced by the program's developmental sensors, the leveraged sensors may have been more cost-effectively or expediently deployed if they had been disaggregated from the larger NPOESS program.

The primary reason that the program prioritized developmental sensors like VIIRS over CMIS or other leveraged sensors was that it prioritized NPP's development over the operational system [I11, I16, I46]; as one interviewee described it: "We were trying to make sure we delivered everything possible to NPP while slipping everything else basically" [I11]. Since NPP was scheduled to launch before NPOESS, its prioritization makes sense; however, because the program did not have sufficient funding to develop *both* NPP and NPOESS, the programmatic relationships between the two systems represent an important architectural complexity mechanism that increased the cost and schedule of the operational system.

[14] Unfortunately, APS was placed aboard the ill-fated Orbiting Carbon Observatory, which suffered a launch failure.

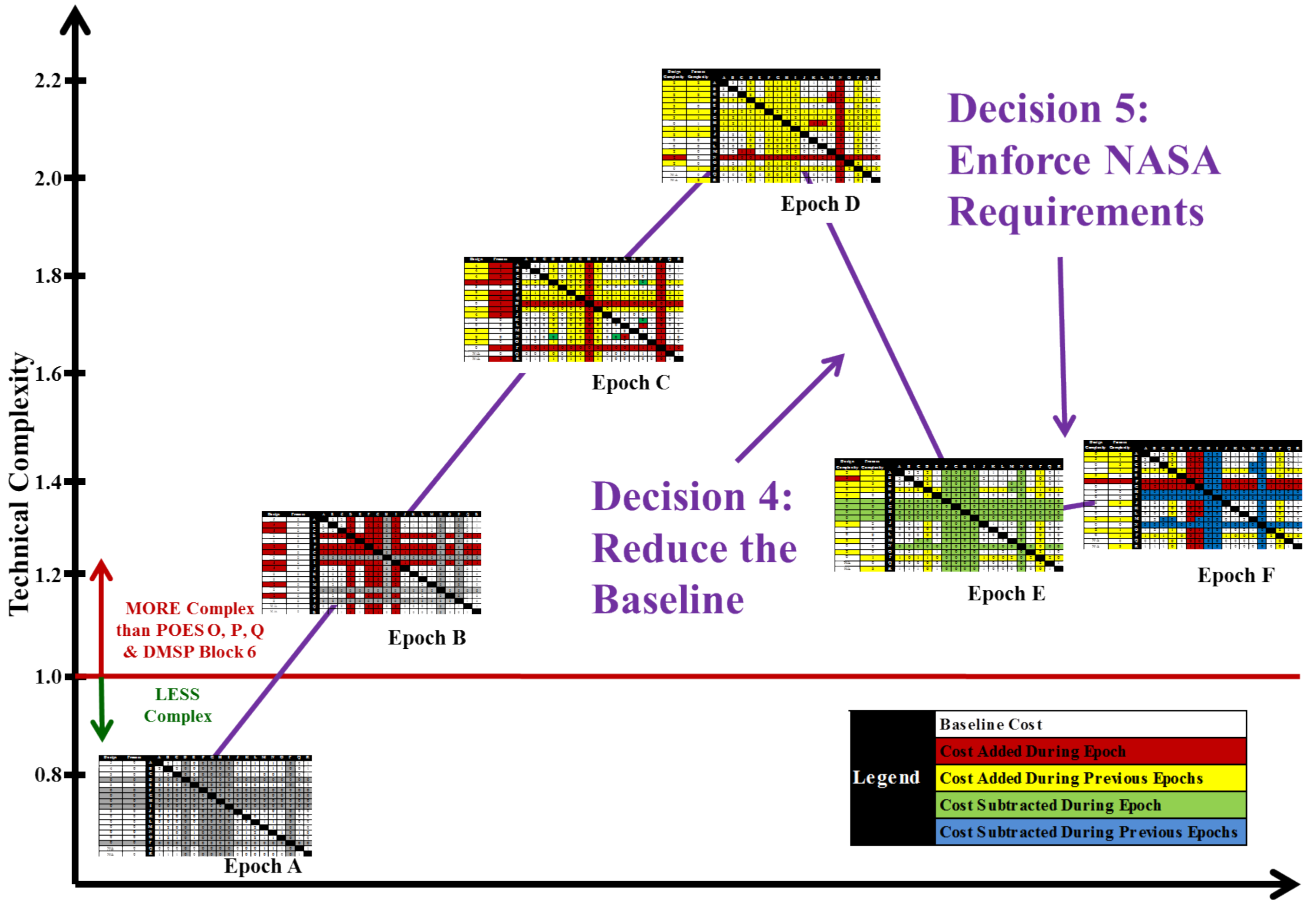


**Figure 30: Decision 5 Complexity Impacts**

## 5.5 Decision 5: Enforce NASA Requirements

A final decision during Epoch F, to enforce NASA-specific requirements on components of the operational system, induced additional process complexity. Interviewees reported that at multiple design reviews, representatives from NASA would question the requirements that the IPO-managed hardware had been developed against [I18, I23, I31, D158]. One interviewee described the dynamics of such reviews as: "And [with] multiple instruments and at multiple reviews….multiple times in the same review, a NASA review board member would say, 'Well why didn't you use a NASA standard?' Because our contract is to a Mil-Standard. 'Well why didn't you use a NASA standard?' An hour later, 'Why didn't you use the NASA Standard?'….It was just over and over and over again…we had to justify why NASA standards weren't used to build these instruments when they weren't procured through NASA" [I31]. Typically, NASA formalized its concerns about the program's Mil-Standard requirements by opening requests for action, which generated additional work for the IPO and in many cases, simply could not be resolved [I23, I18]. Besides questioning the program's military standards, NASA representatives also questioned the Air Force's launch vehicle selection policies [I18, D158] and component selection in the individual instruments [I23]. In the examples cited by interviewees, many of these requests for action not only failed to add value to NPOESS system but also generated additional work for the program's engineers and managers who were tasked to respond to the agency's inquiries and to resolve the requirements conflicts that they generated.

## 5.6 Decision Enablers

In addition to using qualitative data to identify mechanisms that increased technical complexity, I also used the data to understand *why* the program made the costly decisions discussed above. In each case, the decisions were motivated by the need to execute each agency's unique mission and the program did not recognize the cost of executing those missions because it under managed and underestimated its system's complexity. Essentially:

- During the program's early epochs, the system's complexity increased in order to execute its users' evolving missions.
- The program did not recognize the cost impacts of this complexity until Epoch D, when its cost estimates began to grow.
- Even when its cost began to grow, the system's complexity was preserved during Epoch D because all of the system's capabilities were necessary to meet the agencies' missions.

In fact, only Decision 4—the decision to reduce the baseline—decreased the system's ability to meet the agencies' missions rather than enhanced it. Until that point, the system's complexity evolved to meet each of NOAA, NASA, and the DoD's missions, even if doing so required the system's complexity and costs to increase. In contrast to the other decisions, Decision 4 prioritized NOAA and the DoD's shared operational weather mission over NOAA and NASA's unique climate missions. Therefore, Decision 4 was the first and only time that the system's ability to execute the agencies' missions decreased rather than increased or evolved to meet the agencies' dynamic mission requirements. Of course, Decision 4 was legally mandated by the Nunn-McCurdy Act and NOAA and NASA's climate sensors were quickly re-manifested after the certification process was complete.

Finally, the program's ability to make costly decisions highlights the critical role that its organizational architecture played in *enabling* decisions. As will be discussed below, costly decisions were enabled by:

- A need to execute each agency's unique mission,
- An underestimation or under management of complexity.

Qualitative evidence that describes both of these decision enablers is presented below.

### 5.6.1 Decision 1: Enablers

The first source of instrument design complexity was the program's joint requirements, which equally prioritized NOAA and the DoD's missions by levying each agency's unique or driving requirements on the system. Interviewees described the document that resulted as a "concatenation of the requirements of the two individual agencies" [I48] and as a requirement set which "to the 90$^{th}$ percentile…took the most stringent requirement" [I3] between the NOAA and the DoD. Instead of trading EDRs or their associated attributes, interviewees recounted that "if NOAA had set A and the DoD had set B and they differed…[and] something in set B was more stringent than in set A, we automatically defaulted to B….Everybody was going to get what they wanted [I3]."

The program did not recognize the full cost impacts of the IORD's requirements until Epoch D, when instrument subcontractors began reporting cost and schedule delays. Cost estimates in prior epochs were able to remain low because the program incorrectly assessed its ability to leverage heritage designs for the converged system [D195]. While many of EOS's instruments did meet NOAA-specific requirements, the program did not realize that adding the DoD's requirements increased heritage instruments' design complexity. As a result, cost estimates remained low until Epoch D, when the IPO transferred contractual authority for the instruments to the prime contractor. Shortly after this transfer, the prime realized that the instruments were technically immature and were exhibiting significant mass and power growth even after their CDRs [I10, I24, I23, D178, D149].

The program's underestimation of design complexity and its inability to leverage instrument heritage was further hindered by parts obsolescence, since many of NOAA and the DoD's heritage instruments were originally designed in the 1970s and 80s. One interviewee recounted how parts obsolesce contributed to cost growth on CrIS as: "They didn't even have a micro-processor in the 1985 design. Micro-processors were out but they were wary of using it so they built their own micro-sequencer device. So when CrIS comes along, they are dealing with the next generation of parts and requirements. And I think no matter who you are, unless you do a lot of this…that presented some challenges [I14]."

Interviewees recounted similar challenges in the OMPS development, where the sensor vendor's heritage detector design dated from the mid-1970s and had to be updated to include modern technologies such as charged coupled devices and array detectors, two technologies that were common in instruments at the time but were not utilized on DMSP or POES [I14, I20]. Essentially, in addition to increasing instrument performance and capability, the NPOESS program also infused modern technologies into DMSP and POES's heritage instruments, which had not had their electronics or data-processing systems upgraded since the 1970s and 80s. Had the program's development period been shortened, it could have infused technology upgrades incrementally or separated performance and functionality enhancements from upgrades to instrument electronics and processing systems. Instead, the extended development period allowed to program to undertake both projects concurrently and to induce additional cost growth as contractors struggled to leverage instrument heritage. Importantly, the cost trade-off between incremental development and NPOESS's more aggressive development strategy is uncertain; therefore, it is unclear which approach would have been less costly over the program's lifecycle.

Finally, the underestimation of ground system complexity manifested itself as requirements creep, when the program's users realized that their missions could not be executed using the universal EDRs that were defined in the IORD. As users came to this realization, they either requested that the IPO actively manage non-EDR performance attributes [I22, I45, I61] or that their home agencies develop external systems to convert NPOESS data into usable formats [I35, I66, D186, D179]. Interviewees suggested that a more cost-effective approach to the NPOESS ground architecture might have been achieved by levying requirements on instrument performance and by allowing users to collect raw data and to process it independently instead of within the NPOESS IDPS system [I22, I35].

In addition to underestimating component design complexity, prior to Epoch D, the program under managed the interfaces between its components. By ineffectively managing component interfaces, the program failed to realize their costs until Epoch D, when the prime contractor assumed the program's system integrator role and began to more actively manage the system's interfaces. One critical interface that was under managed during the program's early years was between the instruments and the spacecraft bus. Specifically, at the start of Epoch D, the prime assumed contractual responsibility for multiple instruments that had already completed CDR. As a result, when Northrop prepared a cost estimate for its proposal, it assumed that critical instrument design properties, such as power and mass, would remain relatively constant for the remainder of the program [I23, I46]. As noted above, this assumption proved flawed when instruments like VIIRS and CMIS exhibited significant mass and power growth after CDR [D178, D149, D240].This growth affected Northrop's proposed spacecraft design—which had planned to leverage much of the company's standard T430 bus—since Northrop had to redesign portions of the T430 in order to close its mass and power budgets [I23, I44, D149].

Analogously, the program did not actively manage the interface between the instrument algorithms and the IDPS. In particular, interviewees reported that instrument algorithms were in varying states of maturity when they were delivered to Raytheon for integration into its IDPS system [I22, I30, I46]. For example, since no coding standards were levied on the instrument contractors, they delivered algorithms in different coding languages [I30]. Furthermore, before instrument algorithms were delivered to Raytheon, they were not required to meet a specific latency requirement [I22, I30, D40, D77]; as a result, interviewees recall receiving algorithms that required additional, unanticipated work to meet the system's requirements for data latency [I22, I30].

When Raytheon and Northrop prepared their proposal for the NPOESS prime contract, they assumed that all algorithms would be at a CDR-level of maturity, or that algorithms would meet their performance requirements, be executable in a time consistent with the system latency specification, and would utilize reasonable coding standards and protocols [I30, I47]. Since the contractors priced their bids according to those assumptions, once they assumed responsibility for the instrument algorithms, costs were incurred as new requirements had to be levied on all of the algorithms to enable them to be integrated into the IDPS segment and to be compliant with the system's data latency requirement.

### 5.6.2 Decision 2: Enablers

All of the complexity induced by adding NPP was motivated by the need to execute NASA's unique climate science mission using components of the NPOESS system. Because NASA's mission required NPOESS data to provide continuity with the EOS system, instrument design and performance requirements were updated to make them consistent with EOS; as described above, new requirements necessitated additional technical development and therefore, increased instrument design complexity. As with the IORD-I, the program underestimated the complexity impacts of these requirements because it assumed that heritage instruments would be capable of meeting them.

It is also important to note that while levying new requirements increased complexity, these new requirements responded to the government's increasing interest in climate change and global warming. While the specific relationship between climate change, global warming research, and the NPOESS program is not the focus of my work, I note it here because during the program's early epochs, NOAA and NASA's mission requirements really did evolve alongside the program's architectures. Specifically, as government leaders' interest in climate science increased, they looked to agencies like NOAA and NASA to produce climate science data. Faced with this new and continually reinforced imperative and the fate of NASA's EOS, a climate science program that was descoped, NOAA and NASA were left with few options, other than aggregating requirements onto the NPOESS program, that would allow them to meet the government's growing demand for climate science data [D33, D193, D32].

Like design complexity, process complexity was caused by trying to execute NASA's unique climate mission within the larger NPOESS program and this complexity was initially underestimated because many aspects of the NPP program were unprecedented. For example, no prior programs have attempted to execute dual risk reduction and climate science missions and in fact, there was no precedent for integrating a risk reduction and operational mission using shared instruments on a single spacecraft. As a result, the agency leaders who crafted the MOA assigned mission and budget responsibility according to the needs of each agency and failed to anticipate the implementation challenges that would result from integrating the diametrically opposed climate science and risk reduction missions within a single program. The program's TSPR-like acquisition approach further exacerbated the differences between NPP's climate science and risk reduction missions since TSPR-like processes were often incompatible with NASA's preferred management approach. Finally, when assigning agencies mission and budget responsibility for NPP components, the MOA failed to specify which agency's standards should apply to which components. This ambiguity provided a mechanism for individual agencies to apply their own standards and to induce unnecessary complexity in the instrument verification and validation process, when different agency standards had to be reconciled.

Once the program began to recognize the cost impacts of NPP's process complexity, it attempted to reduce cost by more clearly prioritizing NPP's risk reduction mission, cancelling NPP entirely, or re-assigning it to serve as a ground spare for the program's operational satellites [D240]. While any of these options would have eliminated the process complexity that NPP induced, NASA opposed any plans that affected NPP's climate science mission. One of the reasons that NASA officials were able to prevent the program's attempts to deprioritize climate science stems from an unofficial partnership between NOAA and NASA. As noted in Chapter 4, NASA and NOAA's climate interests were complementary and the agencies shared an overlapping user community; as one interviewee noted: "Neither NOAA nor NASA knew who was responsible for climate. NOAA thought that they were responsible for operational climate and NASA thought they were responsible for climate research but that's just a matter of semantics" [I15]. In addition to sharing climate interests, NOAA had previously relied on NASA's technical expertise when the agency served as the acquisition agent for NOAA's POES program. As a result, NOAA and NASA naturally partnered to oppose any attempts to reduce the program's cost by deprioritizing its climate missions [I7, I13, I15, I18, I23, I27, I38, I52].

This partnership often placed NOAA and NASA at odds with DoD and IPO management, whose leaders attempted to cut costs by reducing the program's focus on climate science. One interviewee described the dynamics as "NOAA had some climate zealots who were right in there agreeing with everything that NASA said so it really was like NOAA and NASA…ganging up on the Air Force" [I15]. Another interviewee echoed this sentiment by stating "NOAA and NASA basically teamed up and it became NOAA and NASA versus DoD" [I27] and another summarized it as "it was sort of NOAA and NASA banging up on the IPO" [I23]. When faced with decisions to reduce the program's climate capabilities or to reprioritize its climate missions, agency leaders and IPO managers were confronted by a collaboration where two of the three partnering agencies resisted any attempts to control cost that had adverse effects on system's climate missions. As a result, the NPP program's missions continued to conflict and to induce process complexity and cost growth throughout the remainder of the NPOESS program.

Finally, the NPP MOA also allowed architectural complexity to be underestimated because it failed to adequately define NPP-NPOESS interfaces. Specifically, although the MOA defined interfaces between NPP and NPOESS components, funding was not initially allocated to allow NPP and NPOESS engineers to define and manage those interfaces [I29, I31, D127, D60, D84]. By failing to clearly and contractually define interfaces at the program's outset, the MOA set NPP and NPOESS up for cost over-runs since their engineers would ultimately have to define and manage those interfaces anyways.

### 5.6.3 Decision 4 & 5: Enablers

Decision 4, to insufficiently fund the program, was primarily enabled by the factors discussed above: because the program failed to adequately account for complexity in its early cost estimates, the bids proposed by prospective prime contractors and accepted by the government were artificially low [D195]. When the prime contractor began realizing and reporting the system's latent complexity costs, the program manager was unable to decelerate cost growth by reducing the system's capability because doing so threatened the system's ability to execute each agency's unique mission as defined by the IORD [I26, I48, D195, D240]. Furthermore, despite requests, the program manager was unable to obtain an increase in funding that would have allowed him to fully execute the baseline system's development [I16, I46, I52]. As a result, the program had no choice but to prioritize development projects and to reduce the funding allocated to lower priority components.

Decision 5, to unofficially levy NASA-specific requirements on components of the operational system, can be interpreted as a decision motivated by NASA's interest in executing its own missions using NOAA's polar-orbiting spacecraft; this decision will be discussed further in Chapters 6 and 8.

## 5.7 VIIRS: An Illustrative Case Study

The VIIRS development process illustrates each of the concepts discussed above in greater detail. Therefore, in this section, I present VIIRS as a stand-alone case study that demonstrates how technical complexity and cost evolved throughout the NPOESS program. Specifically, using VIIRS, I illustrate:

- How levying each agency's unique and driving requirements increased design complexity,
- How assigning VIIRS to be co-manifested alongside many other instruments on an aggregated spacecraft induced architectural complexity,
- And how both complexity types were underestimated or under managed during the program's early years.

Because VIIRS was slated to fly on both NPP and NPOESS, its development was also affected by the process complexity. However, since my previous discussion of process complexity used VIIRS as an example, in the sections that follow, I focus specifically on the instrument's design and architectural complexity.

### 5.7.1 Overview of the VIIRS Design

VIIRS contained three distinct and separable functions: low light imaging, visible-infrared imagery/radiometry, and ocean color radiometry. Of the two vendors that were awarded risk reduction contacts during Epoch B, ITT proposed a modular instrument architecture that separated VIIRS's three key functions. In contrast, ITT's competitor, Raytheon,[15] proposed an integrated architecture that aggregated all three functions into a single instrument; as noted previously, Raytheon's design was ultimately selected.

Raytheon's integrated design was motivated by the company's desire to preserve its MODIS heritage [I15, I21, I39]. MODIS was a single aperture instrument that used a continuously rotating doubled-sided scan mirror to reflect the Earth's radiation into its optical system [D126]. The optical system itself contained a two-mirror off-axis telescope and four focal plane arrays for the visible (VIS), near-infrared (NIR), short/mid-wavelength infrared and long-wavelength spectral regions [D126]. In contrast, ITT's proposal derived its heritage primarily from OLS, AVHRR, and SeaWiFS, a separate ocean color sensor. Although specific details of ITT's proposal are procurement sensitive, critical aspects of its heritage instruments include OLS and SeaWiFS's scanner designs, which employed rotating telescopes that were also incorporated into Raytheon's VIIRS design [I39].

Interviewees recounted several trade-offs between Raytheon's integrated and ITT's modular designs. For one, the integrated design consumed fewer spacecraft resources than the modular one [I9, I39]. Interviewees also noted that Raytheon's design reduced complexity at the system level since a single instrument was easier to integrate onto a multi-sensor spacecraft than three separate sensors which would consume greater volume and could induce conflicting field of view requirements across the platform's multiple sensors [I9, I12]. However, one interviewee noted that by avoiding complexity at the system level, the program necessarily accepted it at the instrument level since the integrated VIIRS was more compact [I9]; as another interviewee noted: "It wound up being a really densely, closely packed instrument [and] that hampered its development a little bit. Because if you had to go in to change a board, you would have to remove 19 boards in order to get to the 20th board" [I10]. Since the program did not develop a modular design for VIIRS, I cannot assert that the costs incurred were only a function of VIIRS' integrated design. Instead, in my subsequent discussion, I will consider the effect that design and architectural complexity had on VIIRS, given Raytheon's integrated design.

### 5.7.2 Architectural Complexity on VIIRS

The NPOESS program's aggregated spacecraft architecture induced several types of architectural complexity onto the VIIRS instrument. First, because the program selected an integrated instrument architecture, VIIRS had to be assigned to all three operational orbits. Although VIIRS's heritage MODIS instrument had been designed to operate in orbits with afternoon crossing times, it had never been assigned to an early morning orbit. As a result, Raytheon had to modify its MODIS heritage design to account for the different optical and thermal conditions that were present in NPOESS's early morning orbit. Second, unlike MODIS, VIIRS was assigned to share the same spacecraft platform with several instruments that were either EMI-sensitive or were active emitters of electromagnetic energy. Again, to account for this deviation from heritage, Raytheon had to update its MODIS design. Because the design updates to accommodate new thermal, optical, and EMI requirements were not realized and implemented until after the instrument's CDR, they induced cost growth that was not included in the program's early cost estimates.

[15] As noted in Chapter 4, ITT's competitor was actually Santa Barbara Research Center, which was subsequently acquired by Raytheon. For simplicity, I refer to this organization as Raytheon throughout this discussion.

The NPOESS technical architecture included a spacecraft in an early morning orbit because low light imagery from this orbit was critical to the DoD's national security mission [D61]. Although the specific impacts of the DoD's agency unique requirement for low light are discussed in the next section, I note this requirement here because had the program selected a modular design for VIIRS, it could have assigned only the low light sensor to the early morning orbit [D61]. The early morning orbit's geometry is unique and as a result, it places the sun directly in VIIRS's line of sight; one interviewee described the impact of having an optical instrument like VIIRS directly in line with the sun as "not good, [it will] fry everything" [I49].

In the heritage DMSP system, which also encountered this issue, the DoD used a glare obstructer, a boom that was mounted to the side of the spacecraft and used to shade the OLS as necessary [D180]. Since glare obstructers were not required for the NPOESS mid-morning or afternoon orbits and Raytheon proposed an integrated design that would be common to all three, it modified its MODIS heritage scan technique. Specifically, Raytheon replaced MODIS's double-sided scan mirror with a rotating telescope cross-track scanner that was intended to mitigate the sun glare issues that were present in the early morning orbit [D180]. Although the cost of this specific design change was included in Raytheon's original proposal, it resulted in unanticipated modulated instrument background that had to be corrected in a post-CDR redesign [I39, I54, D178, D181]; this issue is discussed in greater detail in the next section. Furthermore, it is also unclear if Raytheon fully realized the cost of multi-orbit commonality prior to the program's cancellation. Specifically, although VIIRS's performance was verified in the mid-morning and afternoon orbits, interviewees disagreed on the instrument's ability to meet requirements without a glare obstructer in the early morning orbit; this remained an open issue when the program was cancelled [I49, I54].

Besides different optical conditions, the NPOESS early morning orbit also had a distinct thermal environment that MODIS had not previously encountered. Specifically, the colder temperature of the early morning orbit affected the optical mechanical module's motor encoder assembly by reducing its ability to meet the torque margin standards that were specified in MIL-A-83577B [D178]. Raytheon identified this requirement deviation after instrument CDR and took several corrective actions. First, it added heater elements to the rotating telescope and to the instrument's interior half angle mirrors [D178]. Next, it updated the heater mechanism in the VIIRS electronics module so that it could better regulate the instrument's temperature [D178]. Finally, it modified the electronics module's voltage level capabilities so that it could provide the additional power required to increase the motor encoder assembly's torque and bring it into compliance with its Mil-standard specifications [D178]. As noted above, these changes were implemented after the instrument completed CDR and therefore, came at an additional and unanticipated cost to the program.

Finally, architectural complexity also impacted the heritage MODIS design by levying more stringent EMI requirements on the VIIRS instrument. Specifically, after instrument CDR, Raytheon increased VIIRS's mainframe wall thickness and added additional shielding to its cables, mainframe, and electromagnetic structure so that the instrument could meet EMI requirements that were not levied on MODIS [D178]. Scalione et al. also noted that these post-CDR changes were incorporated "to ensure electro-magnetic compatibility and to meet stringent on-orbit electro-magnetic interference avoidance requirements" [D178] and while I was unable to determine a direct linkage between these changes and the requirements levied by instruments like SARSAT, DCS, and the altimeter, my engineering judgment suggests that since these instruments did not fly alongside the heritage MODIS instrument, they likely levied new requirements that required changes to Raytheon's MODIS heritage. To further support my claim, multiple interviewees noted that stringent EMI requirements were levied on all of the NPOESS instruments as a result of SARSAT, DCS, and the altimeter's presence on a shared spacecraft [I8, I9, I15].

Another post-CDR design change that can be attributed to an under management of architectural complexity was to the electronics module, which had to be redesigned when the contractor discovered that its MODIS heritage design was incompatible with thermal conditions found in the early morning orbit. Scalione et al. noted that "Certain VIIRS orbit conditions not found in the MODIS operations may expose the opto-mechanical module motor encoder assembly (MEA) bearings and lubricants to lower temperatures than can be accommodated by the MEA drive electronics, resulting in unacceptably low torque margin" [D178]. In order to meet the torque margin requirements specified by the program's applicable Mil-Standard, Raytheon had to redesign elements of its electronics module [D178].

### 5.7.3 Design Complexity on VIIRS

In Section 5.2, I identified several agency unique or driving requirements that increased instrument design complexity; on VIIRS, the two most significant complexity-inducing requirements were:

- NOAA's requirement for high radiometric accuracy,
- And the DoD's requirement for high resolution imagery [D61].

Typically, in order to achieve high spatial resolution imagery, instruments designers sacrifice radiometric accuracy and vice versa; however, on VIIRS, both requirements—which historically drove instrument designs in different and opposing directions—were integrated and achieved within a single sensor [D61].

In addition to meeting these two fundamentally opposed requirements, VIIRS met three related derived requirements whose impact on design complexity can be traced throughout VIIRS's development history; these requirements include:

- NOAA's requirement for EOS quality data,
- The DoD's requirement for low light imagery,
- And the DoD's requirement for constant resolution across the instrument's scan.

Figure 31 illustrates how each of these requirements impacted the VIIRS design process, which began with the assumption of MODIS heritage. By utilizing a MODIS heritage design, Raytheon was uniquely capable of meeting both NOAA's requirements for EOS quality data and of maintaining the backwards design compatibility that was particularly valued by NASA's climate scientists. Interviewees also noted that Raytheon's design was more capable than ITT's at accommodating the new climate science requirements that were added to the VIIRS Sensor Requirements Document and to the IORD-II at the conclusion of the NASA Accommodation Study [I12, I39].

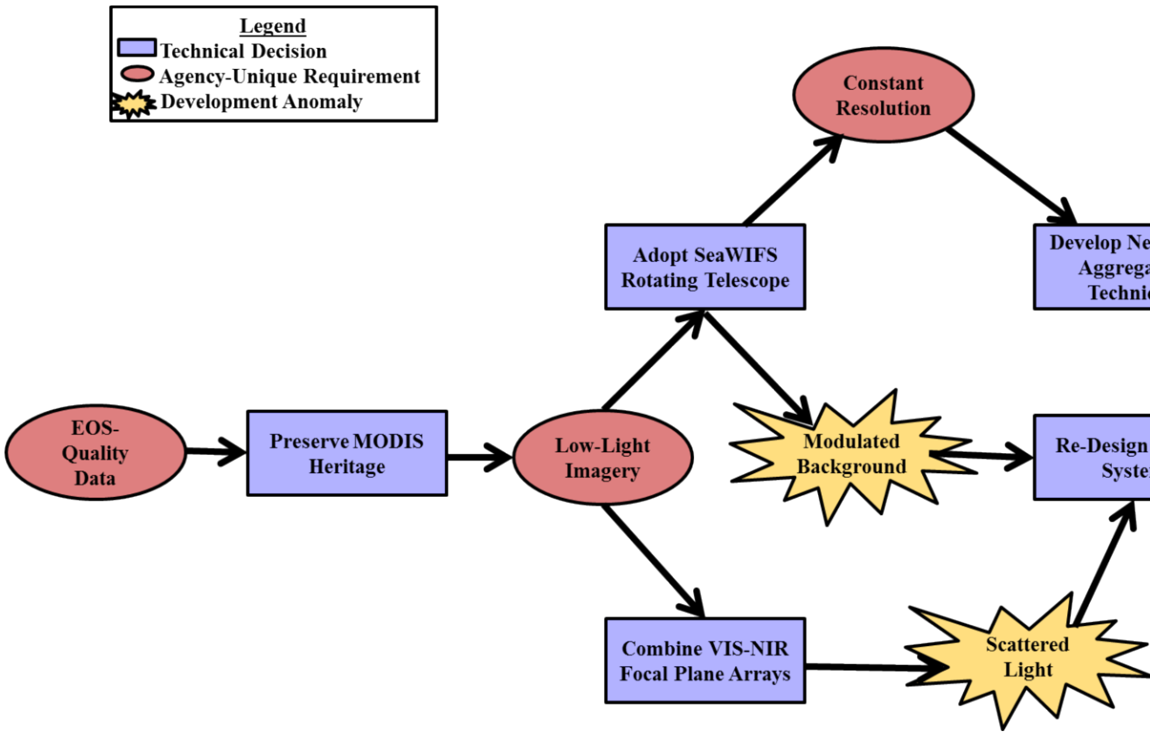


**Figure 31: VIIRS Development Process**

Figure 31 depicts the start of the VIIRS development process with Raytheon's decision to utilize a single-aperture, integrated MODIS-heritage design. In order to accommodate the DoD's requirement for low light imagery, Raytheon made two key changes to its MODIS heritage. First, it replaced MODIS's double-sided scan mirror with a rotating telescope cross-track scanner, which derived its heritage from the SeaWiFS instrument [D180]. Next, Raytheon removed one of MODIS's focal plane arrays and combined MODIS's previously separate VIS and NIR channels onto a shared focal plane array [I21, D126, D181]. Finally, to meet the DoD's requirement for constant resolution across the SeaWiFS telescope's scan, Raytheon developed a new data aggregation technique [D182].

Importantly, Figure 31 also illustrates the connection between several of the major anomalies that plagued the VIIRS development process and design decisions that were motivated by agency unique requirements. In the following sections, I provide additional detail on each of these design decisions, connect them to the program's joint requirements, and describe their significant cost and complexity impacts.

A key design change that enabled MODIS to collect low light data from the early morning orbit was Raytheon's use of the SeaWiFS heritage constant speed rotating telescope cross track scanner [D180]. Despite Raytheon's intentions, it is important to note that the SeaWiFS instrument never operated in an early morning orbit [D103]. Despite this lack of on-orbit experience, the SeaWiFS telescope design was similar to DMSP's OLS instrument, which had significant heritage collecting low light imagery from early morning orbits and which also employed a rotating telescope [D167]. However, unlike OLS, the SeaWiFS-derived design used a rotating half-angle mirror to compensate for image rotation [D180]. In contrast, the OLS design compensated for image rotation by also rotating its detector [D182].

Early in the VIIRS design process, Raytheon determined that an OLS heritage rotating detector design would be incompatible with NOAA's requirements for EOS quality data. Specifically, in order to maintain backwards compatibility with the spectral capabilities of EOS's MODIS instrument, VIIRS required multiple detectors and focal planes (MODIS had four). Furthermore, by maintaining multiple focal planes, VIIRS would be able to scan more slowly than OLS, thereby increasing detector signal and improving sensitivity in order to meet the program's strict signal-to-noise requirements [D182].

Although Raytheon's design for VIIRS maintained much of MODIS's internal optical layout and could claim SeaWiFS heritage for the rotating telescope and half angle mirror assembly, the contractor had to alter its original VIIRS design after it discovered modulated instrument background after CDR. Raytheon realized this issue after performing a reverse ray trace; a reverse ray trace involves tracing incoming light rays backwards from their destination at the detector to their origination outside of the instrument. This exercise revealed that non-optical rays from the rotating telescope could reach the detector; because the number of rays varied with the telescope's rotation, the detector's background was modulated as the telescope's scan angle varied [D178]. After Raytheon determined that the modulated background could not be characterized enough to enable ground processing compensation [D178], it redesigned the affected portions of the instrument after CDR.

The key to eliminating VIIRS's modulated instrument background was the addition of a cold aperture stop, which was placed immediately following the rotating half-angle mirror [D178]. The addition of the new aperture stop also created the opportunity to improve band-to-band registration; as a result, Raytheon also reoriented two detector field stops as a part of its redesign effort. Raytheon also made several other changes to its optical design that were motivated by scattered light in the instrument; these changes are discussed below. Importantly, because these design corrections were made after CDR, they indicate that design complexity was initially underestimated and thus, contributed to cost growth later in the program.

Related to Raytheon's decision to employ a SeaWiFS heritage rotating telescope design was the derived requirement to develop a new pixel aggregation system to meet the DoD's requirement for constant resolution across the instrument's cross-track scan. While the DoD's OLS had this capability, neither AVHRR nor MODIS did. Instead, both AVHRR and MODIS's pixel proportions were distorted at the edge of scan, whereas OLS's dimensions remained proportional; given this pixel proportionality, OLS was compliant with the DoD's requirement for constant resolution.

OLS maintained constant resolution across the scan by physically reducing its detector size off-nadir [D182]; however, because the rotating OLS detector was incompatible with NOAA's requirements for EOS quality data, Raytheon opted to use a SeaWiFS heritage rotating telescope instead and to develop an alternative system to maintain constant resolution. To do this, Raytheon patented a new pixel aggregation system that constrained pixel growth by aggregating detector read-outs in the across-track direction [D182]. By sizing the detector's nadir cross-track projection to be about 1/6th of its projection at the edge of scan and aggregating detectors read-outs in the across-track direction, Raytheon's system was able to meet the DoD's requirement for constant resolution; to achieve the desired result, three detectors were aggregated near-nadir, two mid-scan, and one near the edge-of-scan [D182]. Raytheon developed its pixel aggregation system early in the program and as a result, this particular design decision did not induce cost *growth*; instead, the pixel aggregation system is an important example that illustrates how joint requirements can induce instrument design complexity which can be recognized, managed, and appropriately budgeted for early in an instrument's development.

In addition to motivating Raytheon to use a rotating telescope instead of its MODIS heritage doubled-sided scan mirror, the DoD's requirement for low light imagery also motivated a change to MODIS's internal optical layout. Instead of separating the VIS and NIR channels on different substrates, Raytheon assigned them to share the same focal plane array [I21, D126, D181]. To accommodate the VIS, NIR, and day-night bands on the same focal plane, Raytheon had to densify the plane and reduce the spacing between each band [I21]. One interviewee described the impacts of this design decision as: "Now because you have effectively 25% of the separation between the bands on VIIRS as you had with MODIS, you have a new requirement for what happens to scattered light and stray light in the filters. If you're going to get the same stray light filter effect on VIIRS as you got on MODIS, then you have to do something that is very careful with how you handle the scattering inside the filters" [I21]. The aforementioned filters are those which separate the light contained in each band; essentially, by densifying the VIS-NIR focal plane on VIIRS, Raytheon created a new derived requirement for filter quality [I21]. Further complicating this new derived requirement was the requirement that VIIRS fly in the early morning orbit, since controlling stray light within the instrument was best accomplished using a different aperture in this orbit than was used in the others; however, instead of using a unique aperture specifically designed for the optical conditions in each orbit, the contractor used a common design across all three orbits [I4, I9].

Although Raytheon's original VIIRS design included the shared VIS-NIR focal plane and common aperture, the contractor did not anticipate how significantly filter quality would couple with these design decisions and would ultimately affect the amount of stray light in the instrument [I4, I21, I39]. This oversight induced cost growth by instigating the "Ocean Color War" that was discussed in Section 5.3. Despite the year-long "war" and climate scientists' continued concern over the instrument's ocean color performance, it should be noted that currently, VIIRS's on-orbit performance is much better than was initially expected [I9, I21, I39].

### 5.7.4 Realizing VIIRS's Complexity

Like the complexity enablers discussed in Section 5.6, underestimation of design and architectural complexity enabled the cost growth that occurred after VIIRS's CDR and was a result of the program's over-reliance on MODIS heritage. Indeed, interviewees cited the program's over assumption of MODIS heritage as one of the key reasons that VIIRS experienced such significant cost growth during its development [I10, I11, I12, D195]. As summarized by one interviewee: "The decision to go with MODIS heritage was that it was cheap! We would have built more MODII. The idea was that you could continue with the design but that you would make some improvements to the design to make up for the short-falls" [I15]. Key short-falls of the MODIS design were its inability to produce low light imagery and to maintain constant resolution across the scan. While the program did identify and implement changes to its MODIS design to meet those DoD-unique requirements, they underestimated how significantly those changes would alter MODIS's heritage design. As a result, it wasn't until after completing CDR that the program discovered that its previous design changes induced modulated instrument background and allowed stray light into the instrument. Again, since the program did not implement corrective changes until after CDR, its early cost estimates for VIIRS remained low, because it assumed that it could re-use a significant amount of its MODIS heritage.

## 5.8 Conclusions and Motivation for Upcoming Chapter

This chapter used the quantitative framework to observe that complexity was injected into the NPOESS technical architecture well before the program's cost estimates began to increase. Using the framework, I also identified five decisions that affected the program's complexity and presented detailed qualitative evidence that described complexity's cost impacts within each epoch. I also used this qualitative evidence to understand that the program's costly decisions were enabled by a need to meet the collaborating agencies' evolving missions and by an underestimation of design, process, and architectural complexity.

In summary, the technical complexity mechanisms that affected the NPOESS program's costs included:

**Architectural Complexity**

1) **First, the program's aggregated spacecraft design induced architectural complexity costs when engineers had to compensate for adverse technical interactions between instruments or between instruments and the spacecraft bus.** Raytheon's need to add new costly EMI shielding to VIIRS illustrated how interactions between VIIRS and EMI-sensitive or EMI-inducing instruments like SARSAT, DCS, and the altimeter increased individual instrument's development costs when multiple interacting instruments were placed on an aggregated spacecraft. Northrop's need to redesign aspects of its T430 heritage spacecraft bus to compensate for the momentum and jitter induced by CMIS also illustrates how interactions between instruments and an aggregated spacecraft can induce additional non-recurring bus development costs.
2) **Second, architectural complexity costs were induced when cost and schedule growth on one component induced schedule delays, funding cuts, and lifecycle cost growth on another.** CMIS, which had its funding significantly reduced during Epoch D and therefore failed to mature as quickly as other instruments, was a prime example of this particular architectural complexity mechanism.
3) **Third, architectural complexity costs were induced when components were designed to be common across the NPOESS constellation.** Although the program used commonality to enable cost *savings*, commonality itself had a cost when components had to be designed to meet the system's most stressing requirements or to function in multiple environments.
4) **Architectural complexity costs were induced as the number of interfaces between system components increased.** For example, VIIRS's cost increased because engineers had to analyze its performance in different thermal and optical conditions for each spacecraft and orbit to which it was assigned. Architectural complexity costs were also induced when interfaces between the NPP system and the NPOESS operational system were added to the program.

**Process Complexity**

5) **Process complexity costs were induced when a single system was required to execute multiple missions that had conflicting requirements and an unclear prioritization of those requirements.** The NPP program demonstrated that operational and risk reduction missions have

conflicting and contradictory requirements, particularly when both missions utilize the same payload instruments.

6) **The program's technical architecture induced unnecessary process complexity when contributing partners developed components to agency unique standards or failed to specify the standards that would govern interfaces between components that were developed by separate agencies.** These impacts were primarily realized on NPP's instruments, which were developed to DoD standards but had to be reconciled to the NASA standards that were applied to other components in the NPP space segment.
7) **NASA's preferred approach for managing system development added process complexity because it required more government oversight of the contractors than was typically used on TSPR-like contracts.**

<u>Design Complexity</u>

8) **The aggregated NPOESS spacecraft exceeded the capabilities of Northrop's standard T430 spacecraft bus and induced non-recurring costs when Northrop had to redesign bus subsystems and space qualify a new data bus.**
9) **Ground system complexity was induced by specifying NPOESS performance in terms of EDRs rather than in terms of SDRs or instrument performance.** When users realized that their needs would not be satisfied by the EDRs that were specified in the IORD, they increased the program's cost by attempting to levy SDR or instrument performance requirements. Users also increased the overall cost to the government by requiring that their home agencies develop systems to interface with the IDPS and convert EDRs into data formats that were more easily assimilated by their systems.
10) **By specifying its requirements jointly and attempting to preserve agency equality, the NPOESS program levied each agency's unique or driving requirements on the joint system. This increased the design complexity of the system's instruments and reduced the program's ability to capitalize on any of the partnering agencies' heritage designs.**
11) **Finally, the collaborating agencies' missions evolved throughout the NPOESS program and as agency missions evolved, so too did the complexity of the technical architecture.**

By comparing cost estimates that were corrected for these mechanisms (i.e. my complexity metric) to the program's actual cost estimates, I was also able to identify two types of cost growth on the NPOESS program. The first was the technical cost growth that was discussed in this chapter. This cost growth was induced by complexity in the technical architecture that was motivated by a need to execute each agency's unique mission and was underestimated or under managed during the program's early epochs. The second type of cost growth was non-technical and therefore, was not induced by the program's technical architecture. These two types of cost growth suggest two distinct roles for the NPOESS organization—enabling cost growth and inducing cost growth—and in the next chapter, I discuss how organizational complexity was responsible for both. For a brief discussion of additional sources of cost growth that are not related to the program's technical or organizational architectures, please refer to the Appendix.

# 6 NPOESS Organizational Complexity

*The more complex the organizational structure….the more costly it is. The more complex the organizational structure….the more diffusive is the responsibility, accountability, and authority. That immediately engenders inefficiencies. Inefficiencies engender cost. The two things that you have to do in any program if you want a successful program is to be effective and to be efficient. Effective means you do the job that needs to be done. Efficiency means the way you do that job is the right way to do it.*

–Interviewee 46

This chapter presents an analytic history of the NPOESS program's organizational architecture. Using the quantitative framework defined in Chapter 3, I first represent the NPOESS organizational architectures, quantify their complexity, and observe the evolution of complexity over time. Aided by the framework's global perspective on complexity, I then identify five actions that affected complexity and connect those actions to the cost growth that they enabled or induced. Next, I review the qualitative, within-epoch data that was used to identify complexity mechanisms, to create the DSMs, and to calculate the metric. I also use that data to illustrate how organizational complexity enabled the technical cost growth that was discussed in Chapter 5 and how it also induced additional non-technical cost. Finally, I conclude by summarizing the mechanisms that increased NPOESS's organizational complexity and their relationship to both technical and non-technical cost growth.

## 6.1 Evolution of Complexity

In Chapter 2, I used literature to define organizational complexity in terms of misaligned interdependencies between intra-organizational components and to suggest that complexity hinders an organization's ability to make effective and efficient decisions. Qualitative data from NPOESS enabled me to inductively refine and enhance my understanding of organizational complexity and its impacts. Using this data, I observed that organizational complexity was primarily a function of misaligned authority and responsibility and secondarily, was induced by additional factors that eroded authority. Five factors were observed to erode authority on the NPOESS program; these factors included:

- The program's contract structure,
- The program's ineffective delegation of authority to the EXCOM,
- The misalignment of authority and budget,
- The misalignment of authority and expertise,
- And the misalignment of responsibility and budget.

These factors were observed to affect the organization's ability to make effective decisions in the following ways:

- The program's contract was performance-based and as a result, changes to the contractors' design or implementation plans had to be executed by modifying the contract at additional cost.
- Although the agencies shared decision making authority on the EXCOM, they did not meet frequently enough or with a full quorum of members to make decisions effectively.
- The misalignments of authority and budget and of responsibility and budget hindered the program's ability to appropriately weigh performance, risk, and cost when making decisions.
- And the misalignment of authority and expertise reduced decision quality because the program did not fully capitalize on the technical expertise that was housed in the collaborating agencies.

Additionally, the misalignment of authority and responsibility was observed to have a significant impact on the effectiveness and efficiency of decision making on the NPOESS program. In particular, this misalignment:

- Hindered decision quality because it separated the decision makers from the staff who were affected by and were most knowledgeable about decisions' impacts,
- And it crippled the decision making process by requiring decisions to be elevated and made by agency management rather than by the staff who were responsible for implementing the outcomes of those decisions.

### 6.1.1 Applying the Framework

To apply the framework to study complexity, four DSMs were created for each epoch, with each DSM mapping the authority, responsibility, expertise, or budget relationships between components of the NPOESS organization. The DSMs contained all three government agencies, the program's executive committee, both the NPOESS and NPP program offices, several councils of user groups, and the system's prime and subcontractors for the spacecraft, instruments, algorithms, and ground system. While most instruments and algorithms were represented separately, I grouped leveraged sensors and their algorithms together. Leveraged sensors were those that did not require a significant amount of technology development or their development was not directly managed by the NPOESS program office; I made this decision because I observed that leveraged sensor contractors minimally impacted organizational behavior.

Following the process described in Chapter 3, I calculated the complexity metric for each epoch and normalized it by the complexity of the pre-convergence POES and DMSP organizations. By normalizing the metric in this way, I was able to compare the complexity of managing two loosely coupled non-joint programs (i.e. POES and DMSP) to the complexity of a single joint program.

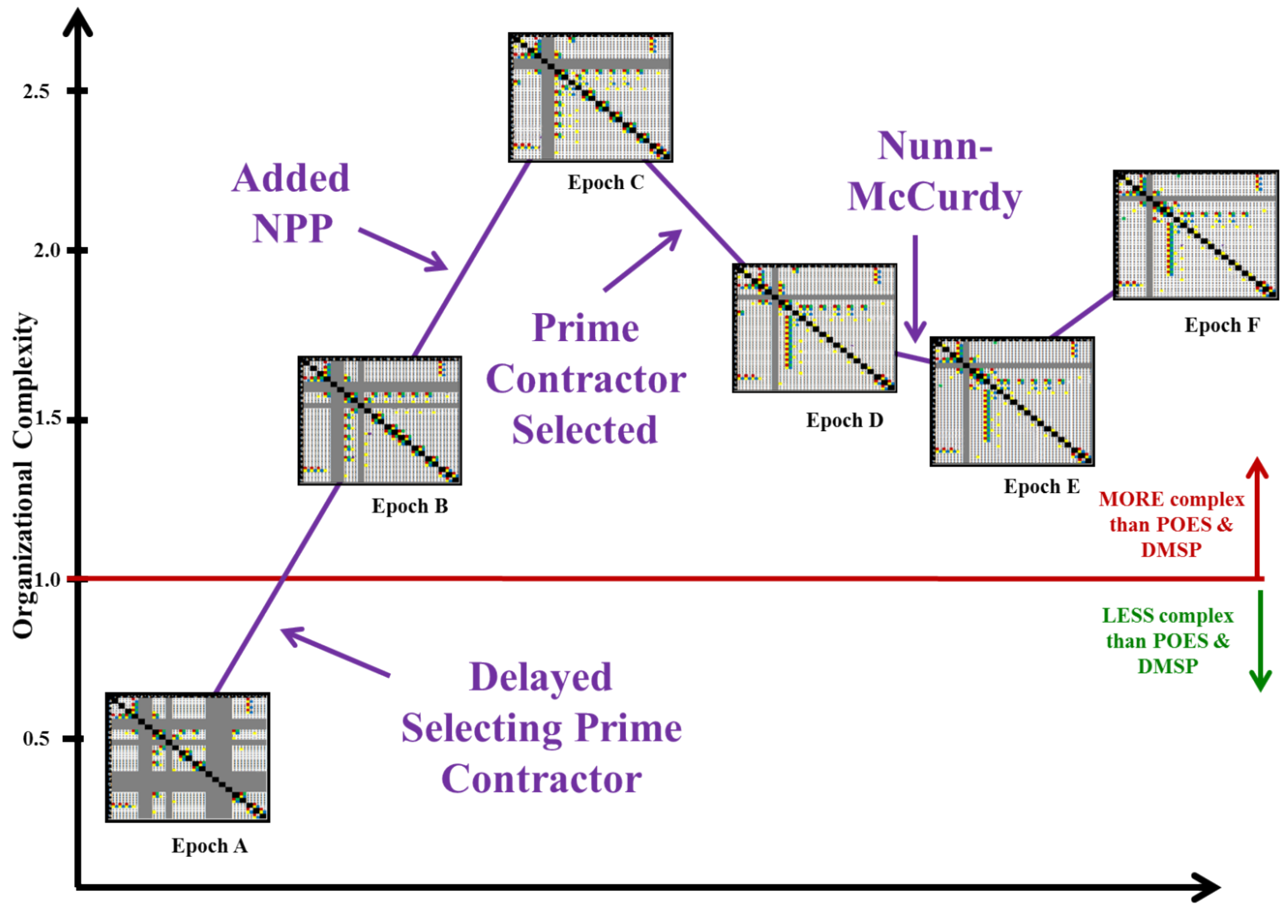


**Figure 32: Global Perspective on Organizational Complexity**

### 6.1.2 Observing the Dynamic Nature of Complexity

Figure 32 illustrates the evolution of organizational complexity on the NPOESS program and its global perspective enables me to draw several conclusions:

- First, the joint NPOESS organization during Epoch A was less complex than two separate POES and DMSP organizations.
- Despite this initial decrease in complexity, the decision to delay selecting a prime contractor increased organizational complexity because it assigned total system responsibility to a prime contractor but did not award that contractor authority over the system until Epoch D.
- Once the prime contractor was selected, authority and responsibility were better aligned and organizational complexity decreased.
- Despite the decrease in complexity after the prime was selected, complexity remained high for the rest of the program because the addition of NPP misaligned NASA's responsibility for NPP's climate science mission with its authority over the instruments that executed that mission.
- Secondarily, adding NPP eroded the IPO's authority over the system by misaligning authority and expertise and budget and responsibility.

- Reforms during the Nunn-McCurdy certification process reduced organizational complexity by aligning responsibility and authority under a single PEO; however, because these reforms did not align authority and expertise and budget and responsibility, much of the organization's complexity remained.
- Finally, just prior to the program's cancellation, the PEO's authority was eroded and organizational complexity increased once again.

These conclusions are consistent with the qualitative data that was used to support the DSMs' construction and the metric's calculation.

### 6.1.3 Complexity-Inducing Actions

Five actions were identified to affect the complexity of the NPOESS organizational architecture; actions were undertaken by the agencies and they affected the agencies' relationship with one another or with the system that was under development. These actions were:

- **Action 1:** Delegating each agency's independent authority over the program to the EXCOM, the tri-agency governance structure where the agencies shared authority.
- **Action 2:** Using the "Optimized Convergence" acquisition strategy and delaying the selection of the prime contractor while issuing multiple risk reduction contracts for sensors that required technology development.
- **Action 3:** Formalizing NASA's role in the program by establishing the dual risk reduction climate science NPP program and assigning NASA the responsibility for managing it.
- **Action 4:** Delegating authority to a PEO who was authorized to make decisions that affected both the operational NPOESS and the NPP systems.
- **Action 5:** Enhancing NASA's role in program's management of the operational NPOESS system.

Table 5 maps each of these decisions to the complexity mechanisms (i.e. the misalignments or additional authority erosion factors) that they induced. As in Chapter 5, since my analysis focused on cost and complexity *growth*, Action 4—which reduced organizational complexity rather than increased it—is not included.

**Table 5: Complexity Mechanisms Induced by Each Action**

| Complexity Type | Complexity Mechanism | Action 1 | Action 2 | Action 3 | Action 5 |
|---|---|---|---|---|---|
| Misalignment | Authority & Responsibility | X | X | X | X |
| Misalignment | Authority & Expertise | | X | X | |
| Misalignment | Budget & Responsibility | | | X | |
| Misalignment | Authority & Budget | | X | | |
| Authority Erosion | Contract Structure | | X | | |
| Authority Erosion | Ineffective Delegation | X | | | |

Finally, as also discussed in Chapter 5, I observed organizational complexity to be responsible for both technical and non-technical cost growth. Specifically, organizational complexity was responsible:

- For technical cost growth because it allowed each agency to use the joint system to execute their unique missions and hindered the program's ability to assess and to manage the system's complexity,
- And for non-technical cost growth because it slowed the decision making process and made it inefficient.

Essentially, organizational complexity induced technical cost growth by *enabling* the costly decisions that were the subject of Chapter 5; Figure 33 maps each of these decisions back to the agency action that enabled them. Organizational complexity also directly *induced* cost growth by slowing the program's decision making process, extending its schedule, and forcing it to pay the cost of employing a marching army to wait while decisions were made.

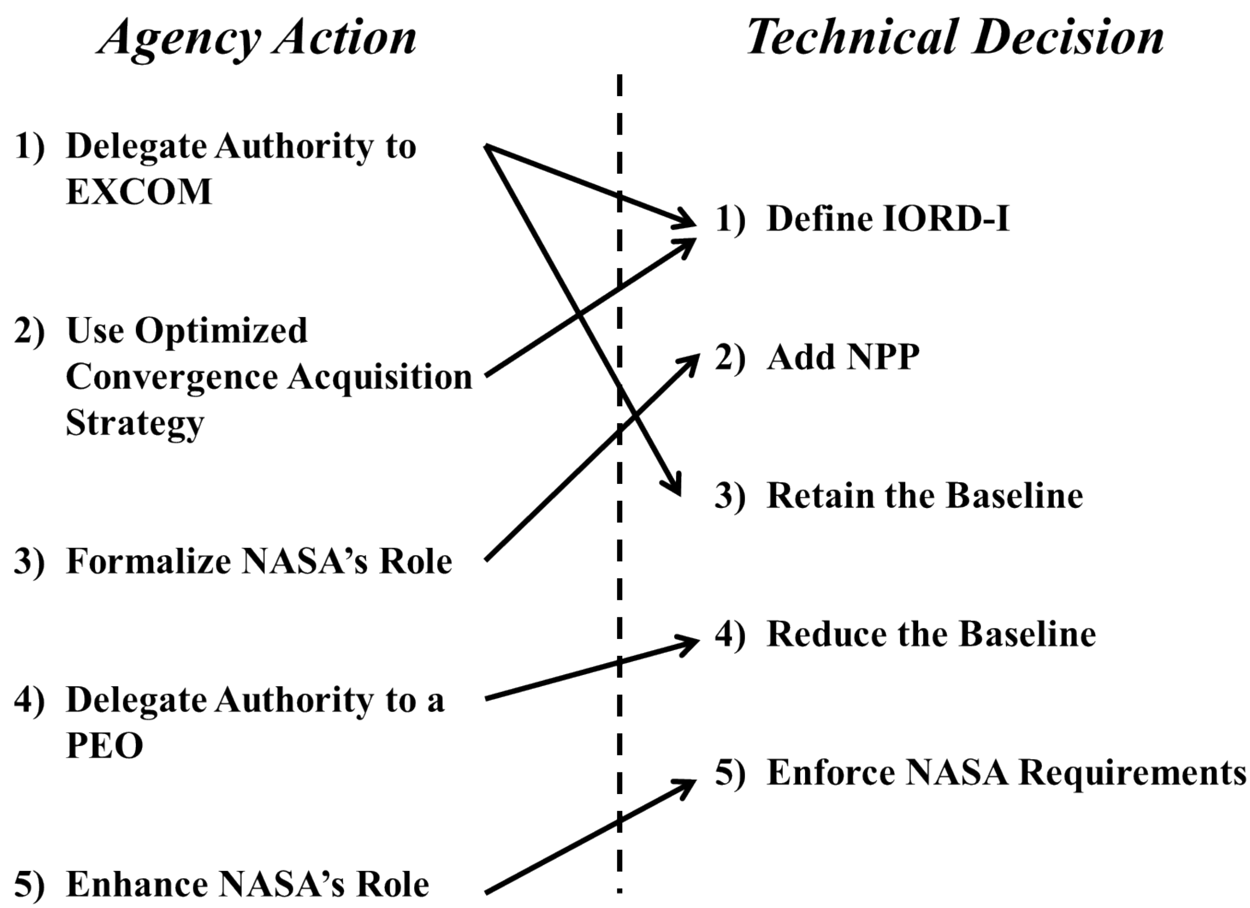


**Figure 33: Actions Mapped to Decisions**

In the remainder of this section, I review qualitative evidence that supported each DSM's construction, each metric's calculation, and the proposed relationship between organizational complexity and cost growth. However, unlike in Chapter 5, where I could easily compartmentalize my discussion into complexity types (i.e. design, process, and architectural), describing the impacts of organizational complexity is more challenging. Unlike technical complexity, which was observed to directly affect the system's cost, organizational complexity affected cost indirectly through the abstract medium of *decision* *making*. Since many factors can affect a decision and its outcome, it was more difficult to identify single examples that illustrated the impact of each misalignment or each authority erosion factor. Therefore, although the impacts of each complexity mechanism were ultimately coupled, in the discussion that follows, I attempt to decouple and distinguish between them.

Furthermore, since the organization's complexity remained high throughout the program, the same organizational complexity mechanisms were observed to affect decision making at different points in time. For this reason, in the sections that follow, I identify the specific organizational complexity mechanisms that were induced by each action. However, when I describe the impacts of those mechanisms, I often zoom into several different epochs and illustrate how complexity affected the program's decisions at different points in time. Again, this perspective was enabled by the research approach that I employed, which allowed me to identify complexity mechanisms, to track their continued presence in the organizational architecture, and to observe their impacts throughout the program's lifecycle.

## 6.2 Action 1: Delegate Authority to EXCOM

As shown in Figure 34, the first action—to delegate authority to the EXCOM—affected decision making throughout the NPOESS program. In particular, Action 1 created an organization where:

- The lead governance structure was an ineffective venue for decision making,
- All decisions had to be made by consensus,
- And agencies' responsibility for their unique missions was misaligned with the authority that agency leaders shared on the EXCOM.

By delegating authority to the EXCOM, the agencies effectively created a governance structure where authority was *shared:* decisions had to be made collaboratively and with the approval of each agency. In the sections that follow, I illustrate how sharing agency authority affected the EXCOM's decisions as well as the decisions and activities that took place in the organizational hierarchy beneath it.

### 6.2.1 Ineffective Delegation of Authority

As has been described by numerous independent review teams [D240, D241, D147] and GAO investigations [D216, D218], although the agencies delegated their independent authority to the EXCOM, the EXCOM was an ineffective venue for decision making. Importantly though, the EXCOM was not supposed play a critical role in the program's management; specifically, the original MOA stated that EXCOM was supposed to provide policy guidance and to ensure that the IPO was properly staffed and funded [D124]. The IPO SPD, who reported to the EXCOM, had the responsibility of executing the agencies' missions and the authority to do so within the program's established baseline [D124]. The EXCOM reserved decision making authority *only* over the program's baseline; therefore, major baseline changes were to be recommended by the IPO SPD and then approved by the EXCOM [D124]. As will be discussed in Section 6.4, once NPP was added to the program's baseline, the SDP's authority was eroded and the interface between the IPO and the NPP program office enabled NASA engineers to elevate technical issues to the EXCOM, because it was the only organizational component that held authority over both the IPO and NPP.

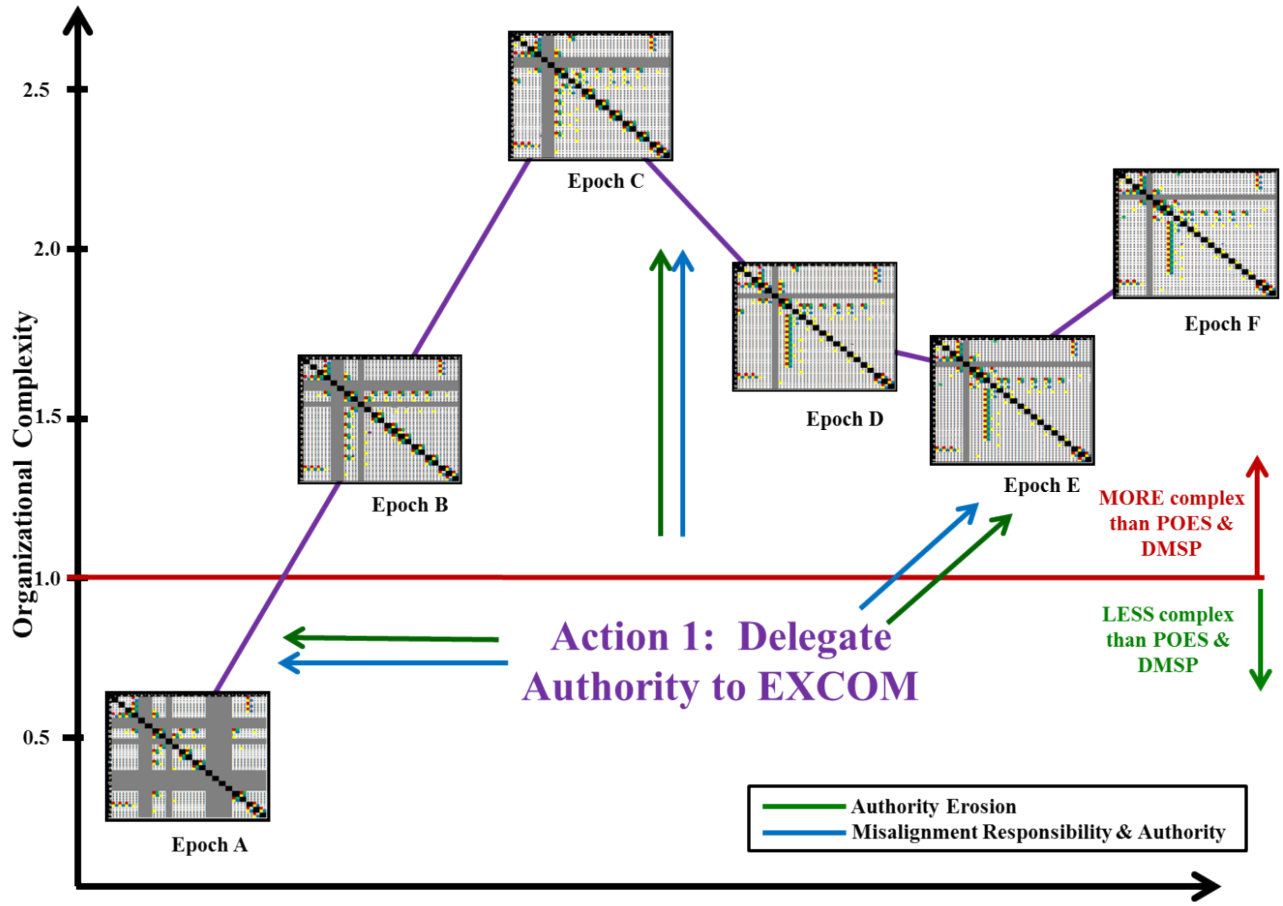


**Figure 34: Complexity Impacts of Action 1**

Although the EXCOM was the only component with authority over the IPO and NPP, it was ill-equipped to exercise that authority because:

- It did not meet frequently enough or with a full quorum of its members to make decisions efficiently,
- And the agency leaders who were members of the EXCOM did have the necessary technical expertise to make the implementation decisions that were required of them.

As a result, the EXCOM's decisions were often delayed and these delays induced non-technical cost growth as the program's marching army stalled and waited for resolution to their technical issues.

For example, between 2003 and 2005 (during Epoch D), the EXCOM only met five times [D216] and at a meeting in August 2005, where the SPD briefed the EXCOM on his recommended changes to the baseline, the EXCOM failed to make a decision [D216]. Even though that meeting occurred just prior to the program's Nunn-McCurdy violation, the EXCOM requested additional analyses instead of making a decision that could have prevented the program's Nunn-McCurdy breach [D216].

Although the EXCOM began meeting more frequently after Nunn-McCurdy [D218], interviewees still noted that their quarterly meetings were insufficient for effective decision making [I24, I25, I26]. Specifically, during Epoch F, the organization increasingly relied on the EXCOM to make "tactical" decisions [D147]. Interviewees and independent program reviews noted that during the final years of the program, the EXCOM served as an engineering review board [D195] tasked to make technical decisions that were inappropriate and ill-suited for agency officials of their stature [I15, I17, I25, I27, D240, D147]. For example, during this period, the EXCOM was briefed on anomalies that had occurred on VIIRS' filter assemblies and launch locks and was asked to choose among possible options for their resolution. Not only was the EXCOM not staffed by representatives with the expertise to make such decisions, but it also did not meet frequently enough to effectively make technical decisions that impacted the program's day-to-day execution.

Complicating the EXCOM's increasingly active role in tactical program decisions was the DoD representative's absence [I22, I26, I32, D147, D220]. When the Under Secretary of Defense for Acquisition and Technology failed to attend an EXCOM meeting, he sent a representative who was not authorized to make decisions on his behalf; this complicated the decision making process because it required additional negotiations between the DoD, NOAA, and NASA that had to occur outside of established EXCOM meetings [D220].

### 6.2.2 Decision Making By Consensus

By delegating their authority to the EXCOM, NOAA, NASA, and the DoD established a tri-agency body where the agencies *shared* authority over the NPOESS program. The unintended consequence of sharing authority was that decisions had to be made by consensus: either all agencies had to agree or no decision could be made. The key outcome of sharing authority was:

- That it maintained agency equality and enabled each collaborator to levy its unique or driving requirements on the NPOESS system,
- And that it prevented any agency from unilaterally authorizing decisions to reduce the system's ability to meet those requirements.

Shared decision authority enabled the IORD to be defined as a concatenation of each agency's unique and driving requirements. First, within the user groups that defined the IORD—the JARG, SUAG, and JARC—no user or agency held authority over the others [I26, I48, D240]; as a result, none of the users could veto the requirements of any other user. Furthermore, if one agency's users requested a unique requirement, users from the other agency could typically find a use for it [I3, I15, D88]. For example, the IORD-II documents how the DoD planned to use ozone and aerosol data from OMPS and APS, even though neither instrument previously existed on DoD systems and both instruments primarily contributed to the NOAA-NASA climate missions [D88]. Additionally, interviewees recalled instances where NASA users found NOAA advocates for their own agency unique climate requirements and were able to get those requirements added to the IORD set *even though their sponsoring agency provided no funding for the operational NPOESS system* [I15]. Essentially, since each user group was able to derive some benefit from another's mission, requirements were easily aggregated onto the NPOESS program. As discussed in Chapter 5, the IORD's aggregated requirements induced both design and architectural complexity in the NPOESS system.

The shared authority within the user community also induced additional architectural complexity by preventing the SPD from making trades to reduce the system's capabilities. The trades that the IPO considered—which would reduce the system's ability to meet non-KPP EDRs—were consistent with the DoD's approach to system acquisition, which defines KPPs as the program's essential EDRs and all other EDRs as tradable [I15, I40]. However, NOAA and NASA contended that *all* of the IORD's EDRs defined the system's baseline and that the IPO had *no authority* to alter that baseline without approval from the EXCOM [I15, I44, D220]. NOAA and NASA users demonstrated this interpretation by refusing to approve any trades that reduced system capabilities and interviewees reported that when the IPO considered these trades, representatives from NOAA and NASA would alert their agency leadership and prevent the IPO's actions [I44, I46].

The organizational architecture enabled this behavior because the program's user groups interfaced not only with the IPO, but also directly with agency leaders who shared authority over the program's technical baseline. By alerting agency leaders of impending trades and seeking their disapproval, the program's users were able to block the IPO's actions. For example, interviewees recalled that when the IPO considered trades that would reduce or eliminate EDRs that were of interest to NOAA and NASA, "NASA could anticipate in advance when [the IPO SPD] was going to say no and they would go around his back before that" [I46].

Even when the IPO attempted to make trades on capabilities that were not formally defined in the IORD, its authority was hindered by the users' direct interface to agency leadership. As previously noted, the IORD did not require that a fully populated SESS suite be assigned to each operational spacecraft [D87, D88]; as a result, in an attempt to reduce cost, the IPO considered assigning a reduced suite to each of the spacecraft. However, because the SESS user community wanted a fully populated suite on each spacecraft, the IPO was unable to make any trades to reduce cost [I15, I23, I26, I40]. Instead, the IPO and Northrop conducted multiple trade studies over the course of year and the DoD's SESS users continually rejected all proposed changes to the system's architecture.

### 6.2.3 Misaligned Authority and Responsibility

Another unanticipated outcome of the sharing authority at the EXCOM was that each agency still individually maintained its responsibility for executing its mission. As a result:

- Each agency's responsibility and authority were misaligned because agencies retained responsibility but shared authority,
- And this misalignment induced non-technical costs by increasing the amount of agency oversight of the program.

Essentially, each agency continued to oversee the program's activities independently and as a result, there was greater amount of government oversight on NPOESS than is typical of a single-agency program. Furthermore, this independent oversight did not add value to the program because although the agencies oversaw the program independently, they could not make decisions without the approval of their collaborators. The following sections review examples that illustrate how this particular misalignment of responsibility and authority affected the program's decisions.

#### 6.2.3.1 Oversight by the Office of the Secretary of Defense

One of the first examples of misaligned authority and responsibility occurred during Epoch B, when the collaborating agencies reviewed the program but had no effective mechanism (other than the EXCOM) to influence positive change. For example, in 1996, the Office of the Secretary of Defense's Program Analysis and Evaluation (PA&E)[16] division performed an independent assessment noted the program's technical architecture would not "save anything relative to pre-convergence plans;" as a result, PA&E recommended that the IPO return to a less complex architecture similar to Epoch A's [D146]. In particular, PA&E emphasized the challenges and cost over-runs that the DMSP program had encountered during the development of CMIS's predecessor (SSMIS) and suggested that NPOESS should use a clone of SSMIS and focus its development funding only on VIIRS [D146]. Furthermore, PA&E recommended that the IPO substitute heritage HIRS for CrIS and remove the altimeter from the architecture [D146].

The IPO's response to PA&E's recommendations, in the form of a Memo for the Record, captures the misalignment of authority and responsibility that enabled the risks identified by PA&E to remain unaddressed. Specifically, the memo notes that PA&E's recommendations reduced the system's ability to meet the IORD's requirements and that, as a representative of a single agency, PA&E had *no authority* to change the program's requirements baseline [D58]. As a result, without the agreement of NOAA and NASA, PA&E's recommendations could not be implemented.

Interestingly, many of PA&E's recommendations *were* incorporated during Nunn-McCurdy certification. The key difference between the DoD's role in 1996 and the role it held during the Nunn-McCurdy certification process was its authority. Specifically, during certification, the DoD held sole authority over the program's baseline and was legally obligated to make changes to that baseline in order to reduce the program's costs.

#### 6.2.3.2 Oversight by the TSC

The misalignment of responsibility and authority continued to affect the program when the TSC was created during Epoch D. As discussed in Chapter 4, the TSC was an intermediary between the IPO and the EXCOM that was composed of representatives from each of the agencies who had responsibility but no authority over the program. The TSC enabled cost growth because it acted as a filter between the IPO and the decision makers on the EXCOM; specifically, interviewees noted that when costs were growing during Epoch D, the IPO SDP made requests for additional funding [I16, I46, I52]. Since the TSC was the IPO's primary interface to the EXCOM, the SPD directed his requests to them; however, interviewees reported that TSC members failed to communicate the urgency of the program's situation to agency leaders who had the authority to make baseline decisions [I16, I46]. In fact, during Epoch D, agency leaders both testified in front of Congress and provided briefings to Congressional staff that failed to emphasize the program's cost risks and certified that the technical architecture under development was necessary to meet the IORD's requirements [D144, D165].

The TSC hindered the IPO's ability to request changes to the program's baseline because it filtered information between the IPO and the EXCOM and slowed the communication process. This enabled architectural complexity because it left the IPO with no option other than prioritizing the development of

[16] PA&E is now called Cost Assessment and Program Evaluation (CAPE).

some components over others. However, the TSC also induced non-technical costs because it slowed decision making at the EXCOM. For example, just prior to the Nunn-McCurdy breach, the TSC directed the IPO to generate a set of alternative technical architectures that would reduce capabilities and cost [D216]. Yet when those options were presented to the EXCOM, its members requested additional analysis and delayed making a decision [D216]. If the EXCOM, rather than the TSC, had been more actively involved in the IPO's initial analysis, it could have requested additional analyses earlier and made a more timely decision. Instead, the program's costs continued to grow after the EXCOM meeting and a Nunn-McCurdy breach was declared shortly afterwards.

Finally, because the TSC was responsible for the program, it was able to request analyses like those discussed above. However, because the TSC lacked authority, it was unable use those analyses to direct meaningful change that was capable of controlling the program's costs. Instead, the TSC's presence induced non-technical cost by generating extra work for the IPO: for this reason, the TSC was eliminated after Nunn-McCurdy [D240].

#### 6.2.3.3 Oversight After Nunn-McCurdy

Although the TSC was disbanded after Nunn-McCurdy, the agencies' independent oversight of the program increased and continued to induce non-technical costs. Interviewees noted that the Nunn-McCurdy breach increased the skepticism with which agency leaders viewed the program [I16, I23, I26]: "The minute you hit Nunn-McCurdy, there's blood in the water...Anybody who was ever against your program is going to use that as proof. And doubt gets sowed in everybody else's mind and it's the start of the end [I26]." Motivated by skepticism and by the publicity and increased Congressional oversight that the Nunn-McCurdy breach brought to the program, the agencies increased their oversight activities between 2006 and 2010 [D241]. Interviewees reported that this oversight did not directly add value to program's activities and instead distracted IPO staff from executing their system's development [I16, I23]: "It seemed like they were spending a lot more time responding back to their parent organizations than furthering the NPOESS mission" [I23]. The Aerospace Corporation echoed this sentiment by noting that IPO management spent 50-80% of their time reporting up-channel, instead of executing system development activities [D195]. Again, because the agencies lacked an effective mechanism to independently direct the IPO's activities, their oversight induced costs by generating additional work for the IPO that was not applied to improve its ability to manage the system.

## 6.3 Action 2: Use the "Optimized Convergence" Strategy

As shown in Figure 35, the second action—using the "Optimized Convergence" strategy—resulted in a program that was more complex than the separate POES and DMSP organizations. In particular, Action 2 induced organizational complexity by:

- Using a performance-based contract,
- Misaligning authority and budget,
- Misaligning authority and expertise,
- And misaligning authority and responsibility.

The key impact of Action 2 was that it enabled the program to underestimate and under manage its system's complexity during Epochs B and C, when requirements for the IORD-I and IORD-II were defined. As a result, the program's cost estimates remained low while its system's complexity increased.

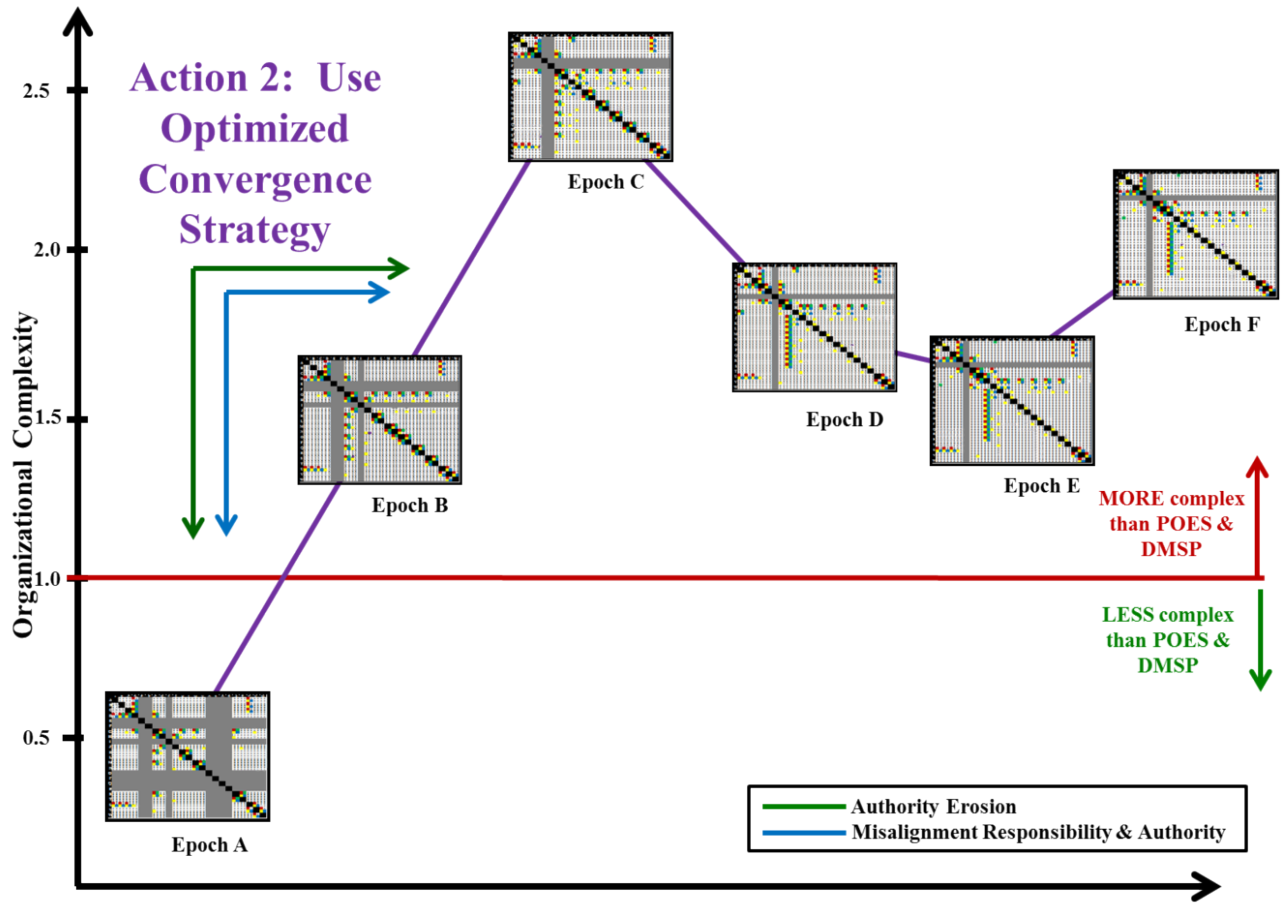


**Figure 35: Complexity Impacts of Action 2**

In the sections below, I describe how the organizational complexity that was induced by Action 2 enabled the program to underestimate and under manage its technical complexity. I also illustrate how, when organizational complexity decreased with the selection of the prime and subcontractors, the program began to realize the complexity that was inherent in its technical system.

### 6.3.1 Contract Structure

A key component the program's acquisition strategy was its use of performance-based contracts; for the most part, the program only levied contractual requirements on its EDRs and it allowed its contractors to develop designs to meet them. An unanticipated outcome of this strategy was that it hindered the IPO's ability to directly manage instruments' designs and their inherent complexity; specifically:

- While sensor vendors were still in competition, the IPO could not offer design guidance for fear of appearing partial during the subsequent down-selection process,

- And once a final sensor vendor was selected, if the IPO wished to make a change to its design, it had to use contract direction and issue a costly contract change in order to exercise authority on the system's design or its performance below the EDR-level.

In practice, these factors reduced the amount of direct authority that the IPO held over instrument designs and hindered its ability to manage their complexity. For example, as discussed in Chapter 5, Raytheon altered the VIIRS optical design *after* instrument CDR, when the contractor discovered modulated instrument background and stray light after performing a reverse ray trace [D178]. Interviewees noted that an IPO engineer requested that Raytheon perform a reverse ray trace at CDR but that instead of placing a lien on the CDR's completion, IPO's acquisition managers approved Raytheon's design [I35, I39]. It was only after CDR, when that IPO engineer kept requesting that Raytheon complete the action, that the design flaw was discovered. An IPO engineer raised a similar concern about the CrIS mechanical design at CDR, when he questioned the use of a braised frame for the instrument's primary structure [I4, I24]. Although the engineer raised a formal action item, the instrument's mechanical design was never changed; as a result, as warned at CDR, the CrIS structure lacked sufficient margin at its joints. Instead of addressing this problem when the issue was raised, the program dealt with it in 2006, when a CrIS flight unit failed during vibration testing [I4, I5, I24, I28].

These examples illustrate that a key impact of the program's contract structure was that it impeded the government's ability to directly manage instrument designs or requirements below the EDR-level. Instead of enabling the government to catch and correct instrument design issues before or during CDR, the contract structure allowed flaws to propagate downstream into the instruments' post-CDR designs [I4, I5, I22, I24, I35, I39, I46] and to emerge once the contractors entered the build-phase of development.

## 6.3.2 Misaligned Authority and Budget

Using the performance-based specifications discussed above, the program issued two risk reduction contracts each for OMPS, VIIRS, CMIS, and CrIS. By funding multiple vendors and delaying contractor selection until after instrument PDR, the program intended for its "Optimized Convergence" strategy to fuel competition between vendors that would ultimately improve proposal quality and produce more detailed technical information that could aid the government's final down-selection [D166]. Despite this intention, the "Optimized Convergence" strategy:

- Delegated design authority but not budget responsibility to the instrument contractors,
- And in doing so, enabled those contractors to underestimate instrument design complexity.

By delegating contractors the authority to make design decisions before they won a final contract and assumed responsibility for their designs' costs, Action 2 misaligned authority and budget. The key outcome of this misalignment was that until winning the final contract, sensor vendors were primarily incentivized to win by meeting all of the government's requirements under aggressive cost and schedule constraints [I12, I14, I15, I26, I36, I46]. As a result, until vendors were under contract, they underestimated the design complexity of their instruments. One interviewee noted that, "no matter what numbers we gave [the vendors] during the proposal stage or the down-select stage…they met. If we told them, this is the amount of money we have for the instrument, non-recurring and recurring, low and behold they met that" [I15].

The behavior of the NPOESS contractors was not inconsistent with other programs; in fact, one interviewee noted that in general, “most companies will find a way—one way or the other—to meet the cost targets that the government gives” [I14]. Given companies’ efforts to meet cost targets, another interviewee noted that until the government awarded its final contracts, it was difficult to obtain accurate cost estimates: “Part of the problem was…you don’t know some of these answers until you get the vendors under contract. Because they are in competition, they are not going to tell you” [I26].

The misalignment of contractor authority and budget was particularly impactful because the government changed its requirements *during* vendor competition. In particular, the NASA Accommodation Study—which explored the cost and design impacts of updating VIIRS’s requirements to execute NASA’s climate science mission—was performed *before* the VIIRS contractor was selected. Again, since the prospective contractors were incentivized to meet the government’s new requirements in order to win the final contract, they reported that the new requirements had little impact on their proposed designs. As described by one interviewee: “The users are there saying they want stuff and pretty soon you go from five channels to 22 channels without really understanding the cost implications” [I36].

One of the key unforeseen impacts of the “Optimized Convergence” strategy was that it extended the period during which companies valued winning the final contract over fully accounting and managing instrument design complexity. As a result, until each of the sensor vendors were on contract—four years after initiating instrument design work—the program underestimated instrument design complexity and cost. In the intervening years, instrument vendors proposed low-cost extensions to their heritage designs that increased their competitiveness but ultimately failed to account for design complexity; as described by one interviewee: “The contractors come back with their plans on how they are going to take legacy hardware…straightforward transformation and extension of heritage…The truth of the matter is…the step from the legacy hardware designs into the next generation design…none of those were followed in the way that the contractors had described them to be” [I46].

Finally, the cost-plus nature of the program’s contracts also contributed to the misalignment of authority and budget. Specifically, interviewees reported that because the program’s contracts were cost plus, contractors had little incentive to refine their initial proposals, since any excess cost would be incurred by the government [I11, I14, I12, I15]. As a result, during Epochs B and C, instrument contractors developed proposals that were consistent with the government’s cost estimates [I11, I12, I15] because it was the government and not the contractors, that would ultimately be responsible for any subsequent cost growth. As described by one interviewee: “Because it was a cost-plus contract in all cases, the only thing that was at risk to the contractor was the amount of fee that they were going to receive” [I12].

### 6.3.3 Misaligned Expertise and Authority

Consistent with its use of performance-based specifications and its TSPR-like contract, the organization tasked to manage NPOESS was small and was created under the assumption that most of the program’s technical work and expertise would reside in its contractors rather than in a government program office. Despite this assumption, interviewees reported that:

- The IPO lacked expertise that was commensurate with its authority over its contractors,
- And that this misalignment of authority and expertise enabled complexity to be underestimated during the program’s early epochs.

Interviewees discussed the IPO's misalignment of authority and expertise in terms of its lack of "bench strength," a noted asset of single-agency institutions like NASA GSFC [I4, I9, I10, I17, I21, D147]. Unlike GSFC, which employs 10,000 civil servants and contractors [D74], between 2000 and 2005, the IPO was understaffed at an average rate of 22% and employed, on average, only 65 people [D195]. Because it was separated from an engineering organization which housed technical expertise, the IPO itself did not contain expertise commensurate with the authority that it held over its contractors; as described by one interviewee: "The IPO just couldn't be a 10,000 person engineering organization the way that NASA can or even the way that Aerospace could" [I9].

Further exacerbating the IPO's limited internal expertise was the fact that its parent agencies failed to adequately staff it [I9, I14, I21, I29]. For example, during the program's early years, NASA provided limited technical support, even though NASA GSFC housed engineers who were experts at building heritage instruments like MODIS. As described by one interviewee, during the program's early epochs: "NASA was not funded to do very much of that work and NASA was concerned about their funding authority and their actual program execution authority. So NASA didn't cozy up an awful lot in those days. And unfortunately, the expertise that we needed to maybe keep this program within cost and schedule bounds, that expertise was resident within NASA" [I21]. As noted by [I21], prior to forming the NPP program, NASA provided no budget nor had any direct authority over the NPOESS contracts. As a result, the agency had little incentive to assign its technical experts to work in the IPO; indeed, rotations from NASA GSFC to the IPO were often viewed as bad career moves and were generally unsupported by the center's management [I9, I29, D195].

Despite small size and under-staffing, the IPO *did* contain a system engineering group that employed technical experts from the collaborating agencies and their related FFRDCs. However, despite containing this group, the IPO's separate acquisition group served as the program's primary interface to its contractors. Unlike the system engineering group, the acquisition group was primarily staffed by young Air Force officers who served in the IPO on two or three year rotations [I14, I21, I22, I23, I26, I35, D195] and who lacked the experience and expertise to properly assess instrument design complexity [I22, I23, I26].

Importantly, this oversight model was not unique to the NPOESS program: Air Force satellite programs are often managed by rotating officers whose expertise is supplemented by engineers from FFRDC's. In a typical organizational architecture, FFRDC engineers are staffed alongside officers and tasked to help them assess contractors' progress. However, in the IPO, technical staff were housed in a separate system engineering group that reported to the SPD (a NOAA employee) while the officers who worked in the acquisition group reported to the Associate Director for Acquisition (a DoD employee) [I23].

A key unanticipated outcome of these dual reporting chains was that they created an ineffective interface between the technical and acquisition groups within the IPO. As a result, when the acquisition officers interfaced with the program's contractors, they often lacked expertise that was commensurate with their authority. Thus, during the program's early epochs, the IPO did not closely manage its instrument contracts [I04, I07, I12, I17, I21]. Without rigorous government oversight, many of the contractor's flawed assumptions about instrument heritage and design complexity propagated through instrument CDR and were not discovered until Northrop's technical experts began actively managing instrument contracts.

### 6.3.4 Misaligned Authority and Responsibility

The final critical impact of the "Optimized Convergence" strategy was that assigned total system responsibility to a prime contractor but did not select that prime contractor until Epoch D. Until the prime contractor was selected:

- Authority and responsibility for the total NPOESS system were misaligned,
- And as a result, architectural complexity was under managed and design complexity was underestimated.

As part of its total system responsibility, the prime contractor was responsible for interfaces between the system's components. However, prior to Epoch D, the IPO retained authority over two key interfaces between the instruments and spacecraft and between the algorithms and the ground system. Key technical parameters that affected the spacecraft-instrument interface were mass, power, volume, and interactions. Key technical parameters that affected the algorithm-ground system interface were computational complexity or timeliness (i.e. how long it took to run the algorithm).

Although the prime and ground contractor were ultimately responsible for these interfaces, prior to Epoch D, interviewees reported that they did not have sufficient insight into the IPO's management of the instruments or their algorithms [I2, I15, I46, I47, I49]. Specifically, in order to maintain the spirit of "Optimized Convergence", which was to prevent sub-optimal instrument-prime partnering, all interactions between the prime contractor teams and the sensor vendors had to be facilitated by the IPO [I2, I23]. Typically, the primes' interactions with the sensor vendors were formal and took place at technical review meetings like CDR. Interviewees reported that these meetings were an ineffective mechanism to assess instruments' technical maturity, since attendance was typically limited to only two representatives per prime contractor [I46, I47]. Importantly, since the prospective primes did not have authority during these reviews, they were primarily observers; as one interviewee noted: "We did not have any jurisdiction over them. We were on the receive mode. We couldn't really transmit saying, 'You know that the VIIRS calibration chain is not right; it won't work.' We didn't provide comments like that. As a matter of fact we didn't provide that any comments at all." [I49]

Without sufficient insight or the authority to direct change prior to Epoch D, Northrop and Lockheed constructed their bids for the prime contract according to the government advised assumption that all instruments and algorithms would be developed to a CDR-level of maturity [I46, I47]. For the instruments, this translated into the assumption that sensors' interface parameters, primarily mass and power, would be fixed [I23, I46]. For the algorithms, this translated into the assumption that the algorithms would follow general coding standards and would be compatible with the ground systems' latency requirement [I22, I30, D40, D77]. Using these assumptions, the contractors estimated costs for the system. However, shortly after winning the prime contract, Northrop discovered both assumptions to be untrue: not only were instruments' mass and power growing [I10, I24, I23, D178, D149] but the algorithms were analogously immature [I22. I30, I46].

These flawed assumptions caused the prospective prime contractors to underestimate the system's cost and in particular:

- To underestimate the spacecraft's design complexity,

- And to underestimate the ground system's design complexity.

As will be illustrated below, the spacecraft and ground system's design complexity was higher than anticipated because the interfaces to both of those components were under managed prior to Epoch D. Put another way, because the IPO was not ultimately responsible for these interfaces, it did not actively manage them. Concurrently, the prime contractor, which would ultimately be responsible for the interfaces, did not have the contractual authority to manage them. As a result, the technical parameters that defined the interfaces were unstable. This instability induced spacecraft and ground system design complexity when the contractors had to adjust their designs later in order to accommodate the system's fluid interfaces. As illustrated in Figure 36, "Optimized Convergence" strategy broke the mirror between the program's technical and organizational architectures; the sections below will provide additional description of the impacts of this socio-technical mirror-breaking.

### 6.3.4.1 Responsibility and Authority for Spacecraft-Instrument Interfaces

Because Northrop assumed that the IPO-developed instruments were at a CDR level of maturity, it underestimated the spacecraft bus's design complexity and the architectural complexity that was induced by CMIS. Specifically, Northrop's spacecraft design assumed that the instruments' mass, power, and volume interfaces were frozen [I2, I13]. With this assumption, Northrop was able to reduce the cost of developing a common spacecraft bus by leveraging a design from its EOS heritage [D17]. Once instrument masses, particularly VIIRS and CMIS, began growing after Northrop won the contract, the prime struggled to close its mass budget and ultimately had to redesign a portion of its proposed bus [I23, I44, D149]. In particular, a review by the Aerospace Corporation noted that between 2003 and 2005, the satellite launch mass increased by 40% [D149]. The Aerospace Corporation emphasized that instead of managing the satellite's mass growth systematically and exploring opportunities for mass reduction both from the payload and the bus, Northrop's spacecraft subsystems held "the entire burden of weight reduction" while the instrument masses remained above their initial specifications [D149]. What this analysis fails to acknowledge is that the primary mass drivers, CMIS and VIIRS, had already completed their CDRs and were the product of nearly eight years of IPO-managed development. In contrast, Northrop's spacecraft contract was less than two years old and consequently, was less mature and easier to change than the instruments' more mature designs. Importantly, although the spacecraft design was easier to alter, the system that resulted was more complex and costly than the heritage design that was originally proposed.

Northrop's design changes and the cost growth that they induced can be linked to its initial underestimation of bus design complexity: specifically, the heritage bus that Northrop originally proposed was incapable of hosting all of the program's sensors at their final weight. Interviewees attributed the resulting bus redesign to Northrop's lack of contractual authority during Epochs B and C [I2, I13, I30, I49]. One interviewee noted that "Whatever the government let those guys get away with, [Northrop] had to put up with" [I2] and another described the resulting situation as, "The contractor just accepts the contract that the government has previously negotiated and then they start digging into it to find out if it was reasonable or not…I would not want to run a program where somebody else negotiated a contract and then I had to accept it. Particularly if the guy who negotiated the contract knew that in the end, he wasn't going to be the guy executing it" [I13]. Essentially, because Northrop lacked authority prior to Epoch D, it had to rely on the technical information provided by the IPO, which as discussed above, lacked sufficient detail. Furthermore, even when the Northrop gained sufficient technical detail and contractual authority over the IPO's instruments, it could not approach the resulting design problem systematically, since the instruments designs were more mature than its spacecraft design.

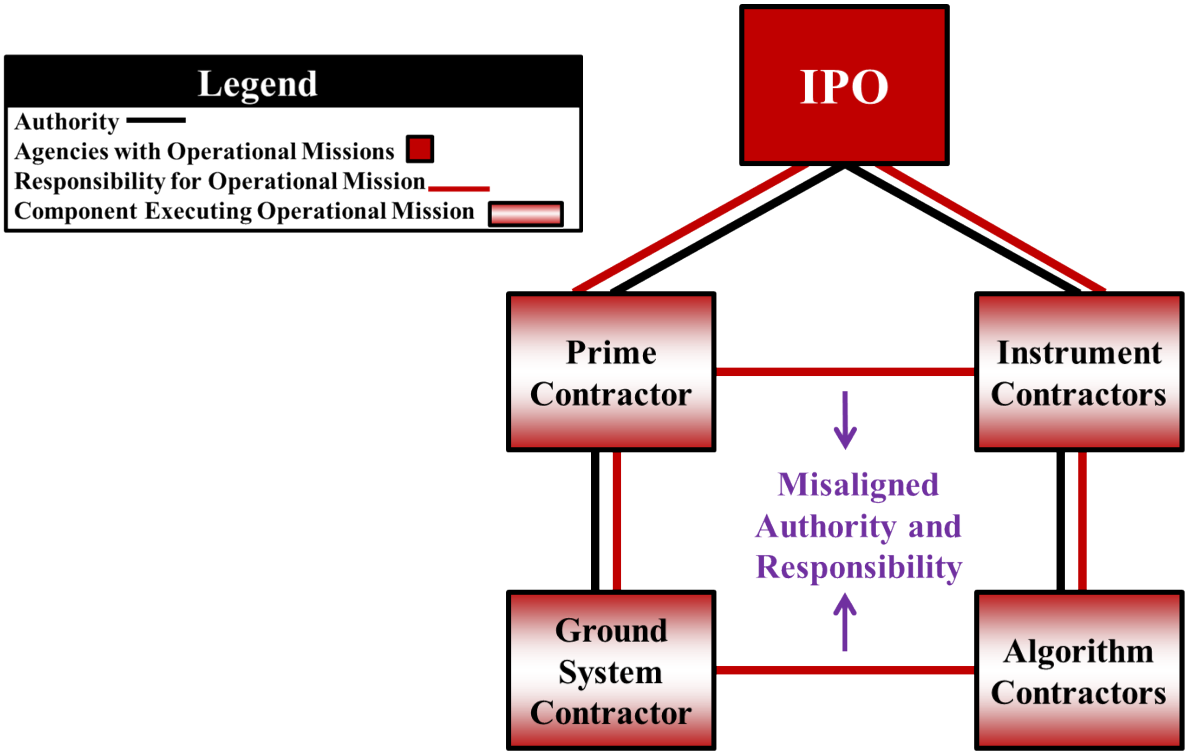


**Figure 36: Misaligned Authority and Responsibility Prior to Prime Contractor Selection**

### 6.3.4.2 Responsibility and Authority for the Algorithm-Ground System Interfaces

Like the spacecraft, the prime's cost estimate for the ground system did not adequately account for design and architectural complexity. Prior to Epoch D, the sensor vendors developed scientific algorithms to convert sensor outputs to EDRs [D236, D40, D45]. After the prime contractor was selected, the sensor vendors submitted their scientific algorithms to the ground system subcontractor, Raytheon, which operationalized them. Scientific and operational algorithms differ primarily in the speed and robustness with which they convert sensor outputs to EDRs; specifically, the program's operational algorithms were subjected to a latency requirement and were required to be robust against input uncertainties [I22, I30].

Since Raytheon and Northrop did not have contractual authority prior to Epoch D, they could not derive and levy an appropriate latency requirement on the scientific algorithms. The latency requirement that the IPO levied in its instrument RFPs in 1997 was ambiguous and stated only that the scientific algorithms should be "compatible" with the latency requirement levied on ground system's operational algorithms; however, no timeliness requirement was derived for the scientific algorithms and the means to verify requirement compliance was left to be determined [D236, D40, D45, D77]. While I was unable to obtain sensor requirement documents after 1997, interview data suggest that a derived latency requirement was not formally levied on the scientific algorithms prior to Epoch D [I22, I30]. As a result, when Northrop and Raytheon finally gained contractual authority, they had to derive and levy new requirements on the scientific algorithms to enable them to meet the latency requirement in an operational setting.

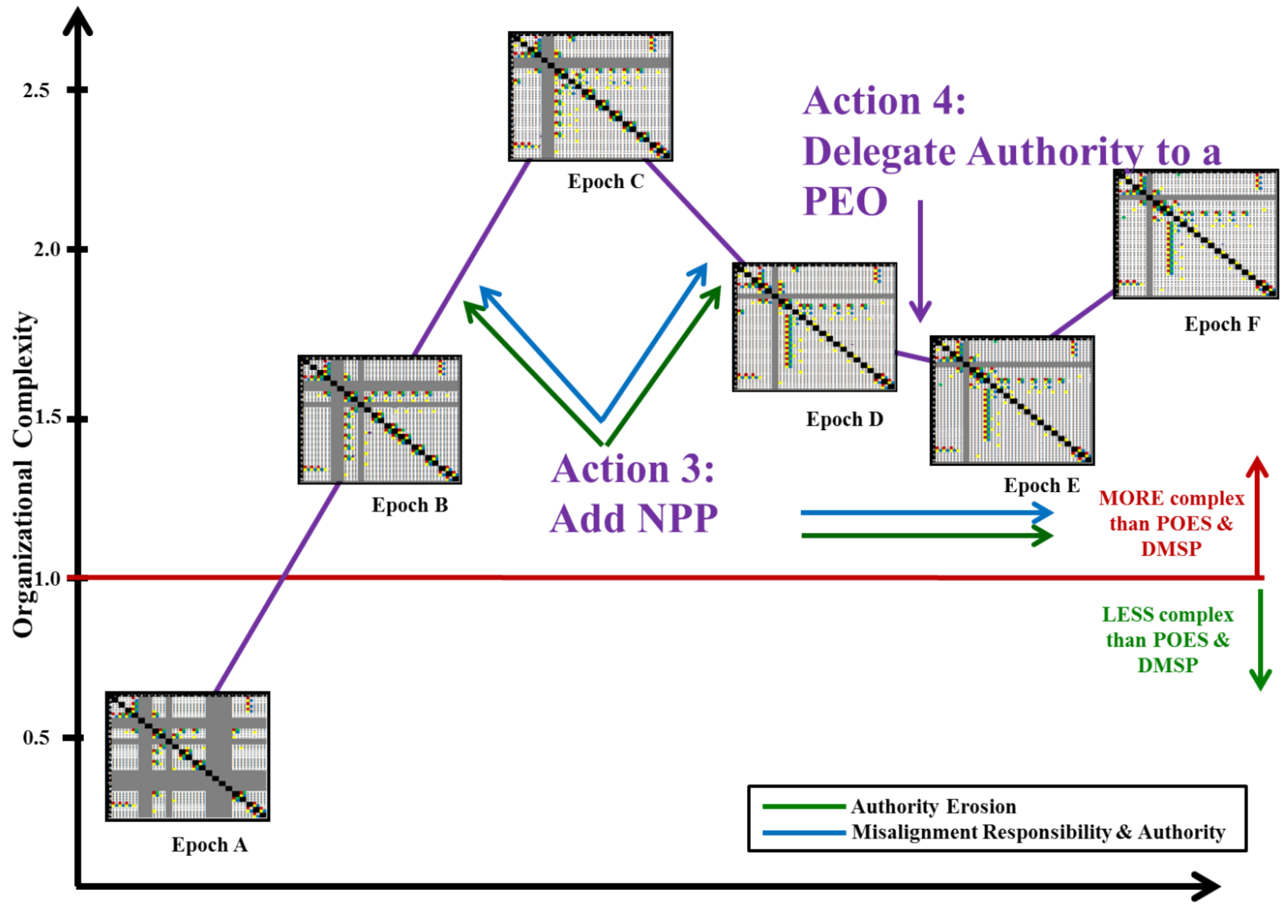


**Figure 37: Complexity Impacts of Action 3**

Furthermore, consistent with the program's performance-based specifications, no coding requirements were levied on the scientific algorithms [I22, I30, I46]; instead, sensor vendors' algorithms were assessed with respect to EDR performance only. Again, because Northrop and Raytheon did not hold contractual authority over scientific algorithm development, they could not direct the sensor vendors to produce algorithms that would appropriately interface with their operational system. Without the authority to manage this interface prior to Epoch D, the primes made the assumption that all of IPO-managed algorithms would all follow reasonable coding standards [I22, I30]. As discussed in Chapter 5, once Northrop won the prime contract and the algorithms were delivered, the contractor had to levy new standardized interface requirements so that it could integrate the algorithms into the IDPS system [I22, I30, I46].

## 6.4 Action 3: Formalize NASA's Role

As shown in Figure 37, the third action—to formalize NASA's role by creating NPP—had a significant impact on organizational complexity that persisted throughout the remainder of the NPOESS program. Action 3 induced organizational complexity:

- Primarily by misaligning responsibility and authority,
- And secondarily, by eroding the IPO's authority over the operational NPOESS system by:
    - Misaligning responsibility and budget
    - And by misaligning authority and expertise.

As also shown in Figure 37, Action 4 reduced organizational complexity by adding a single PEO who had authority and responsibility for both the NPOESS and the NPP systems. Although the PEO did correct some of the misalignment induced by Action 3, it did not correct the misalignments of responsibility and budget and of budget and expertise; as a result, the reforms that followed the Nunn-McCurdy breach were incapable of reducing the program's organizational complexity to a level commensurate with Epoch A and the complexity induced by Action 3 continued to affect the program until its cancellation.

The misalignments induced by Action 3 affected all components of the NPOESS organization: from instrument subcontractors, to spacecraft-ground interfaces, to meetings at the EXCOM. Therefore, I divide the remainder of this section according to the portion of the organizational architecture that was affected by complexity. I begin by discussing how organizational complexity affected execution-level of the program, where engineers and scientists did technical work to develop the system. Next, I discuss how complexity affected IPO management's decision making. Finally, I conclude by describing two additional interfaces between NPP and the IPO that were poorly defined by the MOA and where authority and responsibility were misaligned.

## 6.4.1 Execution-Level Interface

Figure 38 depicts a simplified organizational architecture and illustrates how the IPO and NPP interfaced both at the program's execution and management levels. The key characteristics to note about this interface are:

- The IPO had authority over the instruments used to execute NPP's missions,
- NPP's organizational interface with the instrument subcontractors eroded the IPO and the prime contractor's authority over them,
- And the only organizational component with authority over both NPP and the IPO was the EXCOM.

As a result, if issues could not be resolved at the execution-level, decisions had to be elevated to the only organizational component that had authority over both the IPO and NPP: the EXCOM. This elevation process induced non-technical costs by decreasing the efficiency with which the program made decisions. Non-technical costs and technical costs in the form of process complexity were also enabled by the execution-level interface and specifically, by the misalignment of responsibility and budget and of authority and expertise. The remaining sections describe these impacts in greater detail.

### 6.4.1.1 Misaligned Authority and Responsibility

The most prominent feature of the execution-level interface between the IPO and NPP was the misalignment of responsibility and authority: although the NPP program office was responsible for executing NASA's climate science mission, it had no contractual authority over VIIRS, CrIS, or OMPS—three instruments that were critical to executing it [I17, I24, I33, I39]. In particular, after the prime contractor was selected, interviewees noted that NASA had little ability to directly influence the activities of the instrument subcontractors [I7, I10, I28, I39, I52]. As shown in Figure 38, once the prime contractor was selected, it assumed full authority and responsibility for the program's instruments: the government severed its contracts with sensor vendors and Northrop issued new subcontracts in their place. Interviewees noted that not only did the new organization eliminate the government's direct contractual authority over its sensor vendors, but it also reduced their insight into the instruments' development activities [I07, I10, I28]. As described by one interviewee: "It's very unusual for a government customer to try to manage a subcontractor. It's normally not done at all because you run the risk of messing things up with the prime contractor. So the curtain kind of went down a bit" [I10].

While the prime's management of its subcontracts was consistent with the program's contract structure, as noted in Chapter 5, it was philosophically at odds with NASA's historic approach to system acquisition. Specifically, while a NPOESS's performance-based contract vested a significant amount of authority and responsibility in a program's contractors, NASA tended to work "shoulder-to-shoulder" [I17] with its contractors and to develop its systems collaboratively with industry [I10, I17, I38]. Because NASA's preferred approach was at odds with the IPO's contract and the agency needed to insure that its climate science mission was being appropriately executed, mid-way through Epoch D, NASA managers began to explore alternate mechanisms for influencing the instrument development process.

Ultimately, NASA engineers were able to influence the instrument process informally after they established technical credibility with their counter-parts in the IPO, Northrop, or its sensor vendors [I24, I28]. For example, NASA's engineers actively participated in Raytheon's post-CDR VIIRS redesign and made multiple recommendations that were heeded and praised by the program. Shortly after gaining this credibility, NASA embedded its own technical team on-site at Raytheon and used this team both to assist and to influence VIIRS' subsequent development [I9, I24, I28, I39]. With teams like these embedded in the IPO and its contractors, NASA gained increased visibility into the contractors' development processes.

Importantly, gaining greater visibility into the contractors' activities did not immediately insure that their management would follow NASA's preferred processes or prioritize NPP's climate science mission over risk reduction. To accomplish this, NASA needed to influence the organization's decisions or elevate disputed decisions to program management for further arbitration. NASA's ability to take both of these actions was enabled by the misalignment of authority, expertise, budget, and responsibility that are discussed below.

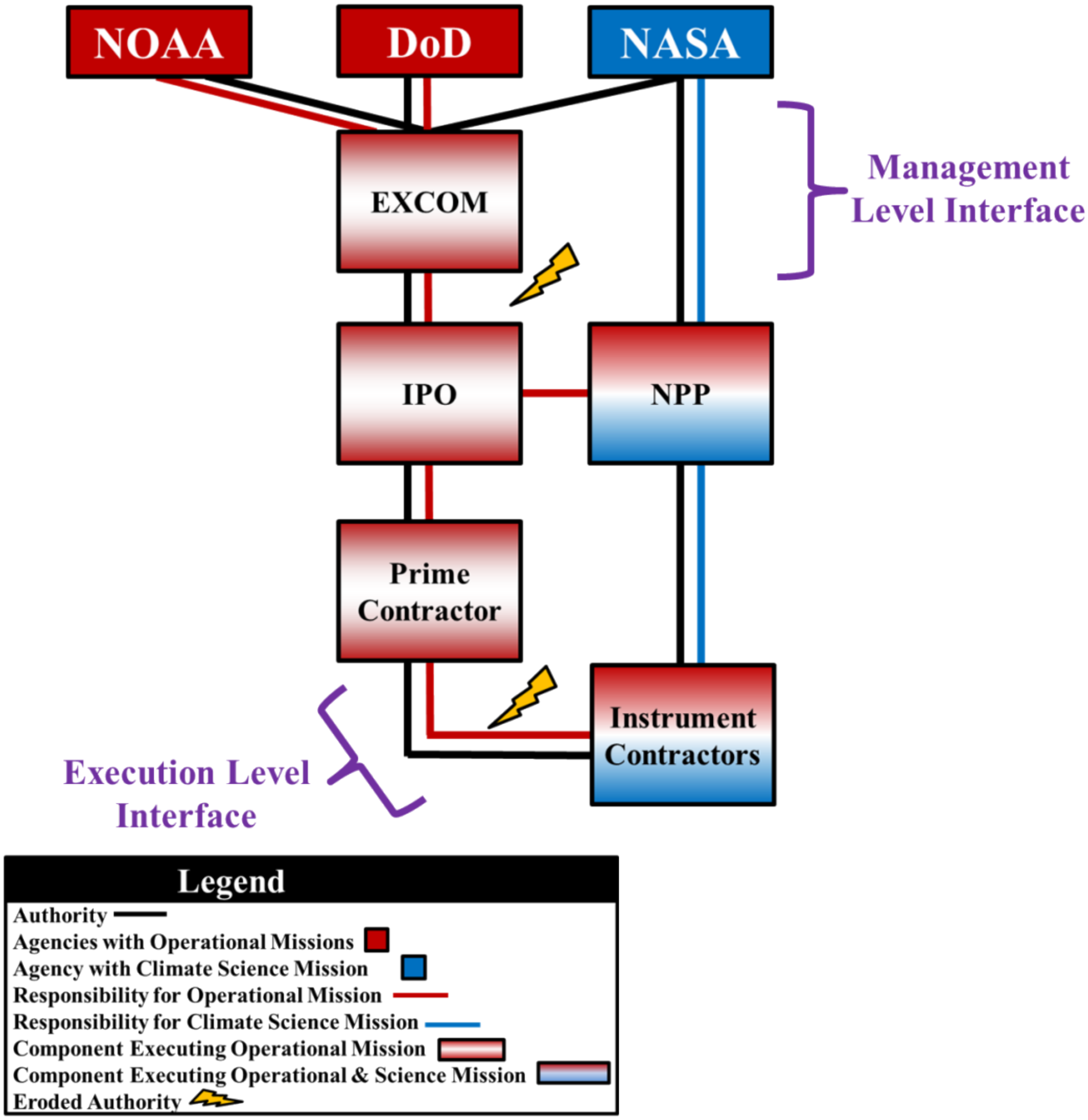


**Figure 38: NPP's Interfaces to the IPO**

### 6.4.1.2 Misaligned Expertise and Authority

Although the technical expertise provided by NASA's NPP engineers did add value to the system development process, it also increased its costs by misaligning expertise and authority. As shown in Figure 39, NASA's additional source of expertise was not aligned with its contractual authority over the instruments and this misalignment enabled process complexity by:

- Establishing a mechanism for NASA to increase the government's oversight of the contractors to a level consistent with the agency's preferred management approach but inconsistent with (and more costly than) the program's original acquisition strategy,
- And by creating an organizational interface by which NASA could request new requirements.

In the first case, once NASA gained technical credibility with the program's other engineers, it used its demonstrated expertise to influence development processes and to make them increasingly compatible with NASA's preferred, more costly, governance model. In the second case, NASA's established technical credibility enhanced the agency's ability to request new and costly requirements through official organizational mechanisms. For example, the request that the ground system save all intermediate data products originated at the working level, where NASA representatives interacted with their contractor colleagues [I48].

NASA also increased its involvement in formal oversight activities such as the NASA Science Advisory Team and utilized its insight into the contractors' development processes to enhance and enforce its recommendations. For example, one interviewee described the interaction between NASA's Science Advisory Team and the NASA engineers monitoring VIIRS' progress as: "This is where NASA enlarged its role. [Raytheon Santa Barbara] didn't expect to have this presence. They thought that the manager at Santa Barbara would talk to the [Northrop] instrument manager and he would report to his management and his management would tell the IPO that everything is ok. Problem comes up, they propose solutions and he decides. The problem is that you have these onlookers who are technically pretty savvy." [I39]. The same interviewee went on to note that because NASA's "onlookers" were in synch with its Science Advisory Team, the agency was able to influence the development process by immediately noticing problems, proposing corrective actions, and aiding in their implementation [I39, D148]. Again, although NASA's increased influence did add value to the development process, the level of oversight and process control that the agency's requested added process complexity and cost to the program.

Importantly, NASA's technical presence also induced non-technical cost growth by:

- Slowing the decision making process by second-guessing decisions [D195] and inducing technical "swirl,"
- And by stalling progress by elevating unfavorable decision outcomes to agency management for further arbitration.

Essentially, NASA's enhanced technical presence confused the lines of authority between the IPO, Northrop, and Northrop's subcontractors [I4, I9, I24, I38, I39] and hindered the program's ability to adjudicate requirements conflicts. Interviewees noted that NASA's technical experts often held different opinions than the IPO's and that as a result, the government did not act as a unified customer that was capable of directing its contractors' activities [I9, I24]. Others noted that as a result, technical decision making tended to "swirl": instead of making crisp, concrete decisions, technical managers on the program invested a significant amount of time considering the disparate options proposed by the NASA and IPO engineers [I24, I38]. Of course, by delaying technical decisions, this "swirl" induced cost growth by extending the time that the program's marching army was paid but not progressing.

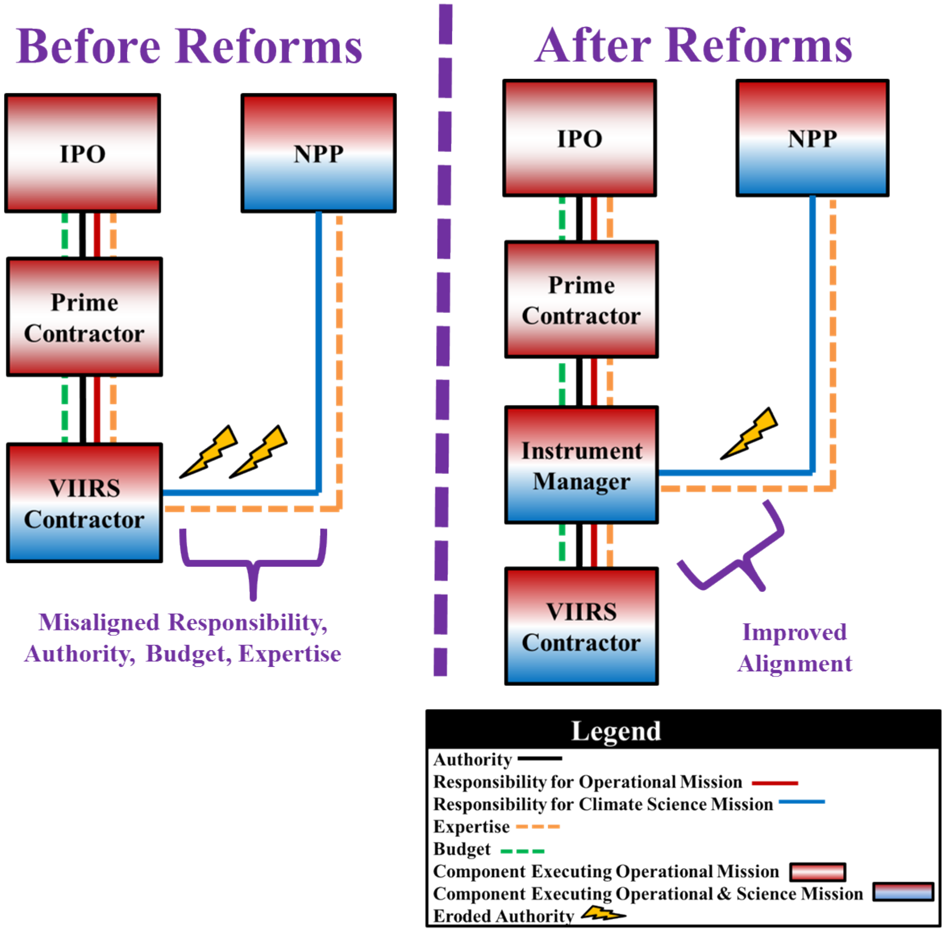


**Figure 39: Authority Erosion at Instrument Contractors, Before and After Organizational Reforms**

If consensus over requirements conflicts could not be reached at the working level, technical decisions were further delayed as issues were elevated through each organization's management chain [I5, I6, I9]. This process was particularly cumbersome because both the IPO and the NPP program office maintained separate system engineering teams; as one interviewee noted: "You had two system engineering teams involved, and…for the instrument side, only one side was paying for the instruments so you had one side versus the other. So it was very slow process. Instead of having one system engineering team look at the problem, you had to get agreement between two groups. They have different interests so it was a very slow and inefficient process" [I5]. Importantly, as was noted above, NPP and the IPO's only mechanism for resolving technical disagreements at the working level was through the EXCOM [I29, I46]. As a result, after unresolved issues were briefed through both programs' management hierarchies, final authority rested with the agencies' representatives to the tri-agency board.

During Epoch F, both NPP and IPO program management took proactive steps to correct these organizational flaws. For example, to combat the technical swirl that was plaguing the VIIRS development process, the IPO and NPP jointly assigned a single instrument manager to make unilateral decisions on behalf of both programs [I5, I9,]. Interviewees reported that once this government manager was deployed on-site at the Raytheon development facility, the contractors' performance increased since decisions could be made on-site and implemented immediately [I5, I9]. Similarly, after CrIS experienced a vibration failure during testing, engineers overcame their organizational impediments by forming a joint failure review board composed of IPO, NPP, and contractor representatives. Interviewees reported that this joint board was more efficient and effective than two separate teams because it engaged all interested parties throughout the decision making process [I5, I28].

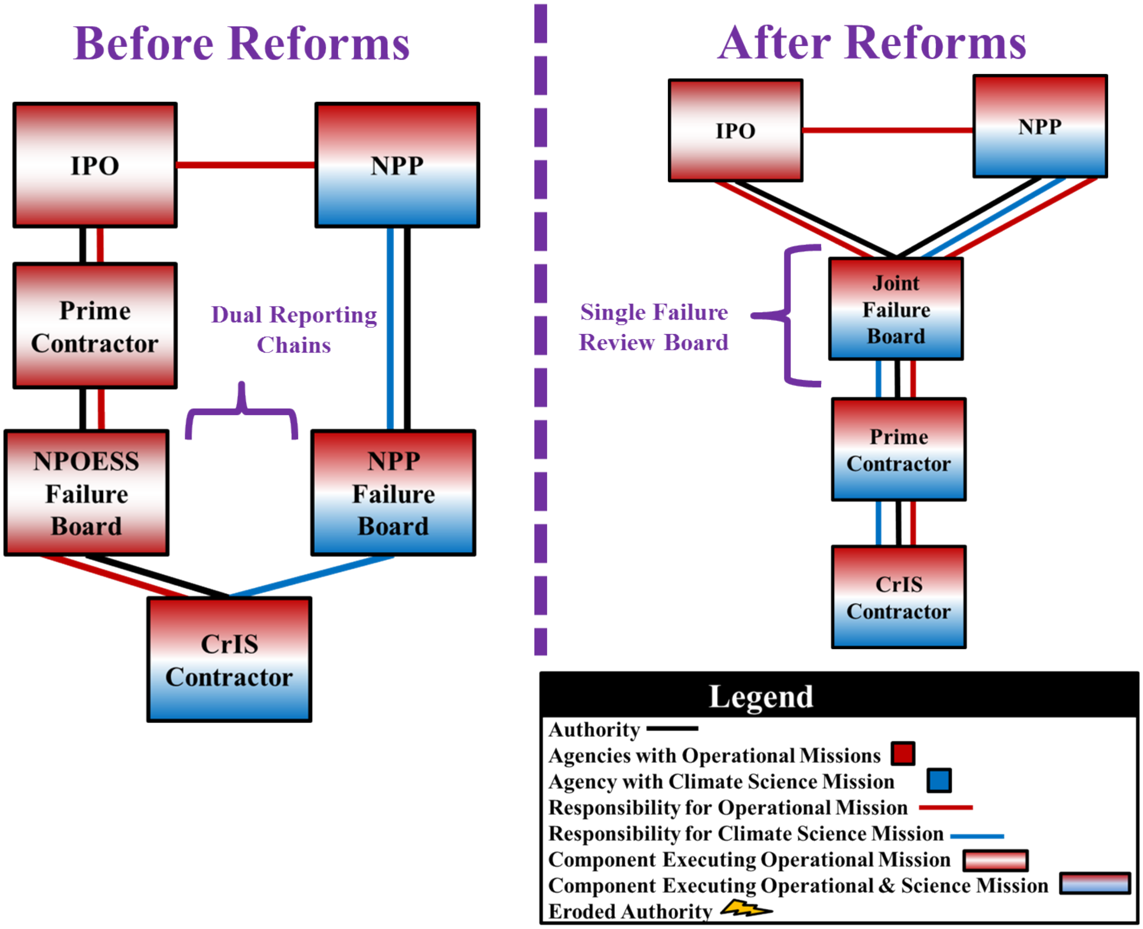


**Figure 40: Authority and Responsibility Misalignment at Failure Review Boards, Before and After Reforms**

Figure 40 illustrates the program's official and inefficient organizational architecture and how program engineers organically worked to overcome its impediments. As shown, once a single government point of contact was assigned to VIIRS and a single failure review board was established for CrIS, authority and expertise in the government were aligned. Of course, the fundamental misalignment—between responsibility and authority—was not corrected by these informal changes, nor was misalignment between responsibility and budget that is discussed in the next section.

### 6.4.1.3 Misaligned Responsibility and Budget

When NASA engineers disputed the IPO's decisions and raised their concerns to agency management for arbitration, the elevation and EXCOM decision making process was slow and arduous. Interviewees noted that NPP engineers often accepted this delay because they held mission but not budget responsibility for NPP's instruments [I5, I13, I18, I46] and therefore, did not incur the cost of waiting for an EXCOM decision or of choosing a more risk-averse and expensive decision option. As described by one interviewee: “Payload Unit #1 was being built by the IPO but it was going to fly on that NASA spacecraft. So you could have an IPO director saying we’re going to take Path A and accept this risk and go forward. Then you have a NASA NPP Project Manager saying, ‘Unacceptable. I won’t accept that risk on my program.’ So those decisions would get kicked all the way up to the EXCOM for resolution, which often took a really long time ” [I29].

Because NASA had mission but not budget responsibility for NPP’s instruments, the primary metric that it used to assess instrument development was risk, not cost. As a result, if any contractor activities diverged from its agency-specific development processes or prioritized the program’s risk reduction mission over its climate science one, NASA interpreted contractors’ actions as posing a risk to NPP’s climate science mission [I5, I9, I25, I26, I29]. One interviewee described how the misalignment of budget and responsibility affected NASA’s approach to approving waivers for the NPP instruments: “From the NPP side, they were not paying for the instruments so they could only see the risk. So there was no reason for them to recommend an exception to a waiver, because they only see the risk, there is no cost or schedule impact to them” [I5]. The same interviewee went on to note that the separate NPP and IPO system engineering teams hindered the program’s ability to appropriately balance cost and risk: “Having a single integrated team would have meant that the group would have been able to make better judgments on if we were going to accept this risk or not.” [I5].

The NPP program management *was* able to make better judgments when its mission and budget responsibility were aligned for its management of the NPP spacecraft. In fact, interviewees noted examples where NPP management waived mission assurance requirements or quickly resolved test anomalies on the NPP bus but were unwilling to make similar compromises for less severe issues that affected the IPO’s instruments [I18, I46]. Interviewees speculated that NASA’s different management approaches for the spacecraft and instruments were derived from the fact that NASA funded the bus but not the instruments [I18, I46].

### 6.4.2 Management-Level Interface

The management-level interface between NPP and the IPO suffered from the same misalignments discussed above and was also directly impacted by the execution-level interface, which enabled engineers to raise issues to management for arbitration. As noted previously, when decisions were raised, the only organizational component with authority over both NPP and the IPO was the EXCOM; the unintended consequences of this organizational construct included:

- The IPO SDP’s authority over the operational system’s baseline was eroded,
- Architectural complexity was enabled because the IPO SDP was forced to prioritize the NPP’s development over the development of the operational NPOESS system,
- And finally, process complexity was enabled and non-technical cost growth was induced because the management-level interface provided a mechanism for NASA to establish tighter control of the system’s development process and to elevate their concerns to the EXCOM.

The first unintended consequence of NPP’s interface to the IPO was that it eroded the SPD’s authority over NPP’s activities, even those which affected the cost of the IPO’s prime contract. As noted previously, the IPO SPD was supposed to have authority to execute the program’s baseline while the EXCOM retained the authority to change it. However, once NPP was added to the program’s baseline, the

IPO SPD had no authority to alter the dual-program baseline *even if NPP development activities adversely impacted the development of the operational NPOESS system.* As noted by one interviewee; "[the SPD] had no top cover. So if he said, 'no,' somebody was going to come around through some direction and say not so much you're wrong but that you don't have the authority to do that" [I46].

Second, since NPP was scheduled to launch before any of the system's operational components, NPP components were prioritized over operational ones. As a result, when costs began to grow and requests for additional funding were denied, the SPD was forced to execute the program's entire baseline with an inadequate funding profile and this induced architectural complexity as lower priority instruments had their schedules extended and budgets reduced. If the SPD had authority to adjudicate between the operational and the NPP programs' baselines, he may have been able to more optimally distribute funding or to reprioritize operational components to enable their development to continue. Instead, the SPD's authority over the NPP program was eroded by a misalignment of responsibility and authority at the management-level interface between the IPO and NPP.

Figure 41 illustrates how the management-level interface between NPP and the IPO eroded the SDP's authority and how the reforms put in place after the Nunn-McCurdy certification were intended to correct this flaw. Specifically, the PEO position was created so that a single point of contact would have authority over *both* the IPO and NPP. The intent of this position was to allow a single person to adjudicate issues between the two programs and to prevent inter-program decisions from being raised to the EXCOM. As will be discussed in Section 6.5, these reforms were undone during Epoch F.

Finally, the interface also provided a mechanism for NASA to inject process complexity. Specifically, when requirement conflicts could not be adjudicated at the working level, they were raised to the EXCOM for a decision. Technical issues that were discussed at the EXCOM were primarily those which impacted instrument cost and required the IPO's contracts to be augmented in order to accommodate NASA's requests. Interviewees recalled requests for NASA to peer-review instrument designs, to chair delta-CDRs, or to hold approval authority over instrument test plans [I17, I24, I38]. Again, since requests of this nature were outside the scope of the instruments' contracts, they could not be resolved at the working-level and instead, required contract modifications and increased funding. In the cited examples, NPP engineers and managers briefed their requests for increased authority or process improvements through the NPP program office, GSFC management, and ultimately up to NASA leaders, who brought these issues to the EXCOM for discussion [I17, I24, I38].

### 6.4.3 Additional IPO-NPP Interfaces

Two additional interfaces between the IPO and NPP also suffered from a misalignment of responsibility and authority; specifically:

- The MOA assigned NASA the responsibility to execute NPP mission system engineering but did not award the agency full authority over all components of the system,
- And the MOA also failed to assign authority for the NPP spacecraft-ground interface.

The impacts of these decisions—underestimating process and architectural complexity—are discussed below.

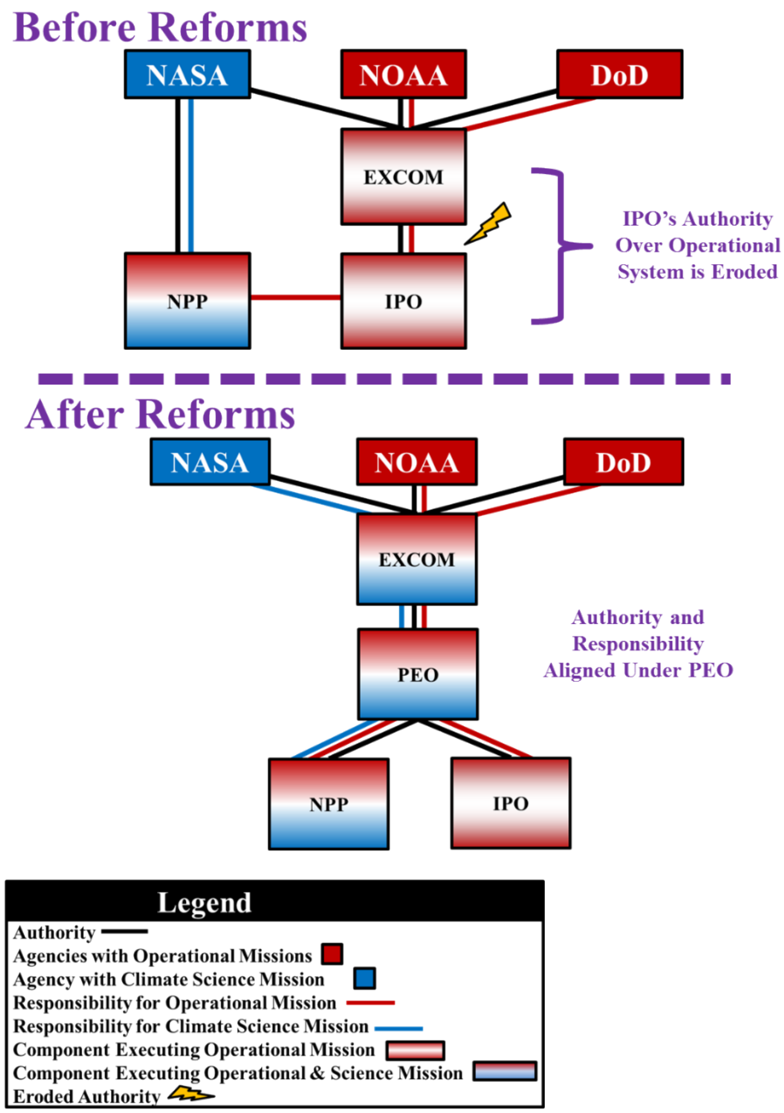


**Figure 41: NPP's Misaligned Authority and Responsibility, Before and After Reforms**

### 6.4.3.1 NASA's Responsibility for Mission System engineering

The MOA that created NPP made NASA responsible for "overall mission system engineering" [D60, D84, D141]. Therefore, even though NASA used IPO-developed components, according to the MOA, it was NASA, and not the IPO, which was responsible for the components' integration into the NPP system and for the successful execution of NPP's dual missions [D141, I23, I28, I31, I33]. To execute this responsibility, NASA followed its typical agency processes for establishing a program office and for applying agency-specific management and system engineering standards [D141]. As discussed in Chapter 5, NASA's standards conflicted with those used on the IPO's contracts and this induced process complexity when engineers had to reconcile different standards during test [I31, I33, I46].

NASA could have eliminated process complexity by accepting IPO-developed components as government-furnished equipment (GFE); however, doing so would have been incompatible with the mission system engineering responsibility that NASA was assigned in the MOA because it placed NASA at risk for improperly executing the NPP mission. Specifically, if NASA failed to verify that all components of the NPP system met a rigorously defined set of engineering requirements, it placed its system at risk for failure [I14, I23, I31, I33]. Since the MOA made NASA responsible for mission system engineering, by extension, NASA was responsible for minimizing, mitigating, and eliminating all risks that threatened the NPP system's ability to successfully execute that mission. As described by one interviewee: "But the NASA side of it is…you hook this GFE up to your bus. It goes up on a NASA booster and you go to turn it on and nothing happens. Who's at fault at that point and whose agency's prestige has just been hurt? And that's that problem with that….they know that their brand name is on there and they can't say on *60 Minutes* or any member of the U.S. public, 'Well it was GFE. We didn't check it out. We just accepted it as it was given to us and put it on orbit.' You get Congress saying, 'NASA how dare you! How could you let down the American people this way?' [I31]. Therefore, had NASA accepted IPO-developed components as GFE and had not verified that they also complied with internal agency standards, the agency would have placed itself at risk for failing to meet the mission responsibility that it was assigned in the MOA.

### 6.4.3.2 Authority for the NPP Spacecraft-Ground Interface

The MOA also failed to assign authority for the NPP spacecraft-ground interface and as discussed in Chapter 5, this enabled architectural complexity to be underestimated. As illustrated in Figure 42, a misalignment of authority and responsibility created this situation. As shown, Northrop held overall responsibility for the NPOESS operational mission and authority over the ground system subcontractor, Raytheon. Given this configuration, Northrop had final authority over the interface between Raytheon's ground system and its NPOESS spacecraft and it defined this interface in a Northrop-controlled interface control document [I29, I30, I47].

As also shown in Figure 42, NASA had authority over NPP's spacecraft contractor, Ball, and its spacecraft-ground interface control document [I29, I30, I47]. The challenge, of course, was that both interface control documents had to be reconciled to insure that the Northrop-Raytheon ground system properly interfaced with the NASA-Ball spacecraft. Complicating this challenge was the fact that neither the spacecraft nor the ground system contractors had contractual relationships with one another and that Northrop retained authority over Raytheon; one interviewee described the organizations' relationship to the interface as: "Everybody had a piece of it so no one, in reality, was completely in charge of it" [I29].

Absent a single organization with authority, *all* organizational components that "had a piece" of the NPP spacecraft-ground interface had to be involved in its definition. As a result, the same interviewee noted that to make any decision regarding this interface, all parties had to participate: "you could never have a meeting without all four or five parties in the room" [I29]. Since this meeting structure was cumbersome and neither Northrop nor Ball had this interface definition process included in their original statements of work, it induced cost growth both for the IPO and for NASA's NPP program office [I29, I30]. Despite the organizational impediments to efficient interface definition and the cost growth that it induced, the engineers and managers involved were able to define a successful (and currently operational) interface. As summarized by another interviewee "We worked within the structure that was set up as best we could. We did a pretty good job…there were very few escapes...but it was very inefficient" [I30].

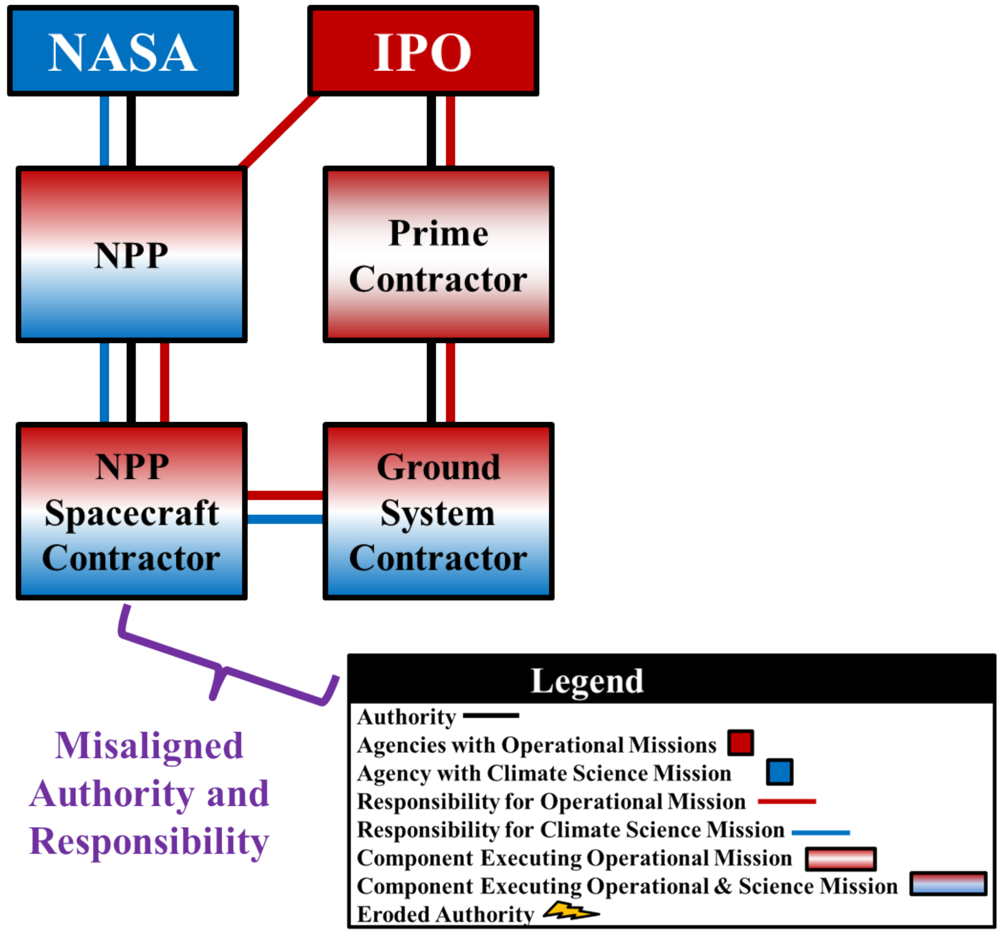


**Figure 42: Misaligned Authority and Responsibility and NPP Spacecraft-Ground Interface**

Even after the interface itself was defined, the lack of clear authority made testing the interface inefficient. Two interviewees recalled the challenge of developing a ground-link simulator and noted that although all involved parties agreed that the simulator was necessary, since no single party had authority, it was unclear who should lead and fund its development [I31, I47]. One of the interviewees described the delay that resulted as: "It took me three months of figuring out ***who*** was going to pay for us even though there was no technical dispute that it was needed. What contract it should be on…we had to go to the prime contractor, Northrop, even though it was a Raytheon provided item and get Northrop to be willing to free up their funds because they had all the money from the program office to do this. It took me three months to get something that was absolutely on the critical path to launch." [I31] As noted by [I31], the organizational architecture surrounding the NPP spacecraft-ground interface made testing this interface unnecessarily time-consuming, inefficient, and costly.

## 6.5 Action 5: Enhance NASA's Role

After the Nunn-McCurdy certification, a PEO position was created and assigned the responsibility of jointly managing NPP and NPOESS. As discussed above, the addition of the PEO *aligned* responsibility and authority between the separate program offices, the EXCOM, and NASA's management of NPP. However, during Epoch F, NASA and NOAA NESDIS eroded the PEO's authority [I18, I33, I46, D145, D195] and as a result:

- The PEO's authority was not commensurate with his responsibility (i.e. authority and responsibility were misaligned),
- And the misalignment of authority and responsibility enabled process complexity.

NESDIS eroded the PEO's decision authority in several ways. First, interviewees noted that NESDIS used the performance evaluations of the PEO as a mechanism to influence his actions and attributed the resignation of several PEOs during Epoch F to the unfavorable evaluations that they received from their NESDIS managers [I18, I33, I46]. Specifically, these interviewees noted that when the PEO took actions that were unfavorable to NESDIS, they were penalized through their performance evaluations as NOAA employees. Second, a 2008 independent review of the program noted that although the PEO was supposed to chair a program management council composed of representatives from all three agencies, NESDIS had established and was chairing a separate program management council [D145]. This hindered the PEO's ability to interact with agency representatives [D145] and thus, to make decisions that effectively balanced their needs.

NESDIS's erosion of the PEO's authority enabled process complexity because it coincided with NASA's enhanced management role in the program: as noted in Chapter 4, in 2007, NOAA replaced its head of NESDIS, the NOAA Administrator for Satellite and Information Services and created a new deputy position to support the administrator [D122, D80]. Both positions were filled by NASA career civil servants who had spent their previous careers working at NASA Headquarters or at GSFC, NASA's home for NPP [D122, D80]. Therefore, when NESDIS officials undermined the PEO's authority, their actions often supported the prioritization of NPP's climate science mission which was of critical importance to NASA GSFC [I18, I26, I46].

Interviewees recalled that if an anomaly was discovered on an NPP instrument during test and the IPO did not implement NASA's resolution, NASA, throughNESDIS, would bypass the PEO's ability to make cross-program decisions and would raise the issue to the EXCOM [I18, I33, D148]. In particular, despite the PEO structure that was in place, during Epoch F, NASA raised two major issues to the EXCOM regarding the NPP VIIRS' ocean color performance and the risk associated with its launch locks [D195]. If the PEO held the authority equal to his responsibility, he should have been able to resolve both of those issues without involving the EXCOM; instead, the PEO was unable to prioritize NPP's risk reduction mission. As a result, the cost growth induced by NPP's conflicting missions persisted in Epoch F.

Interviewees also recalled instances that did not involve raising issues to the EXCOM but similarly illustrated how NESDIS and NASA weakened the PEO's authority. In the cited examples, the PEO was unable to make a unilateral decision to approve the shipment of the VIIRS and CrIS instruments to the NPP program. In the case of CrIS, an electronics issue motivated rework after the instrument had already completed testing [I33, I46]. Although analysis demonstrated that the instrument's performance was not impacted, the NPP program office requested that the contractors repeat a full performance test over temperature [I33, I46]. While a compromise position was eventually found, the several month schedule slip that resulted could have been avoided if the PEO held decision authority over NPP. Instead, interviewees noted that the PEO had to placate the NPP program office because had he not, the NPP program could have refused to accept the CrIS instrument that the IPO delivered [I33, I46].

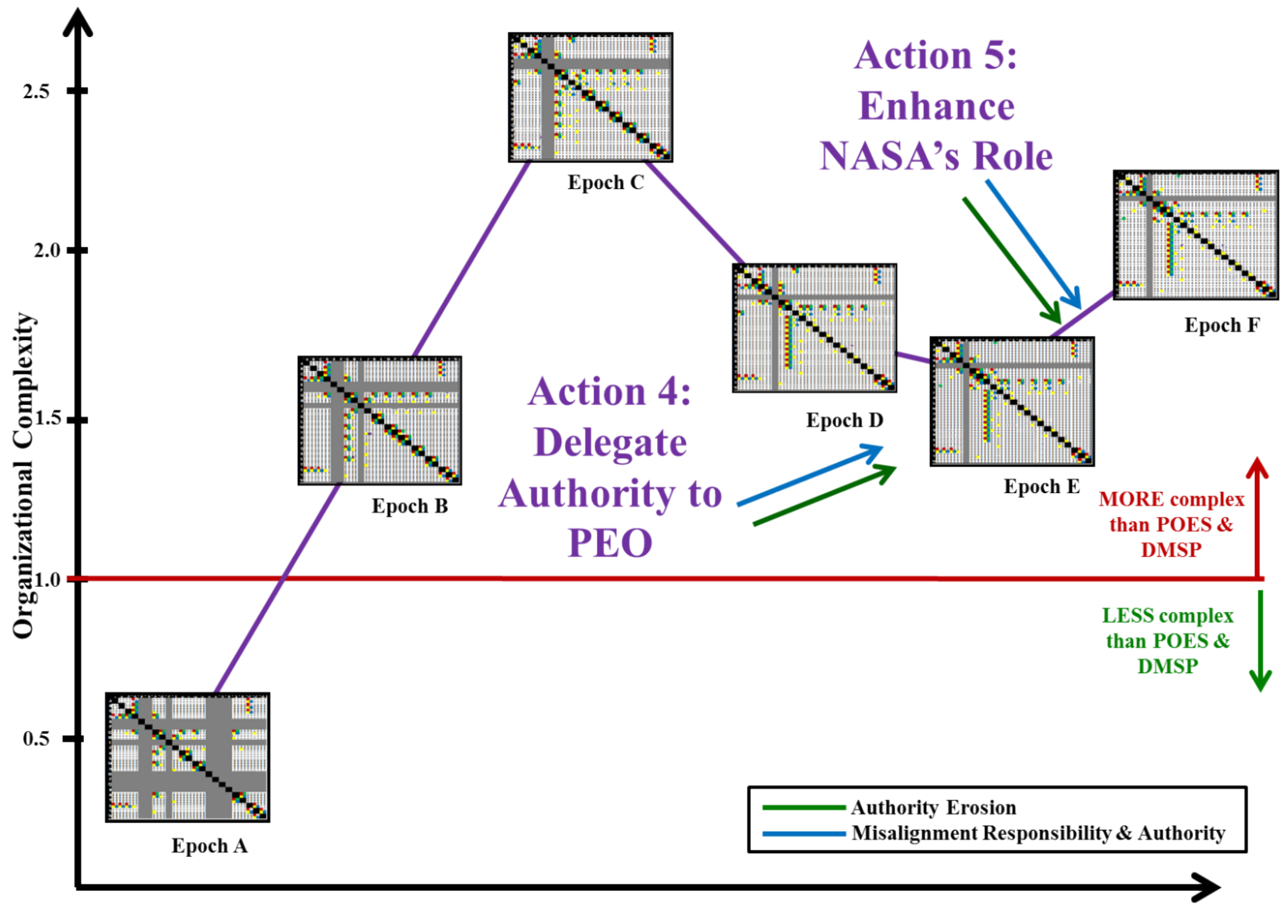


**Figure 43: Complexity Impacts of Action 5**

The NPP program office actually did refuse to accept the shipment of VIIRS after their quality assurance officer discovered an analysis showing that VIIRS failed to meet an end-of-life timing requirement by several nanoseconds [I46]. Even though NPP was partially a risk reduction mission, NASA quality assurance refused to accept the VIIRS instrument for weeks, while the contractors performed additional analysis to satisfy NASA's end-of-life timing requirement [I33, I46]. In this example, the PEO had no authority to direct NASA to accept the VIIRS shipment and instead, had to allow the shipment to be delayed until NASA was satisfied. Importantly, it was the contractors and by extension the IPO, who paid for this analysis and for all of NASA's other requests for additional testing on the NPP instruments.

NESDIS's erosion of the PEO's authority also induced additional process complexity during Epoch F because it allowed NESDIS to play a greater role managing the program's daily activities. Interviewees cited the program's information assurance requirements as an example of NESDIS's increased role during Epoch F. Specifically, NESDIS wanted the contractor to add additional security controls for information assurance and although the DoD did not require higher controls, NESDIS directed the IPO to perform multiple trade studies exploring options to increase the system's security [I18, I33]. Although all security increases had cost impacts that would require approval by the EXCOM, NESDIS went directly to the IPO with its request and bypassed the EXCOM [I18, I33].

A final example illustrating how NESDIS's influence enabled cost growth comes from the operational system's mission CDR. NASA's relationship to NESDIS strengthened its presence and role in the operational program and as a result, the CDR was co-chaired by a representative from the Aerospace Corporation *and* a representative from NASA GSFC [I5, D158]. With this formalized presence in both NESDIS and the operational mission's CDR, NASA was able to levy several liens and requests for action that interviewees described as non-technical and non-value added [I26, I31, I46]. As discussed in Chapter 5, resolving these liens and closing action items induced process complexity because it created additional work for the IPO, which had to resolve conflicting requirements and then track and bring each item to closure. More importantly, according to the MOA that established the NPOESS program. NASA's role in the operational system was technology transition not program management, a role that had been assigned to NOAA [D60]. However, through NASA's relationship to NESDIS, NASA was able to increase its program management role and to authorize the liens that were placed on the operational mission's CDR.

## 6.6 Conclusions and Motivation for Upcoming Chapter

This chapter used the quantitative framework to observe that complexity was injected into the NPOESS organizational architecture during the program's early years and that high levels of organizational complexity persisted throughout the remainder of the program. Using the framework, I also identified five actions that affected the program's complexity and presented detailed qualitative evidence that described how complexity impacted the effectiveness and efficiency of the program's decisions.

In summary, the organizational complexity mechanisms that affected the NPOESS program's decisions included:

<u>**Contract Structure**</u>

1) **The IPO's performance-based contract limited the government's authority to request changes to contractor's designs and development processes without incurring the additional cost of a contract change.**

<u>**Ineffective Delegation of Authority**</u>

2) **The EXCOM was an ineffective mechanism for decision making.** Because the EXCOM met infrequently, it was slow to make decisions. Even when the tri-agency committee did meet, it often delayed making a decision or could not make a decision because it lacked a quorum of members. This enabled architectural complexity because delayed decisions induced cost growth. Importantly, the EXCOM was never intended to be the program's primary decision making body and the role that it served during the NPOESS program is indicative of a larger flaw in the program's organizational architecture.

<u>**Misaligned Authority and Budget**</u>

3) **By extending the length of time prior to sensor vendor down-selection, the NPOESS program also extended the period of time during which contractors' cost estimates were optimistic and focused on winning the final contract rather than identifying and managing instrument design complexity.** During the extended competition period, both the climate science mission and IORD-II requirements were aggregated onto the program. Because sensor vendors were still in competition when new requirements were added, they reported that the new

requirements would minimally affect their proposed designs, costs, or schedules. It was not until after the vendors were placed on contract that they began to fully recognize, report, and manage the design complexity induced by these new requirements.

**Misaligned Authority and Expertise**

4) **The IPO did not contain the amount of in-house technical experience that was contained by larger institutions like NASA GSFC or the Aerospace Corporation.** This hindered the IPO's ability to recognize and to manage the design and architectural complexity that was induced by the program's requirements.
5) **The IPO's contracts were managed by Air Force officers who did not fully capitalize on the in-house technical expertise that was available within the IPO.** Again, this enabled design and architectural complexity to be underestimated and under managed during the program's early epochs.
6) **The technical assistance that NASA's NPP engineers provided to the joint NPP-NPOESS instruments and algorithms enabled process complexity by providing NASA with a mechanism to request new requirements.**
7) **NASA's NPP engineers also induced non-technical cost growth by second-guessing contractor and IPO decisions and by inducing decision "swirl."**

**Misaligned Responsibility and Budget**

8) **NASA was responsible for NPP's climate science mission but did not provide any budget for VIIRS, OMPS, and CrIS. This misalignment of budget and responsibility caused NASA to inappropriately balance risk vice cost.** Ultimately, this misalignment induced process complexity when NASA preferred decision options that minimized risk, while the IPO, which had to pay for decision outcomes, preferred options that more equally balanced cost and risk.

**Misaligned Responsibility and Authority**

9) **Because agencies shared authority over the NPOESS system, decisions were made by consensus.** As a result, each agency was able to levy the requirements which insured that the system would execute its unique mission. Each agency was also able to veto any attempts to reduce the system's capability to execute that mission. Both design and architectural complexity were enabled as a result.
10) **Although the agencies delegated their independent authority to be shared at the EXCOM, they retained their responsibility for the program and continued to independently oversee it.** Because any recommendations made by independent overseers had to be implemented collaboratively by the EXCOM—and ineffective venue for decision making—agency oversight of the program failed to add value and instead detracted program staff from their work.
11) **The "Optimized Convergence" strategy enabled architectural and design complexity by assigning total system responsibility to a prime contractor but delaying the selection of that prime contractor until Epoch D.**
12) **By delegating "mission system engineering" responsibility to NASA and not the IPO, the NPP MOA enabled process complexity by motivating NASA to levy its own engineering standards on NPP's components that were developed by the IPO according to DoD standards.**

13) **When requirements conflicts between NPP and NPOESS could not be resolved at the working level, they had to be raised to the EXCOM. The EXCOM was the only organizational component with decision authority over both NPP and the IPO.** Raising decisions to the EXCOM induced non-technical costs by hindering the efficiency with which the program could make decisions.
14) **The NPP MOA failed to delegate decision authority over the NPP-NPOESS spacecraft-ground interface.** By omitting this interface, the MOA underestimated the cost of architectural complexity and induced organizational complexity, when multiple organizational components had to be involved in a simple interface's definition.
15) **The PEO structure reduced the misalignment of decision authority and mission responsibility and had the potential to reduce the process complexity induced by the NPP program.** The PEO structure delegated authority over NPP and NPOESS to a single decision maker who could be more responsive to the needs of both programs and who could more effectively and efficiently adjudicate requirements conflicts between them. Without the PEO, process complexity was sustained as the program's decisions typically prioritized the NPP system over the development of operational one.
16) **NASA's increased role in the program's management during Epoch F eroded the PEO's authority and enabled process complexity.**

Ultimately, the data that I collected on the NPOESS program emphasized the critical role that a program's organizational architecture has on its ability to effectively and efficiently manage a system's development. In particular, I observed that the misalignment of authority, responsibility, expertise, and budget to hindered NPOESS's ability to make decisions and noted that these misalignments existed both between agencies and between the NPOESS organization and its system. In Chapter 8, I use this NPOESS data to motivate a general model that explains cost growth on joint programs and suggests that ultimately, cost is induced by misalignments between agencies and between joint organizations and the systems that they manage.

# 7 The Cost of Environmental Monitoring in Low Earth Orbit

> *The major challenge of NPOESS was jointly executing the program between three agencies of different size with divergent objectives and different acquisition procedures. The new system will resolve this challenge by splitting the procurements. NOAA and NASA will take primary responsibility for the afternoon orbit, and DoD will take primary responsibility for the morning orbit. The agencies will continue to partner in those areas that have been successful in the past, such as a shared ground system. The restructured programs will also eliminate the NPOESS tri-agency structure that that has made management and oversight difficult, contributing to the poor performance of the program.*
>
> –The Presidential Decision Directive that Cancelled NPOESS, 2010 [D175]

This chapter serves two purposes. First, it presents analytic histories of the JPSS and DWSS programs' technical and organizational architectures. Second, it presents a cross-case comparison of complexity mechanisms and identifies mechanisms that were shared or unique across the three case studies. Again, using the quantitative framework defined in Chapter 3, I first represent DWSS and JPSS's technical and organizational architectures and observe how their complexity compared to NPOESS. I also review the types of complexity mechanisms that affected JPSS and DWSS and compare those to the hypotheses that originally motivated my research. Next, I review the qualitative data from JPSS and DWSS that was used to identify and compare complexity mechanisms, to create the DSMs, and to calculate the metrics. I continue with a more detailed discussion of the complexity mechanisms that were unique or shared across case studies and use this to motivate Chapter 8's general model that explains cost growth on joint programs.

## 7.1 Evolution of Complexity

Unlike my investigation of NPOESS, which spanned 16 years and six epochs, my study of DWSS and JPSS was limited to a single two-year epoch. Several reasons motivated the decision to study these programs for a shorter period of time:

- First, my study of the DWSS was limited by the program's cancellation, which occurred less than two years after it was formed.
- Second, to keep my comparison with JPSS consistent with DWSS, I studied the JPSS program for approximately the same period of time.

- Finally, JPSS is a current program of record and as a result, interviewees were justifiably hesitant to discuss the program's present activities or those that occurred in the recent past.

Despite studying these programs for less time and in less detail than NPOESS, as plausibility probe cases, the data from JPSS and DWSS were invaluable. In particular, the case studies:

- Enabled me to refine my understanding of complexity and to define complexity mechanisms more generally,
- Allowed me to continue observing the evolution of complexity and in particular, to observe how complexity was impacted by the policy directive that cancelled NPOESS,
- And provided comparison case studies to "test" of the starting hypotheses that motivated this research.

The remainder of this section provides greater detail on the role that the plausibility probe cases played in understanding the cost of jointness.

### 7.1.1 Applying the Framework

The technical and organizational DSMs for JPSS and DWSS were calculated in the same way as was done for NPOESS. As before, the technical DSM contained spacecraft, instruments, and ground processing systems but the metric itself focused on the complexity-corrected cost of the space segment. Again, the technical complexity metric included non-recurring, recurring, and launch costs and was normalized by the complexity of the same systems prior to convergence. As with the complexity-corrected cost of the pre-convergence systems, I assumed no commonality between the DoD and NOAA programs. Although JPSS and DWSS intended to use the same VIIRS instrument, I included VIIRS non-recurring costs in both programs to capture a more realistic cost of divergence (i.e. the cost when two non-joint programs develop similar instruments). Finally, as with my analysis of NPOESS, the complexity metric for JPSS and DWSS did not account for the benefit delivered by either system; in fact, although their costs grew during Epoch G, both programs' capabilities decreased relative to NPOESS.

The organizational DSMs and complexity metrics were calculated similarly as well. The JPSS organizational architecture included separate program offices for NOAA and NASA, GSFC management, the Joint-Agency Satellite Division (JASD), and the program's user community. Contractors for the spacecraft, algorithms, ground system, leveraged sensors, and CrIS, ATMS, OMPS, and VIIRS were also included.

The DWSS organizational architecture included a DWSS program office, an Air Force PEO for Space Systems, a separate user community, and the spacecraft, VIIRS, CMIS, and leveraged sensor contractors. The DSMs also captured residual relationships between the programs that persisted in Epoch G; as will be discussed below, the programs continued to interface at the ground system and VIIRS contractors. As with the NPOESS metrics, the organizational complexity metric was normalized by the complexity prior to convergence (i.e. DMSP and POES). Normalizing by DMSP and POES is particularly enlightening because it enables one to observe how the JPSS and DWSS programs differed from the organizations that they were intended to replicate.

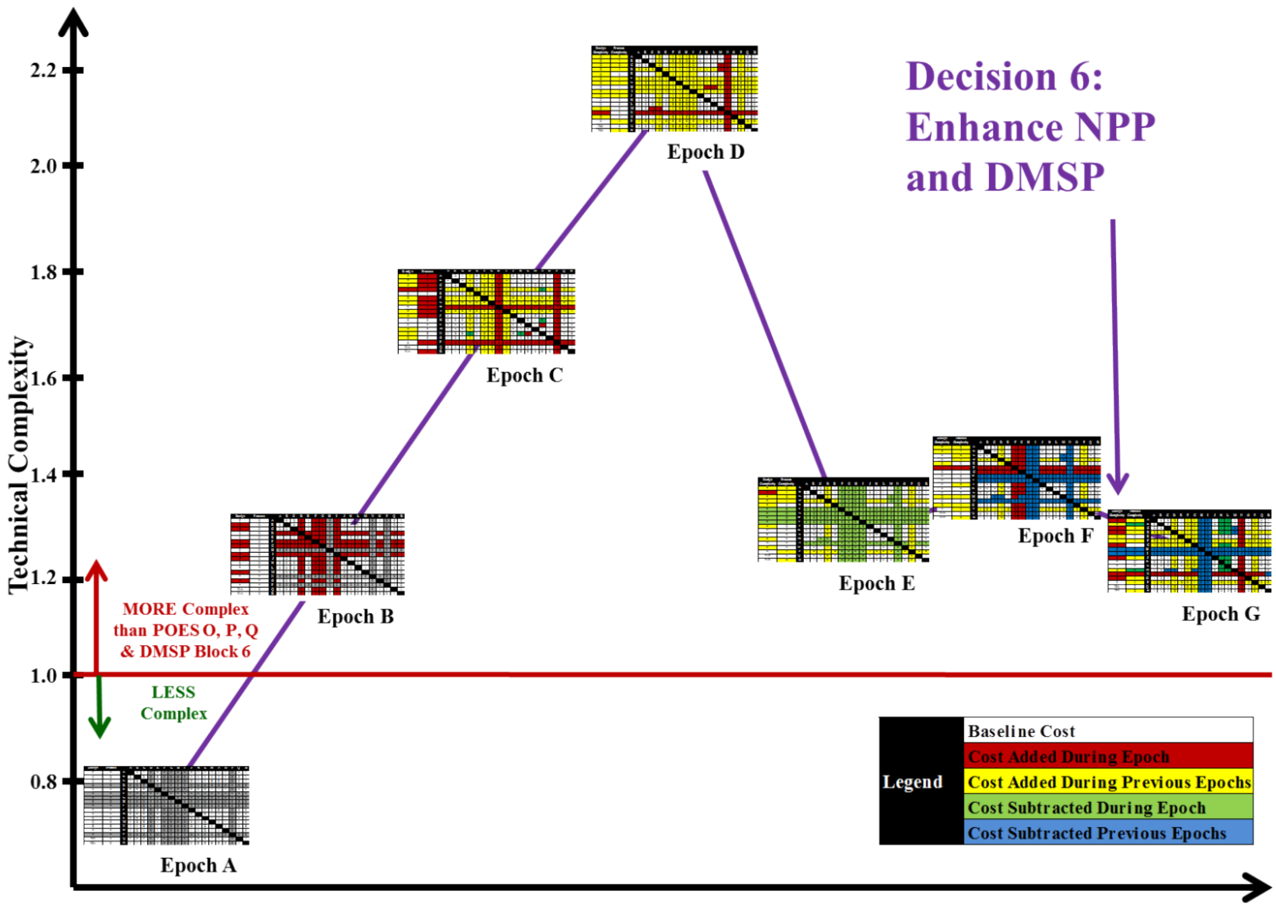


**Figure 44: Complexity Impacts of Decision 6**

### 7.1.2 Observing the Dynamic Nature of Complexity

Figure 44 and Figure 45 illustrate how the complexity of the JPSS and DWSS programs compared to the NPOESS program that preceded them. As shown, both programs were slightly less complex than the Epoch F NPOESS program but still contained more complexity than the pre-convergence DSMP and POES programs. Primary drivers of persistent technical complexity included:

- Both programs continued using NPOESS instruments, which were more complex than the instruments planned for NOAA O, P, Q and for DSMP Block 6.
- Both programs had to update their heritage spacecraft buses to accommodate new payload requirements.
- And the JPSS program made additional changes to its instruments and spacecraft.

Primary drivers of JPSS and DWSS organizational complexity included:

- The JPSS and DWSS programs interfaced at the ground system and VIIRS contractors where authority and responsibility were misaligned.

- The separate NOAA and NASA JPSS program offices and the JASD organization that served as an interface between them misaligned authority and responsibility within the JPSS program.
- And finally, the misalignment of responsibility and budget and of authority and expertise persisted on JPSS as well.

Given the complexity that persisted after NPOESS, one can assess that the policy directive to cancel the program was either ill-informed or poorly designed to correct the deficiencies that were contained in the NPOESS organizational and technical architectures: my data suggest it was a combination of the two.

Like the epoch shifts that occurred during the NPOESS program, the policy directive that cancelled NPOESS and formed JPSS and DWSS can be decomposed into an action that affected organizational complexity and a decision that affected technical complexity. Thus, the final action and decision are defined as:

- **Action 6:** Separating NOAA and the DoD's authority over NPOESS and assigning each agency authority over the separate JPSS and DWSS programs.
- **Decision 6:** Enhancing each program's heritage system to serve as its next generation weather satellite system—where heritage for the DoD was DMSP and heritage for NOAA was NPP.

Finally, as with each of the actions and decisions in the NPOESS program, the final action and decision can be mapped to the complexity mechanisms that they induced. Table 6 lists these mechanisms for both the JPSS and DWSS programs.

**Table 6: Complexity Mechanisms Induced by the Final Action and Decision**

| Complexity Type | Complexity Mechanism | DWSS - Action 6 | JPSS - Action 6 |
|---|---|---|---|
| Misalignment | Authority & Responsibility | X | X |
| Misalignment | Authority & Expertise | | X |
| Misalignment | Budget & Responsibility | | X |
| Misalignment | Authority & Budget | | X |
| Authority Erosion | Contract Structure | X | |
| Authority Erosion | Ineffective Delegation | | |
| **Complexity Type** | **Complexity Mechanism** | **DWSS - Decision 6** | **JPSS - Decision 6** |
| Design | Instrument Design Maturity | X | X |
| Design | Spacecraft Design Maturity | X | X |
| Design | Ground Design Maturity | X | X |
| Process | Oversight Requirements | | X |
| Process | Requirements Conflict | | |
| Architectural | Design Relationships | | |
| Architectural | Interferences | X | X |
| Architectural | Programmatic Relationships | X | X |

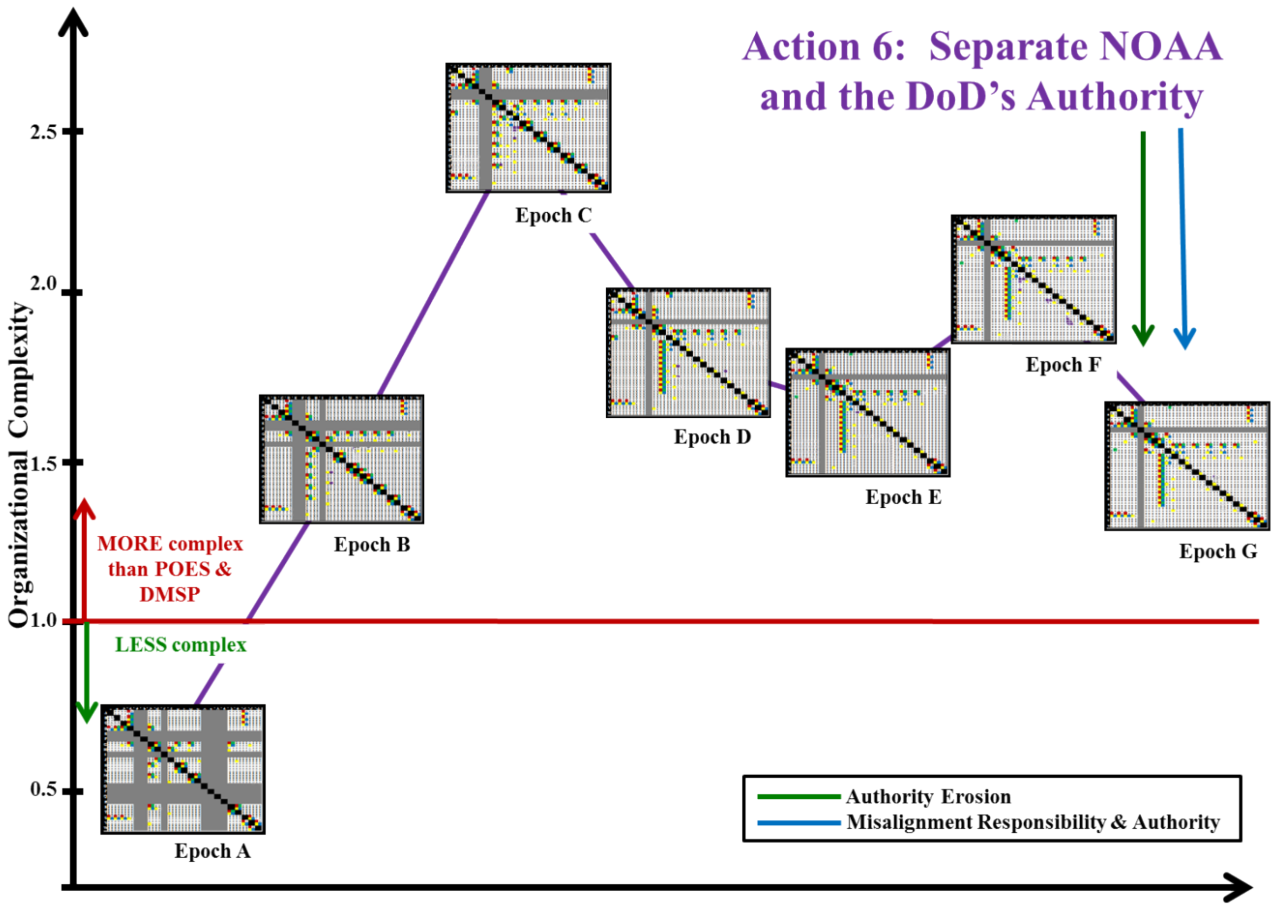


**Figure 45: Complexity Impacts of Action 6**

### 7.1.3 Evaluating the Starting Hypotheses

This research was originally motivated by the hypothesis that technical aggregation induces technical complexity and cost growth and that organizational aggregation induces organizational complexity and cost growth. From these hypotheses, I expected that cost growth on NPOESS (a program that was both organizationally and technically aggregated) would be induced by both technical and organizational complexity. I expected that cost growth on the technically aggregated DWSS program would be predominately induced by technical complexity. Finally, I assumed that cost growth on the organizationally aggregated JPSS program would be primarily induced by organizational complexity.

As shown in the Table 7, the data did not exactly conform to these hypotheses. Specifically, although NPOESS and, to a lesser extent, DWSS did, I observed that JPSS's cost growth was induced by *both* organizational and technical complexity. This finding suggests that when considering cost growth on joint programs, one cannot simply decouple programs' organizational and technical architectures; indeed, Chapter 6 illustrated how closely related both architectures were on the NPOESS program. Therefore, in this chapter, I present the technical *and* organizational complexity mechanisms that I observed on DWSS and JPSS and compare both types of complexity across all three case studies. In doing so, I generate conclusions on the complexity impacts of aggregation versus disaggregation and motivate Chapter 8's discussion, which integrates technical and organizational complexity mechanisms into a more holistic understanding of the cost of jointness.

**Table 7: Complexity Mechanisms on NPOESS, JPSS, and DWSS**

| Organizational Complexity | | | | |
|---|---|---|---|---|
| **Complexity Type** | **Complexity Mechanism** | **NPOESS** | **DWSS** | **JPSS** |
| Misalignment | Authority & Responsibility | X | X | X |
| Misalignment | Authority & Expertise | X | | X |
| Misalignment | Budget & Responsibility | X | | X |
| Misalignment | Authority & Budget | X | | X |
| Authority Erosion | Contract Structure | X | X | |
| Authority Erosion | Ineffective Delegation | X | | |
| **Technical Complexity** | | | | |
| **Complexity Type** | **Complexity Mechanism** | **NPOESS** | **DWSS** | **JPSS** |
| Design | Instrument Design Maturity | X | X | X |
| Design | Spacecraft Design Maturity | X | X | X |
| Design | Ground Design Maturity | X | X | X |
| Process | Oversight Requirements | X | | X |
| Process | Requirements Conflict | X | | |
| Architectural | Design Relationships | X | | |
| Architectural | Interferences | X | X | X |
| Architectural | Programmatic Relationships | X | X | X |

## 7.2 The Costs of DWSS

With the formation of DWSS, the DoD was directed to use elements of the NPOESS technical architecture, to only meet IORD-II requirements that executed the agency's unique mission [I65, D51], and to make the resulting system more affordable [I68, I71, I67, D51]. Pursuant with their emphasis on affordability, the DWSS program explored trades to reduce the system's capabilities [I62, I67, D51] and quickly concluded that, in its given form, the program was too costly; indeed, interviewees cited the programs' persistent high cost as a major motivation for its cancellation [I70, I68, I65, I67]. In the sections that follow, I use the trades that the program conducted to identify the complexity mechanisms contained in the DWSS technical architecture. I also identify the organizational complexity mechanisms that may have affected the program's decision quality, if DWSS had not been cancelled.

### 7.2.1 DWSS Technical Costs

DWSS inherited most of its technical complexity mechanisms from NPOESS, since the instruments, spacecraft, and ground system slated for DWSS were originally developed during NPOESS. DWSS's technical complexity was primarily driven by component design complexity; in particular, the DWSS program:

- Assessed its instrument designs to be too complex and explored trades to reduce their complexity and to focus their capabilities on the DoD's unique mission.

- And assessed its spacecraft bus design to be too complex and costly and explored trades to reduce its cost.

Secondarily, DWSS's costs could have been affected by the architectural complexity mechanisms that were induced by interactions between VIIRS and CMIS [I70, I65]. Since JPSS also planned to procure VIIRS from DWSS's planned vendor (Raytheon), process complexity was also a possibility, since the agencies may have levied conflicting requirements on the instrument. Furthermore, since Raytheon only had one set of VIIRS test equipment, DWSS could have been adversely impacted by its programmatic relationship with JPSS if delays on NOAA's VIIRS induced delays in the DWSS VIIRS's test schedule [D51, D223, I65, I68]. However, since DWSS was cancelled before those complexity mechanisms impacted its cost, in the section that follows, I focus on the design complexity mechanisms which did.

As on the NPOESS program, VIIRS remained one the most costly components of the DWSS system; as a result, it was the focus of several studies which attempted to make the instrument more affordable. However, given VIIRS's highly integrated and "exquisite" [I62] design, DWSS engineers concluded that there were few opportunities to de-scope VIIRS without completely redesigning it [I62, I65]. With this conclusion, the program began exploring alternative instrument designs that would require additional non-recurring investment. Because these alternatives contained fewer channels and had lower performance than VIIRS, the program hoped that they would be less complex and costly and would be better focused on executing only the DoD's mission [I68, I62, I67]. DWSS engineers also explored ways to reduce the cost of MIS by removing its channels [I65] or by replacing it entirely with a smaller sensor [I68, I67]. Similar trades were also performed on SEM [I67]. However, despite these studies, when DWSS was cancelled, none of the trades had been officially implemented.

Like its instruments, much of the design complexity of the DWSS bus was inherited from NPOESS. Specifically, DWSS used NPOESS's bus design but scaled back key subsystems to match its reduced payload requirements [I68, I65, I67, D51]. However, because DWSS still contained NPOESS's greatest resource consumers—VIIRS and MIS—significant changes to the bus design were not possible; as noted by one interviewee, "The DWSS bus was essentially a slightly down-sized version of the NPOESS bus. So not a whole lot of trade space there. And since we were flying the EOIR sensor [i.e. VIIRS], a very sophisticated EOIR sensor, [and] a spinning mechanism for the conical radiometer [i.e. MIS]…that kind of forced you down the path of having pretty large reaction wheels and limited your design space" [I65]. As noted, VIIRS and MIS drove the design of the DWSS spacecraft and therefore, made it challenging to reduce its complexity.

Concurrent with studies to reduce the size and capabilities of the bus's driving instruments, DWSS engineers also explored alternative architectures that used smaller, standardized buses [I68, I67] or that disaggregated VIIRS and MIS onto standard buses that were capable of fitting on less costly launch vehicles [I65, I67]. One interviewee described these studies as: "We looked at everything. We looked at Northrop and we also looked at the catalog buses. The trade was very wide" [I67]. Although this wide trade space opened up opportunities for cost savings, it also added a uncertainty to the program's technical, cost, and schedule baseline. The 2012 Defense Appropriations Act that cancelled the program cited this uncertainty as motivating its action, noting that, "Redesign efforts are being conducted simultaneously with efforts to examine capability trades. Options for capabilities trades result in billions of dollars of uncertainty in cost estimates, and may lead to significant redesigns. Each of these areas of risk indicates that DWSS is not on sound acquisition footing" [D49]. As with the instrument trades, the DWSS program was cancelled before any changes could be incorporated into its complex bus design.

Finally, the design complexity of the heritage NPOESS ground system presented another potential cost to the DWSS program. Although NOAA and NASA managed the ground as part of the JPSS Common Ground System, agency management indicated that the DoD might need to fund the continued development and the subsequent operation of the Centrals that catered to DoD users (AFWA, FNMOC, NAVOCEANO) [I62, D42]. While the details of the agencies' continued collaboration were still being negotiated when the program was cancelled, interviewees noted that DoD leaders preferred paying only for the specific data products that they required, rather than for the entire IDPS system to be installed and maintained at one of their Centrals [I68, I71]. One interviewee also noted that because the systems at each of the Centrals were designed to be common and JPSS planned to upgrade their ground system, the DoD would need to fund similar upgrades in order to maintain the Common Ground System's common configuration [I62].

### 7.2.2 DWSS Organizational Costs

Compared to its technical architecture, which inherited a lot of complexity from NPOESS, the DWSS organization was considerably less complex. Key residual complexity mechanisms included:

- A misalignment of responsibility and authority over the VIIRS and ground system contractors,
- And the ineffective heritage NPOESS contract.

All remaining complexity mechanisms, including misalignments of budget, expertise, responsibility, and authority were absent on DWSS, as was an ineffective delegation of authority. In fact, one interviewee praised DWSS management's ability to react quickly and to cancel the program once it was assessed to be unaffordable [I68] and another noted that the Air Force was able to act decisively because it held full authority, responsibility, and budget for the program, whereas other DWSS users did not [I62]. Thus, DWSS's organizational architecture distinctly contrasts with NPOESS and illustrates that when authority, responsibility, and budget are aligned, program management can make effective and efficient decisions—even if those decisions result in cancelling a program.

Interviewees described DWSS's misaligned responsibility and authority for VIIRS and the ground system as a coordination challenge that faced the program in the future; of course, much of this coordination was left unfinished when DWSS was cancelled. In particular, although one copy of VIIRS was slated to fly on JPSS-1, Raytheon continued to manage the development and production of VIIRS as a subcontract to Northrop, which had a contract with the DoD [I68, I65, D51]. As shown in Figure 46, although NOAA and NASA held responsibility for the VIIRS that would fly on JPSS-1, the DoD ultimately held contractual authority over the instrument; this configuration is similar to the IPO-NPP program office interface of prior epochs, when NPP was responsible for instruments over which it did have authority. Despite this similarity, the DWSS program was cancelled before similar organizational dynamics could occur.

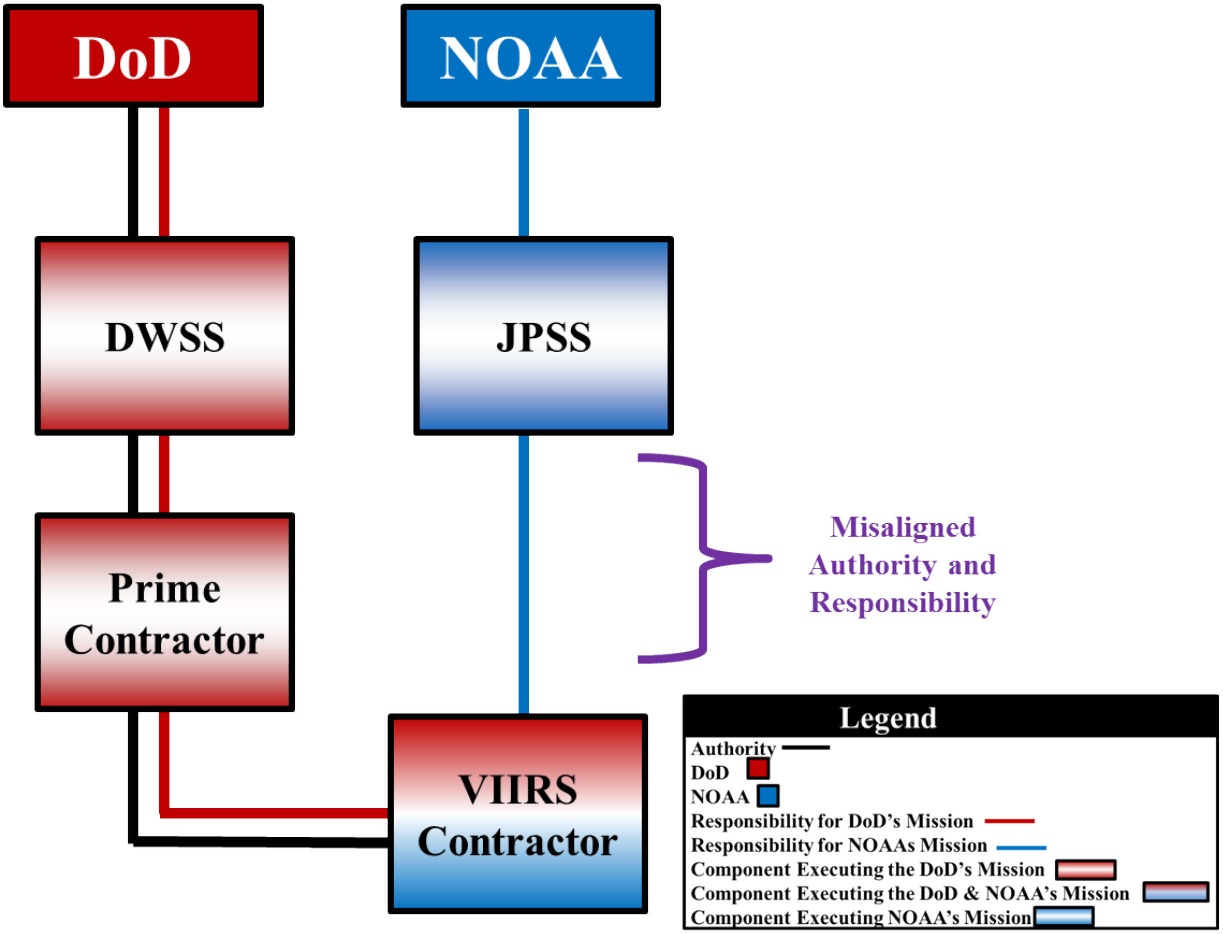


**Figure 46: Misaligned Authority and Responsibility Over the VIIRS Contractor**

The relationship between agencies presented another potential coordination challenge over the CGS, since the DoD relied on CGS to complete its DWSS mission, but NOAA and NASA held authority over its development and operation [D51]. Again, this interface was similar to one from prior epochs, when the IPO's ground system was responsible for executing NPP's mission, but the NPP program office held no authority over the IPO's contractors. While the details of the agencies' organizational relationship were not finalized before DWSS was cancelled, one interviewee described the coordination challenges that faced DWSS and continue to face future DoD programs that interface with domestic or international partners as: "We have to work within the DoD system and we have to coordinate our activities with other federal entities and international partners and that just adds complexity and makes things harder. It makes it harder to talk to people and to share documents and plans. And that all adds to additional man power to try to put some of the ideas and concurrence on the way ahead. And then trying to stack that up through multiple entities…multiple departments adds additional complexity and draws out the program" [I67].

Finally, because DWSS maintained the heritage NPOESS contracts, the program office's authority over its contractors' designs and development processes remained limited. Despite espousing a "back to basics approach" that emphasized more active management of the program's contractors [D51], the performance-based structure of the NPOESS contract remained the same [I68, I65, D47]; as a result, it was difficult for the government to direct the contractor to implement any of the cost-reducing trades discussed above without issuing a costly contract change order. This inability to directly request design changes of the contractor [I68, I65], coupled with the DoD's interest in totally revisiting its requirements [I62, I68, I65], served as another key motivation for DWSS's cancellation.

# 7.3 The Costs of JPSS

With the formation of JPSS, NOAA and NASA were directed to return to the relationship that they held on the heritage POES program. On POES, NOAA was the lead agency that employed NASA as the acquisition agent for its space segment. NOAA independently acquired its ground system and required a spacecraft that flew only weather-centric instruments. Despite this original direction, the JPSS program that emerged after NPOESS was quite different from POES. In particular, NASA's role was enhanced, the system collected both weather and climate data, and it more closely resembled NASA's NPP rather than NOAA's POES. Both of these changes played a critical role in the inducing the technical and organizational complexity that is discussed below.

## 7.3.1 JPSS Technical Costs

Like DWSS, JPSS also inherited technical complexity from NPOESS. However, unlike DWSS, JPSS's cost growth was also induced by mechanisms that were added after NPOESS was cancelled. The complexity added to the technical architecture enabled the program to implement Decision 6 and to produce a system that was upgraded version of NASA's NPP. To do this:

- JPSS instrument, spacecraft, and ground system designs were enhanced,
- Process specifications were updated to be compatible with NASA's preferred approach to program oversight,
- And design and process complexity were induced as a result.

The sections that follow provide additional description of these design and process complexity mechanisms as well as an additional architectural complexity mechanism that was induced by programmatic relationships between components.

### 7.3.1.1 JPSS Design Complexity

Although the JPSS design was based off the NPP system, the program implemented upgrades that increased the design complexity of the system's instruments, spacecraft, and ground system. In particular:

- Design requirements were levied on the heritage NPOESS instruments that had been previously managed to performance specifications,
- Instrument designs were changed to implement corrective actions that had been identified but not implemented during NPP,
- The spacecraft bus design was altered to upgrade its data bus and communications subsystem and to correct for parts obsolescence,
- And the size of the JPSS ground system was increased to include new components or components that were previously housed outside of the NPOESS program.

Starting with instrument design complexity—unlike DWSS, where instrument performance was a key complexity driver, *relative* to new design and mission assurance requirements, performance requirements were not a key complexity driver on the JPSS program. First, design requirements were levied on each of the heritage NPOESS instruments that had previously been developed to the IORD's performance-only specifications [I56, I63, D100, D135]. Interviewees noted that, in most cases, levying these requirements did not fundamentally change the design of the NPOESS instruments—in fact, many requirements were "backed out" or derived from existing designs [I56, I63]. The purpose of this exercise was to enable NASA to directly manage instruments that had previously been managed by Northrop and to transition their contracts to NASA's preferred style of requirements specification [I56, I63]. Importantly, although in most cases these changes did not fundamentally alter the instruments' designs, the process of developing design specifications and of ensuring that JPSS's instruments met these new requirements was not without cost.

Other changes to the instruments *did* alter aspects of their designs by changing how they interfaced with the spacecraft bus or by implementing corrective actions for issues that were discovered during NPP's development. In terms of new interface requirements, all instruments were augmented to use a SpaceWire data bus instead of the NPOESS IEEE1394 data bus [I63, D135]. In terms of post-NPP corrective actions, NASA engineers recommended 525 individual changes to VIIRS, CrIS, and OMPS [D135]. Many of these changes were motivated by issues discovered during NPP; for example, corrective actions were recommended to improve the construction of the VIIRS cryocooler and deployment mechanisms, the CrIS structure, and PCI connections for all of the instruments [D135]. Additional design and process requirements that focused on mission assurance were also levied on the instruments, since JPSS had a longer design life than NPP [D65].

Numerous changes to the heritage NPP bus also increased JPSS's design complexity. Initially, the JPSS bus was supposed to a "clone" of NPP [D175, I56, I57]. In fact, the desire to preserve similarities between NPP and JPSS motivated the program to define a separate free-flyer spacecraft to host SARSAT, DCS, and TSIS even though SARSAT and DCS had flown on all previous POES spacecraft. The program justified this decision because it allowed them to maintain NPP heritage and to award a sole source contract to Ball Aerospace, the contractor that NASA had used for NPP's bus [I50, D5].

Despite their assumed similarity, numerous changes to the NPP heritage design increased the bus's design complexity and ultimately increased the program's non-recurring costs. First, the program had to correct for the parts obsolesce that occurred between the development of NPP (which was originally slated to launch in 2006) and the launch of JPSS-1 (which was originally scheduled for 2015) [I56, I57, D100, D175]. Second, like the instruments, the NPP heritage bus was updated to extend its lifetime, to meet additional mission assurance requirements, and to use a SpaceWire data bus [I57, I59, I63]. Third, a final change was made to the bus's communication subsystem, which was changed from a fixed X-band antenna to a steerable Ka-band antenna [I56, I57, I72, D96]. The purpose of the change was to enable an optional downlink through TDRS—a capability that did not exist on NPP—and to enhance the system's data latency since changes to the JPSS ground system decreased it [I08, I72, I56, I57, I63]. Of course, by adding a new Ka-band antenna, the JPSS program incurred the additional non-recurring cost of designing the spacecraft to accommodate this capability and to control the jitter that it induced on the spacecraft bus [I57]. Therefore, the new antenna not only drove design complexity into the bus, but it also induced architectural complexity by mechanically interacting with the other payloads.

As noted above, a major motivation for adding a Ka-band antenna was to increase the system's data latency after a reduction to the CGS reduced it; in fact, while this change increased design complexity on the JPSS bus, corresponding changes on the ground system decreased its complexity. Specifically, although the CGS originally included SafetyNet™ and planned to install the NPOESS IDPS at all four of NPOESS's Centrals [D100], the ground architecture quickly evolved to include only two ground-based receivers (i.e. no SafetyNet™) and two IDPS's [D224]. While these changes reduced the ground system's cost, they also reduced its average data latency from 30 to 80 minutes [D225]. By adding the capability to downlink through TDRS, JPSS had the potential to increase its data latency and provided backup downlink in case problems were encountered at either of the ground-based receivers [I08, I72, I56, I57, I63].

Although JPSS reduced the number of ground-based receivers and IDPS systems in its ground system, it expanded the system and increased its complexity in two ways. First, the program enhanced the system's ability to command, control, and process data from numerous other satellite systems including POES, Windsat, DSMP, DWSS, the Global Change Observation Mission satellite, and EUMETSAT [I57, I59, I71, I72, I8, D211]. This represented a expansion from the NPOESS ground system's capabilities which one interviewee described as "requirements creep" [I57] and another, as an attempt "to have this grand, gray, ground architecture. Instead of having a JPSS ground and a GOES ground and everything else ground, have one architecture for all of [NOAA's] satellites" [I59].

Second, key components that previously had an external interface to the NPOESS ground system—NOAA's ESPC and CLASS—were re-classified and included as part of the JPSS ground architecture [I60, I63, I66]. Instead of being funded externally (as on NPOESS), these components were funded and developed as a component of the larger JPSS ground system [I60, I63, I66]. A key motivation for integrating these components into the JPSS ground system rather than maintaining them as an external interface was a desire to manage the system's end-to-end data production process and to ensure that the data produced by the JPSS satellite was successfully transformed into a data product that was useful to JPSS's users. As described by one interviewee, "What started cropping up at all of these reviews…was that the ground system wasn't actually feeding the products to the end user—there was something in between the ground system and the end user—and who was worried about that thing to make sure that at the end of the day the end user isn't grossly unhappy with what the system in the center is creating? And so there was this gap with where the boundary of the system was being drawn" [I66]. Ultimately, the JPSS program closed that gap by integrating external systems like ESPC and CLASS into its larger architecture; although actively managing these interfaces was essential to the system's overall performance, adding these components to the official JPSS ground system increased its cost, since these components previously received external funding.

### 7.3.1.2 JPSS Process Complexity

Another key complexity mechanism was the process complexity induced by having NASA, rather than a TSPR-like contractor, oversee the systems' contracts. Interviewees described NASA's role on the JPSS program as similar to Northrop's system integrator role on NPOESS—with the caveat that Northrop was more responsive to requests from the IPO than NASA was to NOAA [I69, I59]. In its system integrator role on JPSS, NASA decomposed NOAA's Level 1 requirements into Level 2 requirements that governed how the system's ground and space segments interfaced and into Level 3 requirements that defined the ground and space segments individually [I60, I63]. Each of these requirements was managed by the JPSS program office and interviewees noted this oversight grew to be so significant that the program office expanded to fill an entire building [I59, I66]. As a result, the program grew into a second building, where most of NOAA's staff was assigned and separated from their NASA colleagues [I72, I59, I66].

Level 4 requirements, which defined components of the space and ground segments, were managed by the program's contractors and with the exception of the design changes discussed above, remained the same as on NPOESS. Despite these similarities, the requirements levied on the component development *process* changed on JPSS. As noted in Chapter 4, after the NPOESS cancellation, NASA began a process that it called "NASA-ification," to convert NPOESS contracts to use NASA standards and to be amendable to NASA oversight processes [D135, I56]. One interviewee described the cost impact of transitioning NPOESS contracts to use NASA standards as: "[New NASA requirements] do point to how we monitor, how things are documented and reported out, different types of reviews and the different types of review teams that are required for missions. Those things require all add work and scope to the project and our contractors" [I56]. The work required to transition NPOESS contracts to use NASA standards and procedures was described as "significant" [D100] and even once that work was completed, interviewees noted that the standards used by the program—theGoddard "Gold Rules"—were more stringent than the Mil-Standards that had been used on the NPOESS program [I56, I69, I59]. Therefore, not only did cancelling the NPOESS program induce additional process complexity as specifications were transitioned from DoD to NASA standards, but the stringent NASA standards themselves also contributed to the program's increased cost.

### 7.3.1.3 JPSS Architectural Complexity

Finally, architectural complexity, induced by programmatic interactions between the system's components—also impacted costs on the JPSS program. Specifically, during Epoch G, the program was under-funded by a continuing resolution and as a result, program management had to prioritize the development of certain components and delay the development of others [I08, D232, D100]. In particular, the NPP ground system was prioritized over JPSS-1 and delaying JPSS-1's development ultimately induced lifecycle cost growth [D232, D100].

A second programmatic interaction also occurred between the system's weather-centric instruments—VIIRS, ATMS, CrIS, and OMPS-Nadir—and its remaining climate-centric instruments. An independent review team noted that the climate-centric instruments constrained JPSS's budget and increased the probability that its satellites' development would be delayed and that there would be a data gap; as a result, the team recommended removing all climate-centric instruments from the JPSS program [D142]. Specifically, the independent review team warned that "The mission and the scope of responsibilities of JPSS are too broad and distracts their attention away from the weather mission" [D142]. An interviewee further described the impacts of JPSS's broad mission responsibilities as "It really does show....whether the leadership really believes it or not…..[that] having the [climate] instruments on-board really is an impact relative to communicating priority. Everybody in the whole organization should be making similar decisions on, 'Let's focus on the high priority weather stuff and not let other things kind of creep in'" [I55]. The debate over JPSS's climate-centric instruments continued after Epoch G, when several instruments were removed or their funding responsibility was transferred to NASA [D227, D189, D115].

## 7.3.2 JPSS Organizational Costs

Just as the JPSS technical architecture became more complex than the NPP system that it originally intended to duplicate, so too did the program's organizational architecture. Specifically, the Presidential directive that cancelled NPOESS ordered NOAA and NASA to "continue [the] successful relationship that they have developed for their polar and geostationary satellite programs to date" [D175]. Despite this directive, the agency relationship that was defined by the JPSS organizational architecture has been described as "more complicated" and as inducing "a little bit more difficulty amongst all of the parties in the decision making process" [I55] compared to NOAA and NASA's more efficient heritage programs [I55, I56, I63, D142, D143]. Organizational complexity was induced:

- Primarily by the misalignment of responsibility and authority,
- And secondarily, by the misalignment of authority and expertise and budget and responsibility.

The impacts of each misalignment is discussed in greater detail below.

### 7.3.2.1 Misaligned Authority and Responsibility

The key organizational complexity mechanism on the JPSS program was a misalignment of responsibility and authority that was induced by establishing two separate program offices to manage the system's development; these offices are depicted in Figure 47. Officially, NOAA held final authority and responsibility for JPSS; however the agency delegated that authority and responsibility *both* to a NOAA program office (the NJO) and to NASA [D142, D225, D143]. NASA further delegated its authority and responsibility to its own separate program office that shared responsibility with the NJO [D142, D225, D143]. As on the NPP program, an effective authority link between the two offices did not occur at the program level, but rather existed only at the highest levels of the organization: through NOAA-NASA agency management, which interfaced at NASA's JASD.

This organizational construct induced cost growth in two ways. First, it slowed decision making and added extra oversight. As the lead agency, NOAA held final decision authority on the program's technical, cost, and schedule baseline and the responsibility to oversee its activities; NASA, on the other hand, held authority over all implementation decisions that did not directly affect NOAA's baseline and the responsibility to report on their progress [D190, D97]. Despite this official allocation of authority and responsibility, during Epoch G, NOAA management was actively involved in NASA's implementation decisions [D142] and requested an "enormous and excessive" amount of information from program implementers that placed a "big burden on the project" and resulted in a slow and "highly diffuse decision making process" [I55].

Outside of NOAA's initial involvement in NASA's implementation decisions, interviewees reported that the two program offices added additional oversight that created unnecessary work [I08, I55, I56, I60]; one interviewee even described the situation as, "you have a program office overseeing a program office" [I56]. Another interviewee described the cost impact of the dual office structure as, "Every time you add a level of management, you add a layer of interface and interaction that eats up your time" [I56]. The same interviewee went on to describe how each program office had to participate in monthly reviews by their managing agency and indicated that completing such reviews was necessary to get major programmatic decisions made: "Every time you add another level of management, you add another review to the process. I call it the kissing of the rings, in order to get anything flown to the top" [I56]. In addition to duplicating the communication process that proceeded major decisions, JPSS's dual authority chains also occasionally resulted in poor coordination between offices when one took actions that conflicted with the other's [I60].

Second, the two program offices also impacted cost by confusing the lines authority and responsibility within the NASA program office. Specifically, NOAA staff were embedded in the NASA program office and assigned to work on either the ground or space segment. Interviewees reported that although NOAA personnel were formally assigned and responsible to NASA management, they also received tasking from the NJO [I56, I60, I66]. In most cases, the NJO simply requested information on the program's activities [I8, I56, I60]; however, some interviewees also reported being directly tasked by NOAA [I60, I66]. In both situations, the interaction with the NJO added extra work for the NASA program office and distracted them from their technical tasks [I56, I60, I66].

In addition to describing the cost impacts of the two program offices, interviewees also recalled the reasons that motivated the agencies to architect the organization in this way. First, in 2010, NASA formed JASD within its Science Mission Directorate in an attempt to establish a formal mechanism for NASA Headquarters to oversee its joint programs according to NASA policies and procedures [D65, D57]. In accordance with these procedures, NASA established a program office at GSFC to oversee JPSS's flight and ground projects [I08, I66]. One interviewee described the motivation for establishing JASD and NASA's program office as: "NASA Headquarters…is really responsible for insuring that NASA policies are being implemented and that good people are put on the program and that it is being run in a way that NASA thinks a program should be run. They have the oversight responsibility" [I55]. Furthermore, other interviewees noted that JASD provided a mechanism that shielded the NASA program office from excessive oversight by NOAA [I08, I63, I66] and that it enabled NOAA to formally transfer money to NASA [I69, I63, I66].

Despite the noted advantages of JASD and NASA's program office, a key disadvantage was that it provided no formal mechanism for NOAA to independently oversee the activities of the program [I08, I55, I66]. Without establishing a NOAA program office to independently oversee NASA, all information regarding NASA's implementation activities would have had to flow through NASA Headquarters first. Furthermore, in addition to overseeing NASA, NOAA required a program office to insure that the NASA-developed system would meet the needs of the larger NOAA user community [D142, I63, I66].

This requirement became particularly apparent with respect to NASA's management of the JPSS ground system. On the heritage GOES and POES programs, NOAA managed the development of the ground system and NASA managed only the programs' space segments [I55, I66]. After a contentious negotiation process [I69, I60, I66], the agencies determined that NASA should also manage the JPSS ground segment. Interviewees noted that a primary motivation for this decision was a desire to maintain management continuity between NPOESS and the NPP program [I60, I66]; as noted previously, one of JPSS's first activities was readying NPP and its relatively immature ground system for launch [D226, D100, I66].

While assigning NASA ground system responsibility positively impacted the agency's ability to manage NPP, it negatively impacted external NOAA organizations like CLASS, STAR, and ESPC that interfaced with the ground system and that held final responsibility for converting its outputs into data that could actually be consumed by NOAA users. Because these organizations belonged to the larger NOAA enterprise and had previously existed external to the NPOESS IPO, they could not be effectively integrated into a NASA-managed ground project [I60, I63]; as noted by one interviewee, "Funding can't go from NOAA to NASA and back to NOAA" [I60]. As a result, the NJO was assigned the additional responsibility of managing organizations like CLASS, STAR, and ESPC and of insuring that their systems effectively interfaced with the NASA-developed ground system [I60, I63, I66].

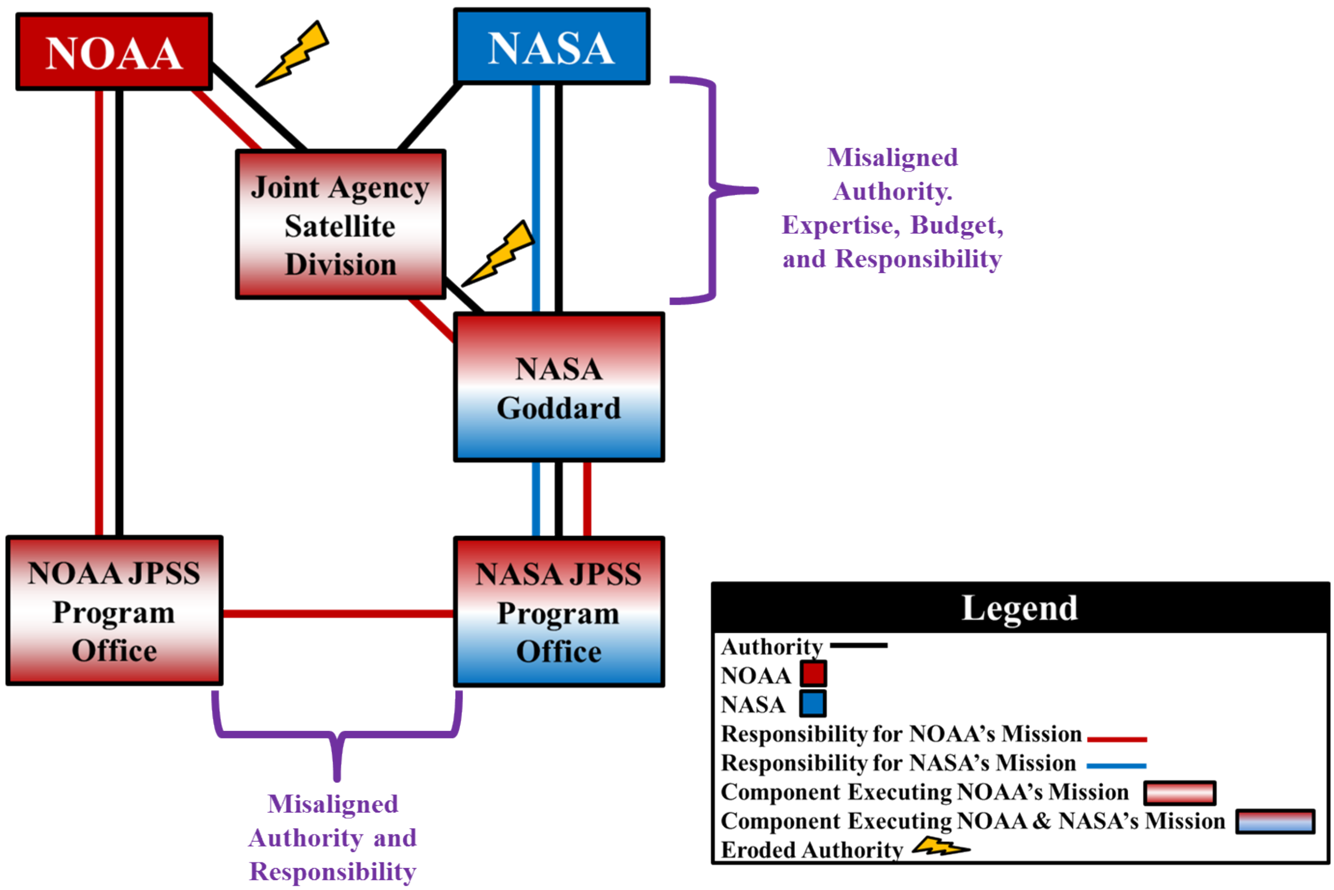


**Figure 47: NOAA-NASA Interface Over JPSS Program**

The relationship between NASA's ground segment and external NOAA systems like STAR was dynamic during Epoch G and the agencies' fluid authority and responsibility hindered decision making and induced cost growth during this period [I69, I60, D211]. One interviewee described the process of transitioning the heritage NPOESS, STAR, ESPC, and CLASS organizations into a single JPSS program as: "I think it was that the lines were drawn in such stark contrast on NPOESS with where the IPO ended and where the actual system ended and what NOAA needed. Lots of things cropped up that were add-ons around the periphery to try to get the job done. And then to try to transition those into the new structure and pull that all together as an integrated organizational picture…has been a long process and it is not done yet" [I66]. Importantly, despite the challenges and organizational acrimony that were experienced during Epoch G, the roles that each agency played in managing the ground system, as well as the NJO's responsibility to integrate both agencies' contributions, appears to have recently solidified and the agencies' overall management of the program has reportedly improved [I66, D143].

### 7.3.2.2 Misaligned Authority, Expertise, Responsibility, and Budget

Further exacerbating the complexity induced by the misalignment of responsibility and authority between NOAA and NASA was a misalignment of expertise and authority and of responsibility and budget. First, interviewees were critical of NOAA's oversight of the JPSS space segment: because NOAA is not primarily a space acquisition organization, interviewees noted that their oversight of the program did not enhance or improve how NASA was technically managing it [I08, I59, I66]. One noted problem was NOAA's inability to prioritize the program's requirements [I08, I66, I59]; as described by one interviewee: "One of the things that both USGS and NOAA have done poorly is understanding how to speak to NASA in NASA's language. If they were good at delineating their requirements and folding the operations aspects into that…then NASA would build them exactly what they gave them. But the problem is….they don't communicate that well through requirements and so it leads this fuzzy grey zone and that is where all the problems come out" [I66].

Essentially, because NOAA held the final authority over JPSS's requirements, its inability to prioritize requirements hindered NASA's ability to trade between system capabilities and cost: an outcome that enabled cost growth**.** Furthermore, interviewees also reported that NOAA's weak technical expertise motivated NASA's interest in gaining greater control and autonomy over the system's development [I08, I72, I55, D211, D9]. To counter this interest, NOAA is currently working to strengthen its technical capabilities and its ability to effectively manage NASA's development of the JPSS technical system [I59, I60, D142, D143].

One motivation for NOAA to strengthen its technical ability to manage NASA's implementation points to the second complexity mechanism that eroded NOAA's authority: the misalignment of responsibility and budget. First, NASA's official mission responsibility on the JPSS program was to manage the development of NOAA's JPSS system [I55, D65, D97]. Importantly, NASA's activities were entirely funded by NOAA: no NASA funds were used to support the development of JPSS [D65, D99]. NASA's misalignment of mission and budget enabled cost growth by failing to incentivize NASA's program office to drive down the system's costs [I69, I72, I59]. Interviewees described the cost impacts of this misalignment as, "[NASA is] spending NOAA's money to maintain their own civil servants and contractors. Good deal, who wouldn't want that?" [I69] and "Would this program cost so much if NASA was spending NASA's money? What incentive does NASA have to really drill on these instrument guys…to really squeeze the belt and get the lowest possible cost….it's not their money" [I72].

This misalignment was particularly impactful because NOAA prepared its budget using cost estimates developed by NASA [D211] and an audit of the program indicated that there were significant discrepancies between both agencies' cost estimates and that NOAA's cost analysts lacked detail on how NASA had performed its work [D211]. In addition to these discrepancies, NASA also held a fraction of the program's management reserve that it could use without requesting approval by NOAA [I72, I57, I63]; this illustrates that even though NOAA ultimately held the budget for the program, NASA had the ability to spend some of the budget without explicit approval from NOAA. Thus, it seems that this misalignment of mission and budget enabled NASA to increase cost of the technical system by requesting numerous changes to its heritage NPP system that it was not responsible for funding.

A secondary misalignment of mission and budget derived from JPSS's relationship to NPP and EOS: although JPSS was officially a NOAA program, it used instruments that had been developed for NPP to maintain EOS data continuity. Since JPSS followed NPP and took the same measurements, by default, NASA remained a stakeholder in JPSS's data [I69, I63]. One interviewee noted that NASA's interest in climate data and NPP significantly altered NOAA and NASA's relationship before and after NPOESS: specifically, because NASA was a stakeholder in JPSS's data, it could no longer effectively act as a disinterested acquisition agent for the system [I69]. Thus, it seems that as on NPP, NASA was relying on JPSS to complete its climate science mission while simultaneously not funding it. Again, this misalignment of mission responsibility and budget may have hindered NASA's ability to make cost-risk trades and enabled much of the design and process complexity that was discussed above. This misalignment also enabled architectural complexity because NASA prioritized the completion of NPP over the development of JPSS-1 and aggregated climate-centric sensors onto the same spacecraft bus as NOAA's higher priority weather sensors.

Finally, the third complexity mechanism—a misalignment in authority and budget—eroded both agencies' authority over the program's contractors was induced by the program's acquisition strategy. Specifically, instead of issuing competitive contracts for multiple copies of the same component, during Epoch G, the program defined single sole source contracts for JPSS-1's components only [D114, D12]. By eliminating competition that could have driven down costs, the acquisition strategy reduced the government's ability to negotiate the prices that the contractors proposed. Furthermore, the program missed the opportunity to reduce its lifecycle costs by utilizing a more efficient strategy that purchased multiple copies of the same component [I72, I56, D143]. The program is still working to develop its long term acquisition strategy today.

## 7.4 Cross-Case Comparison: Technical Costs

Common technical complexity mechanisms (listed in Table 7) were observed across *all three case studies*. To further organize my cross-case comparison of technical complexity, I classify complexity mechanisms in terms of three types of technical aggregation which I define as:

- **Requirements aggregation,** which occurs when numerous unique and driving requirements are levied on a system.
- **Mission aggregation,** which occurs when a system is required to execute more than one mission.
- And finally, **system aggregation,** which occurs when a system's technical architecture executes missions and requirements using the minimum number of components.

### 7.4.1 Requirements Aggregation

First, requirements aggregation induced instrument design complexity on the NPOESS, JPSS, and DWSS programs by levying each agency's unique or driving requirements onto the system. The primary impact of requirements aggregation was that none of the agencies' heritage instruments were capable of meeting the programs' joint requirements. As a result, the NPOESS program had to make an unanticipated non-recurring investment to develop new sensor technology that was capable of meeting joint requirements.

Data from both JPSS and DWSS support my proposed relationship between requirements aggregation and instrument design complexity. Specifically, JPSS continued the NPOESS's non-recurring investment during the "NASA-ification" process, which corrected design flaws and residual risks that had been identified in instrument designs during NPP. JPSS also aggregated new requirements onto the instruments and in doing so, further increased their design complexity. Alternatively, after NPOESS was cancelled and the DoD's requirements were officially disaggregated from NOAA's, DoD management determined that NPOESS's instruments were *too complex* for the follow-on DWSS program; in fact, case study data suggested that the high complexity and cost of DWSS's instruments played a central role in motivating the program's cancellation.

The DWSS and JPSS programs' responses to using NPOESS's instruments illustrate two key findings that relate requirements aggregation to instrument design complexity:

- First, when instruments are developed to meet an aggregated set of requirements, the resulting design will be more complex and costly than an instrument that is designed to meet only a single agency's requirements.
- Second, NOAA aggregated more requirements onto the NPOESS instruments than the DoD did.

VIIRS provides an excellent example of the first finding: since VIIRS was more complex than an instrument that the DoD would have developed independently, DWSS determined that it would be less costly to develop a new and less capable sensor to replace VIIRS than it would be to continue investing in the existing, but more complex, VIIRS design. The second finding is well illustrated by NOAA's decision not only to maintain NPOESS instruments on JPSS, but also to enhance them. In contrast, the DoD determined that NPOESS instruments met too many non-DoD requirements to justify further investment in their development.

A key reason that NOAA had a larger and more stringent requirement set than the DoD was that NOAA's requirements were *already* aggregated. As described previously, NOAA's requirements for NPOESS were based on capabilities that were provided by NASA's EOS system. Thus, although NASA did not levy formal requirements in the IORD, requirements from its heritage systems ***were*** aggregated into NOAA's requirement set.

> **Therefore, the requirements in the IORD—which induced instrument design complexity—were caused by aggregating <u>three</u> agencies' requirements onto a single system.**

Requirements aggregation also induced process complexity on the NPOESS and JPSS programs when the amount of government oversight increased. On NPOESS, increased government oversight took the form of multiple agency engineering standards that were levied on NPP-NPOESS shared components; specifically, despite being procured to DoD standards, NASA required NPP instruments to also meet NASA standards and process complexity was induced when program engineers had to reconcile both sets of standards. While only one set of standards was used on JPSS, the program similarly incurred process complexity when the "NASA-ification" process formally transitioned NPOESS contracts that used DoD standards to NASA contracts that used NASA standards. Additionally, the Goddard "Gold Rules," which were also applied to JPSS's instruments, were described as being more stringent and costly than the DoD standards that had been used on NPOESS. Similar process complexity was not observed on DWSS.

### 7.4.2 System Aggregation

As shown in Figure 48, requirements aggregation also indirectly induced the remaining complexity mechanisms by motivating system aggregation. First, a cost-effective strategy for satisfying NPOESS's aggregated requirements was using an aggregated system architecture. Although aggregating the system's numerous instruments onto a single spacecraft bus induced architectural and design complexity:

> **For its aggregated requirements set, an aggregated space segment was a cost-effective architecture.**

Within the NPOESS space segment, system aggregation induced both design and architectural complexity. System aggregation induced design complexity when a new data bus needed to be developed to accommodate the aggregated system's high data-rate and when Northrop's heritage bus design had to be enhanced so that it could host NPOESS's entire resource intensive payload. Bus design complexity was also observed on the JPSS space segment, this time because the heritage NPOESS data bus was changed and the heritage NPP bus was upgraded to enable Ka-band communications. Bus complexity was also observed on DWSS, since the heritage NPOESS design had to be de-scoped to accommodate DWSS's reduced payload.

Five types of architectural complexity mechanisms—EMI, mechanical, optical, and reliability interactions, as well as design relationships—were induced by the NPOESS program's aggregated spacecraft architecture. Each of these mechanisms—with the exception of reliability interactions and design relationships—was removed when particular payloads were disaggregated from the NPOESS system. In particular, the EMI and optical interactions were eliminated because neither JPSS nor DWSS hosted instruments that induced or were affected by them. Due to the relative inclusion or exclusion of MIS, mechanical interactions were present on DWSS but absent on JPSS. Architectural complexity that was induced by design relationships between components was only observed on NPOESS because neither DWSS nor JPSS planned to fly different payload manifests in multiple orbits.

Ground system design complexity was also observed on all three programs. In particular, for each program, data users assessed that the ground system was processing *too much data* or *not the right type of data.* Users in all three programs established alternate systems to interface with the IDPS and to collect or convert data into a format that they preferred. Furthermore, both JPSS and DWSS assessed that the complexity and cost of the IDPS system was too great for their individual needs and decided to cancel plans to install the system at two of NPOESS's four Central locations.

The JPSS and DWSS programs' response to NPOESS's aggregated system illustrate two key findings on the complexity and cost impacts of system aggregation.

- First, *given* the instruments that they inherited from NPOESS, JPSS and DWSS both determined that an aggregated spacecraft architecture was less costly than a disaggregated one.
- Second, both JPSS and DWSS determined that despite the NPOESS ground system's complexity, it did not provide data in the format that was required by their users.

With regards to the second finding, both JPSS and DWSS developed alternate systems to interface with the NPOESS ground system, to collect only the data that was required their users, and to convert that data into a format that was acceptable to them. As noted previously, many of these systems were developed during NPOESS but were external to the program; as a result, the cost of these systems should be considered as an *addition* to the cost of the NPOESS ground system. Perhaps more importantly though, not only did system aggregation induce design and architectural complexity on the NPOESS ground system, but it forced the system into a configuration that was incompatible with its large and diverse user community. Therefore,

> **The cost of ground system was greater than the lifecycle cost that was reported because each agency's user community was forced to develop an additional system to interface with NPOESS or to incur the unquantifiable cost of losing NPOESS-produced data because it was not in their required format.**

### 7.4.3 Mission Aggregation

In addition to motivating system aggregation, requirements aggregation also enabled mission aggregation. In turn, mission aggregation induced process complexity on NPP when requirements for the system's dual missions were in conflict and architectural complexity on both NPOESS and JPSS when cost growth and delays on one of the system's components induced lifecycle cost growth on its others. Mission aggregation occurred because each program's aggregated requirements set could be clearly divided into distinct subsets, or missions. For example, NPOESS's requirements could be divided into three missions: operational weather, operational climate, and climate science. Even though JPSS was officially an operational mission, its close relationship with NPP's climate scientists insured that NPOESS's climate science mission was also preserved on JPSS. Finally, NPP was both a risk reduction and a climate science mission.

The key distinction between requirements and mission aggregation is that mission aggregation impacted cost when the programs' requirements *were not clearly prioritized.* For example, without a clear prioritization of its missions, the NPOESS IPO and NPP program office found themselves in conflict over which mission's requirements should implemented. The conflict between missions induced process complexity when representatives from both missions had to negotiate their requirements or default to the more stringent and costly requirement. This type of process complexity was not observed on JPSS or DWSS, because in both cases only one agency, NASA or the DoD, controlled the system's process requirements.

Alternatively, on NPOESS and JPSS, mission aggregation induced architectural complexity when cost growth and delays on one system component induced lifecycle cost growth on others. Outside of NPOESS's KPP's, all of the system's EDRs were officially equal; as a result, it proved impossible to achieve consensus among the program's users on which EDRs could be traded to reduce the system's cost. Unable to reduce the system's capabilities and faced with growing costs, NPOESS management was forced to temporarily prioritize the development of some of the system's components, while delaying—but not officially cancelling—the development of others.

By levying each agency's unique and driving requirements on the system's instruments and forcing the program to develop new technology, requirements aggregation also contributed to the cost impact for architectural complexity. Specifically, since the cost of developing new sensors is uncertain and requirements aggregation forced the NPOESS program to invest in multiple uncertain development projects with a limited budget, overruns on one project induced lifecycle cost growth on others. This suggests that when an aggregated architecture contains numerous technically immature components, not only can the components themselves induce cost growth, but so too can the resource dependencies between them. As a result,

> **The risk of cost growth on an aggregated program is not only a function of the number of immature components but it is also a function of the number of potential interactions between them.**

Programmatic interactions between instruments also impacted cost on the JPSS program and motivated an independent review team to recommend that JPSS prioritize its weather mission by disaggregating its weather and climate-centric sensors; the Nunn-McCurdy certification attempted a similar prioritization when it de-manifested climate sensors. Of course, both attempts ultimately failed because climate instruments were returned to the program shortly after their removal. Finally, the NPP program itself induced architectural complexity on both JPSS and NPOESS since development of components for the operational systems were delayed when NPP's development was prioritized. Notably, although DWSS hosted multiple sensors which could have interacted programmatically, no interactions were observed. The absence of this particular type of complexity mechanism could be a function of DWSS's short lifetime (i.e. there was not enough time for complexity's impact to be observed) or it could be because DWSS had only a single operational weather mission: once DWSS management determined that executing its mission would exceed the program's cost constraints, it acted swiftly to cancel the system in its entirety.

### 7.4.4 Conclusion: Technical Aggregation, Complexity, and Cost Growth

Of the three types of technical aggregation, requirements aggregation had the most significant impact on the complexity and cost of the NPOESS, JPSS, and DWSS programs. Figure 48 provides a schematic that relates requirements aggregation to mission and system aggregation and to the complexity mechanisms that each aggregation type induced. As noted in Figure 48, it is important to begin this discussion by distinguishing between synergistic and non-synergistic requirements because each had different complexity impacts.

NOAA and the DoD's requirements were non-synergistic because both agencies ultimately required different instruments: the DoD required data from CMIS and VIIRS whereas NOAA required data from ATMS and CrIS. The lack of synergy in the agencies' requirements can be observed in the systems that were formed after NPOESS's cancellation: since DWSS claimed CMIS and VIIRS but not ATMS and CrIS, which were included in JPSS instead. Alternatively, NOAA and NASA's requirements were synergistic because both agencies' required similar data from VIIRS, ATMS, and CrIS and secondarily, required climate data from instruments like TSIS, ERBS, and OMPS. The synergism in NOAA and NASA's requirements can be observed in the instruments that were assigned to JPSS, which included each of aforementioned sensors. As noted previously, NASA did not formally levy requirements on NPOESS or JPSS; however, in reality, NASA maintained a requirement for data continuity with its EOS system.

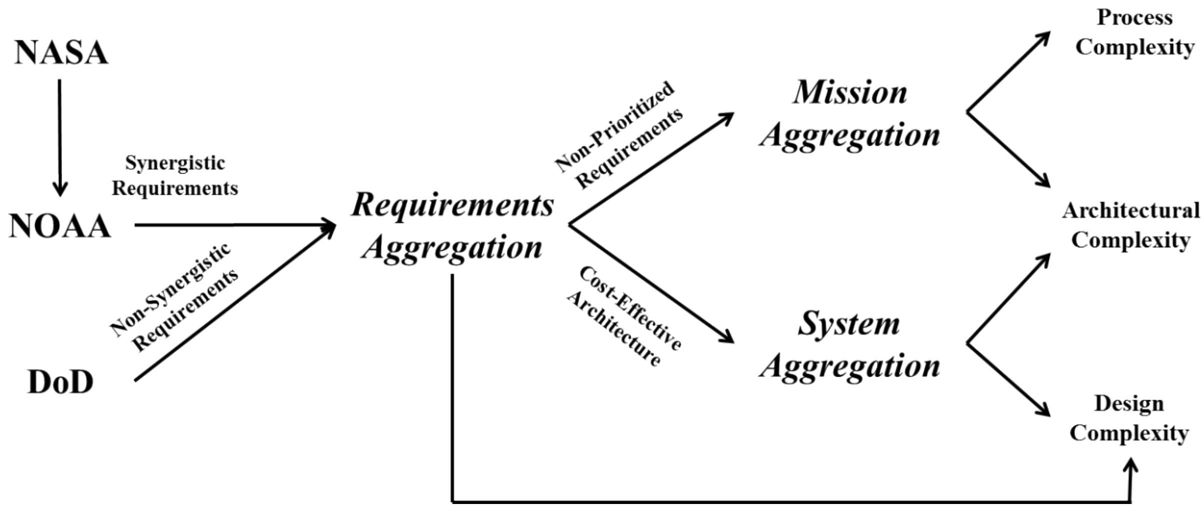


**Figure 48: Relationship Between Different Types of Technical Aggregation**

As discussed above and shown in Figure 48, requirements aggregation induced instrument design complexity since none of the agencies' heritage instruments were capable of meeting the aggregated requirements set. Additionally, requirements aggregation induced mission and system aggregation. Mission aggregation resulted from an unclear prioritization of requirements that could otherwise be clearly separated into distinct missions. Without a clear prioritization of requirements, it was difficult to make trades that reduced the system's capability and cost. As a result, when the programs' costs grew but their budgets remained fixed, architectural complexity was induced, when cost growth on one component of the system induced schedule delays and lifecycle cost growth on others.

The severity of the cost impacts from this particular architectural complexity mechanism depended on the synergy that was present in the agencies' requirements. The lack of synergy between NOAA and the DoD's requirements prevented any of the agencies' critical instruments—VIIRS, CMIS, ATMS, and CrIS—from being cancelled during the NPOESS program. Therefore, the cost growth that was induced by the programmatic interactions between these instruments was largely unavoidable:

> **Given the agencies' non-synergistic requirements—which resulted in each instrument being critical to one agency or the other—essentially no instrument could be cancelled or have its performance significantly reduced.**

The synergy between NOAA and NASA's requirements exacerbated the lack of synergism between NOAA and the DoD's. Specifically, after climate requirements were added, NOAA's requirement set was even less synergistic with the DoD's. The addition of the climate-centric sensors increased architectural complexity by adding more components and component interfaces to the system. When costs grew but budgets remained fixed, these sensors exacerbated and increased the cost growth induced by programmatic interactions between instruments.

Unlike NOAA and the DoD's non-synergistic requirements which could not be traded, it *was* possible to trade NOAA and NASA's synergistic requirements, although making those trades was hard. For example, climate-centric sensors were de-manifested after the NPOESS Nunn-McCurdy breach and have been recommended for removal from the current JPSS program. Although both trades were possible, they encountered significant resistance from NASA, who sought external funding to maintain the climate instruments on both programs. Despite the synergy in NOAA and NASA's requirements, the unclear prioritization of each agency's unique mission hindered the programs' ability to cut one requirement over the other. Finally, the requirements for NASA's NPP climate science mission were wholly non-synergistic with NOAA and the DoD's requirements for its risk reduction mission. The unclear prioritization between these missions resulted in process complexity, which I argue had the most significant impact on the NPOESS program's overall technical complexity and cost.

As shown in Figure 48, requirements and mission aggregation also motivated system aggregation, which induced both design and architectural complexity. Requirements aggregation motivated system aggregation—because given an aggregated requirements set—an aggregated system architecture is often less costly than a disaggregated one. Mission aggregation, or the unclear prioritization of requirements, locked the programs into their aggregated architectures by hindering managements' ability to make trades.

With these aggregated architectures, complexity was observed in both the space and the ground segments. Importantly, despite the architectural complexity that was induced by hosting multiple, interacting instruments on the same the bus and the design complexity that resulted from bus commonality, it appears that an aggregated space segment was less costly than a disaggregated one. In contrast, the aggregation of the ground segment motivated the agencies to independently develop additional systems to interface with it and to transform its data into an alternate format preferred by its users. In this way, the ground segment's total costs included the cost of *both* aggregation and disaggregation, since the aggregated ground system ultimately had to interface with disaggregated agency unique systems before the data that it produced could be used.

This discussion of the NPOESS ground system motivates an important distinction between essential and gratuitous complexity. ***Essential complexity*** [24] is an unavoidable outcome of aggregation that can be traded against cost to determine if and when aggregation is appropriate. ***Gratuitous complexity*** [24] is an avoidable consequence of jointness that, if properly managed, does not need to impact the cost of a joint program. On the NPOESS, JPSS, and DWSS programs, essential complexity mechanisms included:

- Architectural complexity induced by spacecraft aggregation,
- Architectural complexity induced by a program's inability to trade non-synergistic requirements,
- And instrument design complexity induced by joint requirements.

In contrast, gratuitous complexity mechanisms included:

- Architectural complexity induced by aggregating additional requirements that exacerbated the impacts of an already non-synergistic requirements set,
- Architectural and process complexity induced by failing to prioritize missions,
- And design complexity induced by employing an aggregated system architecture in the ground segment.

With regards to the last gratuitous complexity mechanism, it seems that a better choice for the ground system architecture would have been one which collected data from the space segment and then provided data products in RDR form to the system's users. The users could have collected this data through a standardized interface and then applied their user-unique algorithms and processing procedures to convert data from its raw form to the specific products that were required. An open ground system architecture would have also facilitated climate science by allowing those users to experiment with and tweak algorithm parameters, knowing that the quality of the RDR that they were receiving would remain fixed. Of course, given NPOESS's acquisition strategy—which used performance-based contracts that levied requirements primarily on EDRs—an open approach to the ground system architecture was impossible. However, it appears that, in the case of the ground segment, perhaps a disaggregated, open architecture that was designed to meet the specific needs of its users would have been more cost-effective than the aggregated NPOESS one. Indeed, such an architecture did emerge *around* the NPOESS ground segment and thus, added additional cost.

## 7.5 Cross Case Comparison: Organizational Costs

Common organizational complexity mechanisms (with one exception) were observed only on the NPOESS and JPSS case studies. Importantly, in both cases, most organizational complexity was induced by misaligned interdependencies between intra-organizational components rather than by organizational aggregation itself. In this way, it appears that organizational *disaggregation* (i.e. misalignment), rather than aggregation, was responsible for organizational complexity. To further organize my cross-case comparison of organizational complexity, I classify mechanisms into two types of misalignment and one additional set of authority eroding factors. I define these categories as:

- **Misaligned responsibility and authority,** which occurs when a component is assigned either responsibility or authority but not both, or when a component's authority is not commensurate with its responsibility. Of the three categories of organizational complexity, this type had the most significant cost impact.
- **Authority eroding misalignment,** which occurs when authority and expertise, budget and responsibility, or authority and budget are misaligned. This type of misalignment induces complexity by eroding decision authority within an organization.
- Finally, **additional authority erosion factors** are organizational variables that were observed to further erode decision authority. These factors induced organizational complexity by exacerbating misalignments that were already present in an organization's architecture.

The impact of each misalignment type as well as the exacerbating impact of the additional authority erosion factors is summarized below.

### 7.5.1 Misalignment of Responsibility and Authority

The critical case of organizational disaggregation—or the misalignment of responsibility and authority—was observed in the NPOESS and less significantly, in the JPSS case study. Generally, when an organizational component was assigned responsibility but not authority, cost growth was *enabled* in two ways. First, organizational components with responsibility but no authority had to elevate decisions to components that held authority. However, since these authority-wielding components were not directly responsible for their decisions' outcomes, they often failed to make timely decisions. Second, to avoid elevating decisions, organizational components without decision authority maintained the status quo—regardless of its cost impacts—in order to avoid the time-consuming and often futile decision elevation process.

On NPOESS, the "Optimized Convergence" acquisition strategy, which misaligned the prime contractors' responsibility and authority, left the IPO without an effective incentive to make timely decisions or to actively manage the system's interfaces. A misalignment of responsibility and authority at the organizational interface between the NPP program and the IPO's instrument contractors also resulted in similar behavior: when disagreements between NPP and the IPO arose, issues had to be elevated to the EXCOM or resolved by selecting the most costly, status quo preserving option. Finally, similar dynamics were also present in the NPOESS user councils, which had responsibility for the system, but limited authority to make changes to it. As a result, when IPO management proposed reducing the system's capabilities to cut costs, the user councils maintained the status quo by vetoing proposed trades and by avoiding the time consuming process of elevating issues to their agencies' management or to the EXCOM for further consideration.

The EXCOM itself provided a vivid illustration of the impacts of misaligned responsibility and authority. Specifically, because all three agencies were responsible for the program, but no one agency held authority over the others, the EXCOM's decision making process was effectively paralyzed: instead of making decisions to reduce the system's capabilities in order to control the program's growing cost, members of the EXCOM maintained the status quo by denying requests to reduce the system's capability or to provide the program with increased funding. Furthermore, until just prior to the program's cancellation, none of the agencies elevated the program's issues to the one organization that held decision authority over all three of them—the White House. Instead, the EXCOM enabled the program's costs to continue growing by failing to intervene with decisive action or to seek guidance from the one office that could.

Although the EXCOM's inaction enabled cost growth, a key finding of this research was that the EXCOM played a greater role in the program's governance structure than was ever intended by the program's MOA. Contrary to other studies of the NPOESS program, which identified the EXCOM as being a key contributor to the program's failure [D216, D217, D220, D147] my data suggest that the EXCOM's enhanced role in program management was a symptom of the larger organization's complexity, rather than a key contributor to it. Specifically, I demonstrated that

> **It was the complexity of the organizational hierarchy beneath the EXCOM—and particularly the misalignment of responsibility and authority—which forced the EXCOM to play a decision making role that it was never intended by the MOA.**

Thus, while the EXCOM itself did contribute to organizational complexity and to the program's costs, it was the complexity of the organizational architecture *beneath* the EXCOM—from the program's user councils, the NPP program, and the "Optimized Convergence" strategy—which most significantly affected complexity and enabled cost growth: because authority and responsibility were misaligned between these components, they were forced to raise issues to the EXCOM because it was the single component in the organizational that had authority over the rest.

While organizational aggregation enabled cost growth on the NPOESS program, it was not observed to enable costs on JPSS.  This difference can be attributed to JPSS's official authority structure, which assigned NOAA final decision authority. To further simply the organizational architecture, NPP was integrated into the larger JPSS program and NASA was assigned decision authority over all of its contracts. Finally, the "Optimized Convergence" acquisition strategy was unique to NPOESS and thus, its impacts were not observed on JPSS.

Despite these differences, organizational disaggregation was observed to *induce* cost growth on both the NPOESS and the JPSS programs. In both cases, the misalignment of responsibility and decision authority *induced* cost growth in two ways.

- First, it slowed the decision making process by causing it to "swirl": without a clear and readily assessable authority to make decisions, both programs invested an unnecessary amount of time debating decisions and options before locating a decision maker with the authority to take action.
- Second, it increased the government's oversight of the program's activities and this additional oversight added extra work for program employees and detracted them from their tasks.

Decision swirl was particularly evident on the shared NPP-NPOESS instruments, where NASA and IPO engineers had different perspectives on how the system should be managed. While representatives from NASA and the IPO debated these perspectives, contractors' progress stalled as they waited for consensus to be reached among their government customers. When consensus could not be reached, NPP engineers elevated their issues to be discussed at the EXCOM. Similarly, NOAA organizations like STAR held different perspectives on how the JPSS ground system should be managed; as on NPOESS , these differences were debated and decisions "swirled" until NOAA intervened by assigning organizations like STAR to the NJO, rather than to the NASA ground project. Finally, JPSS's separate program offices also induced decision "swirl" since authority and responsibility were not clearly allocated to either of them. As a result, the program offices not only debated decisions and decision options, but also *who had the authority* to select an option in the first place.

Finally, the misalignment of authority and responsibility increased the government's oversight of both programs. On NPOESS, each agency audited the program independently and in doing so, generated three times the amount of inquiries and action items for the program office to respond to. Because the agencies had delegated their authority to be shared on the EXCOM—an ineffective tool for program governance—the information that they gathered at the expense of the program's other activities could not be used to influence positive change. Similarly, JPSS's dual program office structure also induced cost growth because both agencies independently monitored the program's activities. As on NPOESS, because NJO was not effectively integrated into the NASA program office, it was hard for NOAA leaders to affect NASA's activities. Instead, this additional oversight generated extra work for the program office that detracted it from its other tasks.

### 7.5.2 Authority Eroding Misalignments

While the degree that authority and responsibility were misaligned on JPSS was only a fraction of the misalignment that existed on NPOESS, both programs exhibited similar misalignments of responsibility and budget, of authority and expertise, and of authority and budget. These misalignments eroded decision makers' authority and enabled and induced cost growth.

On NPOESS, the NPP program office held mission but not budget responsibility for the program's instruments. As a result, when faced with a decision on how to resolve a test or analysis anomaly, NPP favored the option that minimized risk but typically maximized the IPO's cost. Alternatively, when the NPP program office encountered commensurate issues developing components for which they *did* hold budget responsibility, they more equally weighed risk vice cost. For example, the NPP program office was able to quickly resolve issues with its bus but was unwilling to compromise on many corrective actions that could have reduced the time to resolve related issues with the IPO's instruments.

A similar unwillingness to compromise on mission assurance and other requirements was observed on the JPSS program when interviewees questioned whether NASA would manage the program in the same way if it were also responsible for funding it. For example, many of the requirements levied during the "NASA-ification" process were previously requested by NASA but denied by the IPO for being costly or unnecessary; however, once NASA gained full implementation authority over NPP and JPSS, it levied most its desired requirements and implemented previously requested design changes. Importantly, although JPSS officially executed NOAA's mission only, it used instruments that were developed for NASA's NPP program and that provided climate data continuity for NASA's EOS system. Given NASA's close relationship to JPSS's instruments, it is not unreasonable to identify JPSS as a NASA mission as well; indeed, the presence of a climate mission on JPSS and the question of which agency is responsible for climate remains an open question today. Therefore, as on NPP, NASA held responsibility for JPSS's climate mission but no financial responsibility for the system. Thus,

> **On both NPOESS and JPSS, the misalignment of mission and budget responsibility enabled cost growth by hindering decision makers' ability to appropriately weigh risk and cost when making decisions.**

Ultimately, this misalignment weakened decision authority because decisions were made with a biased interpretation of decision options and of potential outcomes.

Alternatively, the misalignment of authority and expertise more directly eroded authority and enabled and induced cost growth on both programs. This particular form of organizational disaggregation was observed to *enable* cost growth when decision makers did not have the requisite expertise to make informed and effective decisions. Both the NPOESS IPO and the JPSS NJO were criticized for being staffed with agency representatives who did not have sufficient space acquisition experience and expertise. In both cases, not only did the decision makers' inexperience reduce the quality of their decisions, but it also made it possible for those decisions to be influenced by organizational components that held both expertise and a stake in decisions' outcomes.

For example, the IPO's early decisions on the system's requirements and technical architecture were influenced by prospective contractors who underestimated the system's cost in an effort to win a final contract. Similarly, NASA had an interest in implementing corrective actions that it had identified during NPP; because NOAA lacked the technical capability to push-back on NASA's suggestions or to question their benefit vice cost, the NJO's authority over its program's overall cost was eroded and the "NASA-ification" process proceeded. Therefore on both programs, I observed that

> **When an organizational component lacked expertise that was commensurate with its authority, its authority was eroded and its decisions were influenced by other components that had greater expertise.**

Finally, the misalignment of expertise and authority also *induced* cost growth. On the NPOESS program, NASA's expertise was misaligned with the authority that the IPO held over the NPP-NPOESS instrument contractors; as a result, NPP technical personnel often second-guessed the IPO's technical decisions. Like the previously discussed misalignment of responsibility and authority at the NPP-IPO interface, this misalignment also induced decision "swirl" as multiple organizations with technical capability debated options and delayed making a decision. On the JPSS program, NASA's interest in applying their technical capability to develop the JPSS system in accordance with its own, technically superior, processes and procedures motivated the formation of the JASD office at NASA Headquarters. In effect, JASD isolated NASA's JPSS program office and minimized NOAA's ability to second-guess NASA's technical decisions. Of course, by isolating itself, the NASA program office eroded NOAA's authority over JPSS and motivated NOAA to establish the NJO to more closely oversee NASA's work. As noted previously, JPSS's dual program office structure induced cost growth by doubling the government's oversight of the program's activities.

Finally, misaligned budget and authority between the NPOESS and JPSS program offices and their contractors also enabled cost growth by hindering the government's ability to make decisions with a full understanding of their costs. First, NPOESS's "Optimized Convergence" acquisition strategy extended the competitive portion of the acquisition process. Therefore, when the government changed its requirements before awarding a final contract, prospective vendors were incentivized to win by estimating that the requested changes had minor impacts; by failing to be more conservative in these impact analyses, contractors' underestimation of the system's cost translated into cost growth later. Alternatively, the JPSS program eliminated competition by awarding sole source contracts. As a result, when the government requested changes to NPP's heritage design, the program's contractors had little incentive to conserve the cost required to implement those changes, since the government had no other options. Thus, in both cases, the misalignment of budget and authority hindered the government's ability to manage their contractors' incentive to both minimize and to conservatively and accurately estimate the programs' costs.

### 7.5.3 Exacerbating Factors

Several other factors also eroded authority on the NPOESS and DWSS programs. For example, both programs were affected by a performance-based contract structure that limited the government's ability to directly control contractors' designs or development processes. In both cases, the contract structure enabled cost growth when the government's requirements changed and it needed to modify its contracts accordingly. Finally, the NPOESS EXCOM itself enabled and induced cost growth by failing to make decisions efficiently and effectively. The primary reason that the EXCOM failed to make decisions was that the agencies ineffectively delegated their authority to be shared on the tri-agency board. Essentially, the board was staffed by agency leaders who were too far removed from program execution to understand the criticality of their role or were too involved in other management activities that were more important to their home agencies than the NPOESS program.

### 7.5.4 Conclusion: Organizational Aggregation, Complexity, and Cost Growth

On NPOESS and JPSS, it was not the aggregation of multiple agencies into a single program office that induced organizational complexity but rather the disaggregation of key interdependencies between the organizations' components. The most impactful type of disaggregation was the misalignment of authority and responsibility, which enabled cost growth in two ways.

- First, it reduced the efficiency at which the organizations could make decisions. Because decision makers were separated from issues that required decisions and from decision impacts, their ability and incentive to make decisions efficiently was reduced.
- Second, it resulted in a tendency to maintain the status quo because the decision making process was cumbersome and required decision makers to collect and process information that was not readily available to them.

A key outcome of the early misalignment of responsibility and authority was that the NPOESS organization underestimated and under managed the complexity and costs of its technical system. Technical complexity was not under managed or underestimated intentionally; rather,

> **The technical system was managed to the best of the organizations' ability, which was limited given the misalignments in its architecture.**

The additional misalignments enabled cost growth in a similar manner.

- First, by extending the competition period and using cost-plus contracts, NPOESS's acquisition strategy misaligned contractors' design authority with their budget responsibility. This enabled the system's complexity and cost to be underestimated because the program's contractors had little incentive to conservatively report their costs until they won a final contract.
- Second, the misalignment of expertise and authority enabled and induced cost growth when a component used its expertise to sway the organization's decisions in its favor.
- Finally, the misalignment of mission and budget responsibility enabled cost growth by reducing the organizations' ability to make decisions that appropriately weighed risk and cost.

Furthermore, these misalignments often worked together; for example, cost growth could be enabled when an agency partner without budget responsibility used its expertise to erode the decision authority of another and to sway that agency's decision in its favor.

As with technical complexity, we can distinguish between essential and gratuitous organizational complexity [24]; in this case, gratuitous complexity refers to complexity that was induced by poor organizational design rather than complexity that is inherent to all joint organizations. The only essential complexity mechanism in JPSS and NPOESS was the misalignment of authority and responsibility that induced cost growth by motivating extra oversight. This misalignment is likely inherent in all joint programs since individual agencies' mission responsibilities are derived from separate Congressional committees. As a result, regardless of the authority relationship between agencies, their separate responsibility to Congress and their authority on the program will be misaligned. As I will discuss in the following chapter, the remaining complexity mechanisms could have been eliminated if the NPOESS and JPSS organizations had been architected to align responsibility, authority, budget, and expertise.

## 7.6 Conclusions and Motivation for Upcoming Chapter

To investigate the cost impacts of jointness, I structured my analysis according to the following hypotheses: that organizational aggregation induces organizational complexity, that technical aggregation induces technical complexity, and that complexity correlates with cost growth. I then proposed an alternative approach for studying complex acquisition programs with the following goals:

- To generate a practical and more detailed understanding of complexity in the context of government acquisition programs,
- To observe how complexity changes throughout a program's lifecycle and is impacted by government actions,
- And to generate actionable recommendations for future policy.

By starting with a practical definition of complexity and conducting process-centric interviews, I was able to observe:

- That technical complexity is induced by the complexity of the system's individual components, the interactions between components, and the process by which those components are developed.
- And that organizational complexity is induced when the authority, responsibility, budget, or expertise relationships between an organization's components are misaligned.

I was also able to observe a relationship between organizational and technical complexity: that as organizational complexity increased, it enabled technical cost growth and induced non-technical cost growth by hindering the organization's ability to make effective and efficient decisions. The process-centric interviews also enabled me to observe other more traditional causes for cost growth and to consider those causes alongside my definitions of complexity. Table 8 lists the traditional cost growth root causes that were identified in Chapter 2 and notes which programs they impacted. The Appendix contains additional description of how these factors affected the programs' costs.

**Table 8: Alternative Sources for Cost Growth**

| Primary Root Causes for Cost Growth | | | |
|---|---|---|---|
| **Root Cause** | **NPOESS** | **DWSS** | **JPSS** |
| **Requirements** | X | X | X |
| **Immature Technology** | X | X | X |
| **Poor Systems Engineering** | X | | |
| **Unrealistic Cost Estimates** | X | | |
| **Secondary Root Causes for Cost Growth** | | | |
| **Root Cause** | **NPOESS** | **DWSS** | **JPSS** |
| **Program Length** | X | X | X |
| **Budget & Schedule Uncertainty** | X | | X |
| **Contracting Mechanisms** | X | X | X |
| **Weak Industrial Base** | X | X | X |

Finally, using the quantitative framework, I was able to observe that organizational and technical complexity were dynamic properties that evolved throughout the programs' lifecycles. Furthermore, by connecting epoch shifts to agency actions and technical decisions, I was able to identify and assess the policy directives that impacted the NPOESS, JPSS, and DWSS programs. Using the perspective gained from that analysis, I generated the following policy recommendations, which should be considered by joint programs in the future. First, to more effectively manage technical complexity, future joint programs should:

- Recognize that joint requirements hinder a program's ability to leverage individual agencies' heritage capabilities and should budget for the technology development that is necessary to integrate all of those capabilities into a single system.
- Acknowledge that aggregated spacecraft architectures are often the least costly way to meet aggregated requirements. Given this understanding, programs should either:
    - Budget for the cost of spacecraft aggregation (i.e. the cost of instrument interactions and bus design complexity)
    - Or explore possible trades between requirements and spacecraft aggregation and disaggregation (i.e. consider levying requirements such that, if preferred, a disaggregated architecture is less costly than an aggregated one)
- Avoid full aggregation of the ground system and use an open architecture instead. Consider sharing core components and defining standardized interfaces that allow users to access RDRs but to define unique systems to independently process them.
- Utilize common engineering standards or invest in non-recurring system engineering effort to reconcile agencies' different standards.
- When defining requirements, recognize that if two agencies have non-synergistic requirements, it is unlikely that they will be able to trade those requirements later on, even if the program's costs grow. Therefore, programs with non-synergistic requirements should include extra contingency budget to prevent cost growth and schedule delays on one component from inducing cost growth on others.

- When defining requirements, recognize that unlike non-synergistic requirements, synergistic requirements can be traded if missions are prioritized. Therefore, programs should prioritize their missions or include the extra contingency budget that was recommended for non-synergistic requirements.
- Do not execute a risk reduction mission and an operational mission using the same set of instruments. An instrument for risk reduction and a separate operational instrument may be hosted on the same spacecraft, but both missions should not be executed by the same instrument.

Second, to manage organizational complexity, future joint programs should

- Award contracts early in the system's lifecycle and concurrently for all of the system's components. If a program wishes to keep multiple vendors in competition for a longer period of time, it must hold its requirements fixed and actively manage all interfaces between components.
- Fully integrate responsibility, authority, budget and expertise into a single program office.
- Fully integrate the government's responsibility, authority, budget, and expertise over its contractors into a single program offices (i.e. do not share contracts between programs as on JPSS and DWSS or transfer critical instruments from one program office to another as on NPP).
- Institute a PEO-like authority structure over a joint program's user community to enable capability reductions.
- Budget for increased oversight that results from the misalignment of responsibility and authority that occurs anytime agencies form joint programs.
- Insure that the organizational architecture "mirrors" the architecture of the technical system under development. Specifically:
    - Aggregated technical architectures should be developed by fully aggregated organizations with single program offices.
    - And disaggregated technical architectures should also be developed by single program offices and importantly, those offices should be disaggregated from one another.

Finally, I generated my most significant policy recommendations not by considering technical and organizational architectures separately (as above) but rather, by recognizing the important relationship between them. Therefore, in the next chapter, I propose the Agency Action Model, which integrates my organizational and technical case study analyses and explains joint program cost growth in terms of institutionally interested agency actions. Using this model, I am able to explain the common complexity mechanisms that were discussed above and the evolution of complexity that was observed in my case studies. Finally, in Chapter 9, I illustrate how future government decision makers can apply the model to architect joint programs in the future.

# 8 The Cost of Jointness

*A central paradox of jointness is the hostility that it has often generated.*

–Roger Beaumont, in *Joint Military Operations: A Short History [3]*

This dissertation began with the hypotheses: (1) that organizational aggregation induces organizational complexity and (2) that technical aggregation induces technical complexity. As described in Chapter 7, the data did not exactly conform to the hypotheses that motivated this study. In particular, despite being only organizationally joint, I noted several technical complexity mechanisms on the JPSS program. In this chapter, I argue that the discrepancy between my starting hypothesis and subsequent observations—as well as the evolution of complexity over time—can be understood in terms agency actions that were intended to retain or regain agency autonomy. I begin this chapter by recasting my analysis of the NPOESS, JPSS, and DWSS programs using an agency action perspective and use this discussion to propose the Agency Action Model, which generally explains cost growth on joint programs. Finally, I conclude by applying the model to my case study data and speculating on its broader applicability to other joint programs.

## 8.1 The Cost of Jointness on NPOESS, JPSS, and DWSS

Complexity was driven into the NPOESS, JPSS, and DWSS technical and organizational architectures by agency actions that were intended to preserve and expand each agency's individual decision authority and its ability to match that authority with its unique mission. Specifically,

***The collaborating agencies' institutional interest in retaining or regaining their autonomy drove complexity into the NPOESS, JPSS, and DWSS programs' architectures and induced cost growth.***

In the remainder of this section, I re-cast my previous case study analysis through the lens of public administration theory and use this perspective to explain the technical decisions and agency actions that induced complexity. I conclude by discussing the checks and balances that may have been capable of controlling agencies' quest for autonomy, but were absent on the NPOESS and JPSS programs.

### 8.1.1 Bureaucratic Politics and the Evolution of Complexity on NPOESS, JPSS, and DWSS

Each of the agency actions discussed in Chapters 6 and 7 can be understood using a bureaucratic politics perspective that interprets agency actions as being motivated by an institutional interest in retaining or regaining autonomy. For clarity, I define *autonomy* to be the freedom to make mission execution decisions independently. The concept of autonomy is closely related to *authority,* or the power to make mission execution decisions; thus, if an agency lacks autonomy, it does not have the *authority* to make mission execution decisions independently. Agencies retain autonomy by sharing authority and regain autonomy by eroding the authority of their partners.

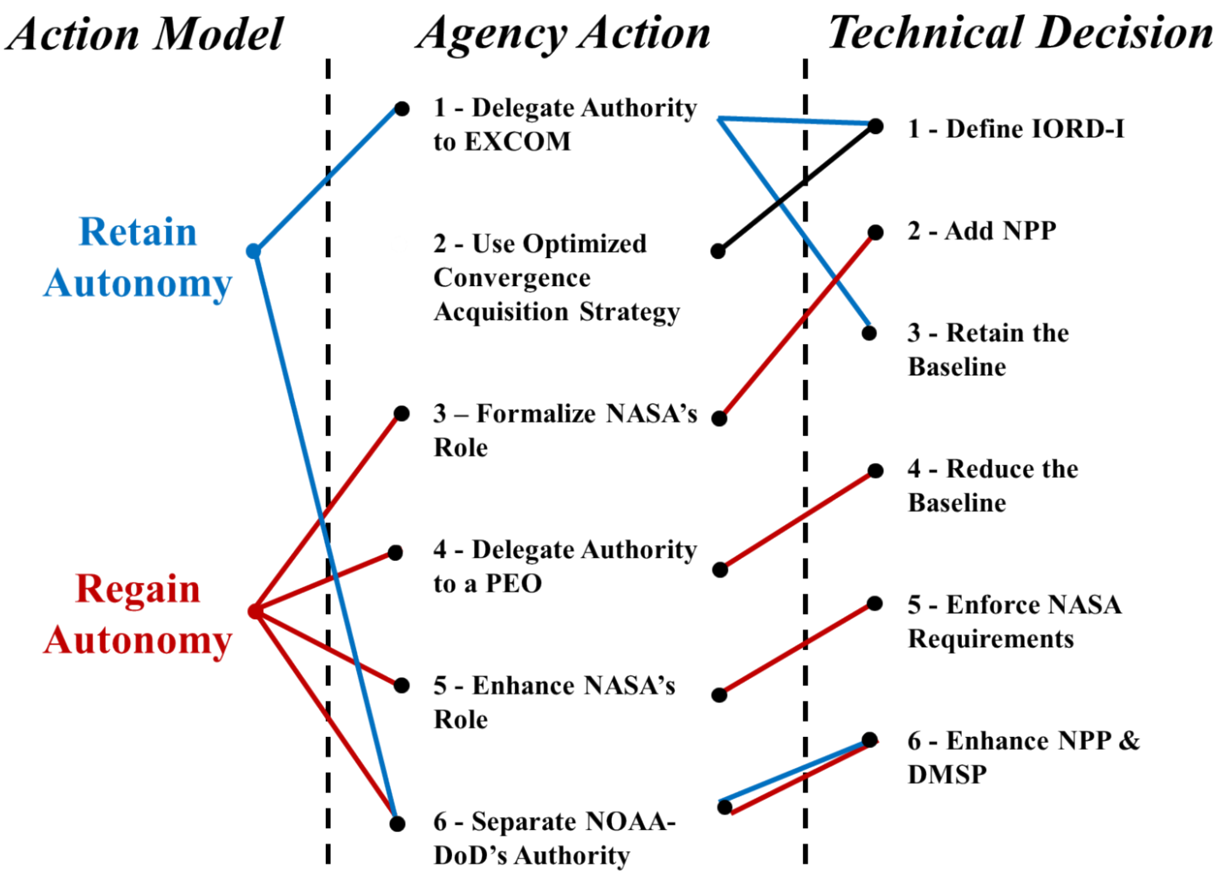


**Figure 49: Agency Actions in the NPOESS, JPSS, and DWSS Case Studies**

Figure 49 maps each agency action—which induced organizational complexity—to the agencies' institutional interest in retaining or regaining their autonomy. As also shown, each agency action can be connected to a decision—made by the joint organization—that induced technical complexity and cost growth. Thus, we observe that the joint organization provides the critical link between interagency politics and both the technical and non-technical cost growth that is incurred on joint programs.

Action 1, which delegated decision authority to the EXCOM, protected the agencies' autonomy. With authority shared in the collaborative body, it was impossible for a single agency to exert decision authority or power over the others. Because decisions were made by consensus, each agency retained the authority to veto any decision that either reduced its authority or its ability to execute its unique mission. The agencies' emphasis on equality translated into the joint mission defined by the IORD, which levied each agency's unique or driving requirements on the system. By doing so, the IORD respected the power balance between agencies and matched their shared authority over the NPOESS system to their unique missions—by requiring the system to execute all of them.

Action 1 also impacted technical costs later, when the program was forced to maintain its baseline despite cost growth and program managers' requests to reduce the system's capabilities. Because the agencies' requirements were non-synergistic, capability reductions threatened agencies' authority to execute their unique missions; therefore, the balance of interagency power was preserved by maintaining the technical architecture that was specified by the IORD.

Agency interactions at the EXCOM are also important to note. NOAA and NASA representatives consistently attended EXCOM meetings, whereas the DoD representative did not. Relative to NOAA and NASA, the DoD yields a considerable amount of bureaucratic autonomy, has a tremendous budget, and executes a unique mission that is critical to national security. Furthermore, compared to the DoD's other missions, NPOESS was inconsequential; as a result, the agency had little interest in exercising its authority over a program that it interpreted to be increasingly focused on climate science. In battlefield of bureaucratic politics, compared to the NOAA and NASA, the DoD had already won; therefore, it had little incentive to engage in a power struggle with NOAA or NASA. However, despite its tacit victory, the DoD's absence at the EXCOM ultimately induced organizational complexity, because it without quorum of members, the EXCOM was unable to make decisions. Of course, given the agencies' interest in retaining autonomy, even if the DoD representative had attended the EXCOM more frequently, it is unlikely that the tri-agency body would have decided to do anything other than maintain the status quo and balance of power between the agencies.

In contrast, from NASA's perspective, the NPOESS system executed two missions that the agency had once autonomously executed. Prior to NPOESS, NASA held full authority over EOS's unique climate science mission and implementation authority for NOAA's POES. Through its initial involvement in the EXCOM and NPOESS, NASA held some authority over those missions but that authority paled in comparison to what it had wielded on POES and EOS. So while the DoD interpreted NPOESS to be inconsequential to its institutional interests—to NASA—NPOESS was critical. By regaining autonomy over NOAA's weather mission and its own climate science mission, NASA could reestablish the bureaucratic autonomy and the relative power that it held prior to convergence.

The first step to regaining NASA's autonomy was Action 3, which formalized the agency's role in the program. To add insult to injury, when NPOESS was established, not only did NASA lose POES and EOS, but the program's MOA failed to clearly define the agency's responsibility for NPOESS. Officially, the MOA made NASA responsible for technology transition but assigned the DoD the authority to manage the system's contracts. How could NASA infuse technology into the NPOESS system without holding authority over it?

The answer of course, was to formalize NASA's technology transition responsibility through the risk reducing NPP program. With the formation of NPP, NASA gained formal authority over technology transition, since most new NPOESS technologies would be tested on NPP. But NPP was also a bureaucratic bargaining chip. In addition to formalizing its authority over the technology transition mission, NPP provided NASA a venue to match its newfound authority with its climate science mission. In exchange for providing a spacecraft and a launch vehicle, NASA got climate science requirements levied on the NPOESS program. In this way, NASA began the process of matching its jurisdiction over technology transition to its agency unique climate science mission.

Despite NASA's relative gains, it lost authority and found its power over NPP significantly reduced after the Nunn-McCurdy certification. Action 4 delegated decision authority from the EXCOM to the PEO and empowered him to make decisions that affected *both* the operational NPOESS system and NPP. The technical decision that resulted, to prioritize weather over climate sensors, also threatened the balance of agency power because it prioritized the operational agencies' missions over NASA's. Critically, even though all three agencies participated, the Nunn-McCurdy certification process was executed unilaterally by the DoD. In effect, the process took decision making out of the hands of the EXCOM—which had been intentionally designed to preserve agency power—and moved it into a venue that was dominated by the DoD. Thus, despite the power that NASA had gained after Action 3, Action 4 demonstrated that the DoD still had greater power than either NOAA or NASA and the ability to re-focus NPOESS's missions according to its own institutional interest.

After reasserting its power during Nunn-McCurdy, the DoD assumed that the authority it delegated to the PEO would be sufficient to represent its interests. As a result, the DoD resumed its pattern of failing to attend EXCOM meetings. However, the DoD's interest in developing a low-cost weather system was opposed to NASA's, which sought to execute its climate science mission using NPP. In the battlefield of bureaucratic politics, the DoD's actions during Nunn-McCurdy warranted a defensive maneuver by NASA to protect its interest in NPP. However, the DoD's continued absence at the EXCOM enabled NASA to pursue a more aggressive and offensive maneuver with Action 5, when NASA formalized its alliance with NOAA by installing its own civil servants at NESDIS and by using these positions to erode the authority of the PEO and to persuade his decisions to favor NASA's interests.

The interagency turf war came to an end with Action 6 when the Administration separated NASA and the DoD's authority and cancelled NPOESS. With Action 6, NASA gained full authority to execute NPP and implementation authority over the entire JPSS system—including both the space and the ground segments. Thus, compared to the power it wielded prior to NPOESS, NASA gained even more bureaucratic autonomy through NPOESS's cancellation than it had lost after its formation: this outcome is unsurprising given the lobbying that NASA did in support of cancelling NPOESS. Also unsurprising is NOAA's response to NASA's power grab: the agencies' struggle for control of the JPSS ground system and the establishment of two separate program offices illustrates that the bureaucratic battle began anew after NPOESS was cancelled. In contrast, once the DoD was freed of its collaboration with NOAA and NASA, it soon realized that the capabilities of the NPOESS instruments that were slated to fly on DWSS were a poor match for its mission. Since the DoD had full jurisdiction over that mission, it was able to respond swiftly and cancel DWSS, only one year after its formation.

The one agency action that does not fit a bureaucratic politics interpretation of events is Action 2, the decision to use the "Optimized Convergence" acquisition strategy. Quite simply, Action 2 was just a bad decision that had impacts which could have affected any government program. From a bureaucratic politics perspective, this action simply slowed down the battle. It hindered the program's ability to estimate its costs and to manage technical complexity and in doing so, allowed the agencies to maintain equality by defining and maintaining a complex technical system that executed everyone's missions. Perhaps if the program had a stronger acquisition strategy, it would have recognized the cost impacts of its decisions and actions earlier. This could have accelerated the interagency warfare that occurred later and resulted in a swifter cancellation of the program or more optimistically, could have forced the agencies to work together to re-architect both their system and their organization.

### 8.1.2 Checks and Balances

Are all joint programs doomed to serve as a battlefield for bureaucratic turf wars in the way that NPOESS, and to a lesser extent, JPSS was? The answer of course, is both yes and no. Theory suggests that agency actions are motivated by institutional interest and therefore, none of the actions described above—which ultimately drove complexity into the programs' organizational and technical architectures and resulted in cost growth—are unexpected. However, closer inspection of the organizational architectures reveals that they left agencies' institutional interests unchecked. By ineffectively balancing agencies' individual mission interests with authority or budget responsibility, the organization allowed agencies to struggle for power. When one agency triumphed, its action caused an epoch shift that changed the programs' organizational and technical architectures and drove both towards increased complexity. Therefore, if the joint organizations had appropriate checks and balances to control the agencies' institutional interests, they may have prevented some of the evolution towards increased complexity and cost.

Two key characteristics defined the organization that was established by Action 1: shared decision authority and misalignment of responsibility and budget. First, NOAA, NASA, and the DoD shared decision authority over a system that would execute a non-synergistic set of requirements. The problems created by the lack of synergy and power sharing were exacerbated by the more critical problem that NASA held authority but contributed no budget for the NPOESS program. Compounding this problem, NASA's agency unique mission was synergistic with NOAA's but was fundamentally misaligned with the operational weather mission that NPOESS was initially established to execute. A classic principal-agent problem, with NASA as an agent facilitating technology transition for the principal (NOAA and the DoD) was the result.

Despite being an agent, NASA exerted considerable power over its principals. For example, NASA exercised the power of its expertise during the requirements generation process: since NASA had previously served as NOAA's acquisition agent on POES, NOAA defaulted to NASA's technical recommendations. Therefore, even though NASA did not formally levy requirements on NPOESS, it actively participated in the requirements development process as an agent working on behalf of its principal, NOAA. Importantly, because NASA's institutional interest was partially aligned with NOAA's (i.e. their requirements were synergistic), NOAA did not immediately notice that it was the agent, and not the principal, who was driving the requirements definition process. The organization provided no check to NASA's pursuit of institutional interest because NOAA lacked the necessary expertise to question NASA's recommendations and because NASA had no budget responsibility for the program. The result was a requirement set for NPOESS that more closely resembled NASA's EOS program than it did NOAA or the DoD's heritage systems; of course, the difference between EOS and NPOESS was that NASA paid for EOS.

The joint organization could have checked NASA's institutional interests by balancing them with budget responsibility and requiring NASA to contribute a portion of the program's budget. In retrospect, an even better solution would have been to exclude NASA altogether. Without NASA, NPOESS still would still have a non-synergistic set of requirements to meet; however, those requirements would have been focused on weather and could have been executed by four instruments, rather than 10+ instruments that were included on the NPOESS program. Therefore, even if the agencies had to maintain their balance of power by not changing the program's baseline later, the initial baseline would have been less costly than what was ultimately established for NPOESS.

The organization created after Action 3 contained a fundamental flaw—the misalignment of responsibility and authority—that provided a mechanism for NASA to openly and detrimentally pursue its interests. Ultimately, it was the interface between the IPO and NPP that crippled the organization's ability to make effective and efficient decisions by "breaking the mirror" between the program's organizational and technical architectures. The interface also created a second principal-agent problem between NPP and the IPO. The NPP program office was the agent executing the IPO's risk reduction mission. However, NPP exerted considerable control over its principal by using its technical expertise to erode the authority of the IPO and its contractors. By eroding their authority, NASA was able to sway decisions toward its institutional interest, which primarily focused on executing NPP's climate science mission. NASA's actions were unchecked by budget responsibility, since it did not fund NPP's instruments and therefore, did not have to pay for the decisions that the IPO made regarding them.

Again, the joint organization could have been architected to check NASA's institutional interest. For example, a risk reduction program could have been formed *within* the IPO and designated to be subordinate to it. This would have integrated the agencies' responsibility and authority and prevented NASA from eroding the authority of the IPO's contractors and from seeking its administration's intervention when it could not sway decisions in its favor. Alternatively, NASA could have been awarded full authority and the budget to develop and field the first copies of each instrument. In this way, NPP could have been similar to the Operational Satellite Improvement Program (OSIP) that was cancelled before NPOESS.

Despite Action 4's attempt to regain the power that NASA had gained after Action 3, it failed to re-architect the organizational interface between the IPO and NPP; as a result, the principal-agent problems discussed above remained. These problems were exacerbated by Action 5, when NASA personnel transferred into NESIDS and eroded the PEO's authority: essentially, at this point in the program, the agent became the principal.

Even after NPOESS's cancellation, the fundamental principal-agent problem between NOAA and NASA remained. NASA used the power of its expertise to claim authority over both JPSS' space *and* ground segments and to justify many of the costly changes to the system's technical architecture. Because NOAA lacked sufficient expertise to question NASA's decisions, in most cases, NOAA simply defaulted to them. As on NPOESS, NOAA and NASA's mission interests were synergistic; therefore, NASA's decisions often benefited NOAA, even though they may have cost more money than NOAA would have spent independently. Again, NASA's primary institutional interest was climate science and in developing a system to succeed EOS and NPP. And as on NPP, NASA held no budget responsibility for its decisions on JPSS, since they were funded entirely by NOAA.

## 8.2 The Cost of Jointness

In this section, I formalize and generalize the discussion above and use my case study data to propose the Agency Action Model to explain cost growth on joint programs in terms of their collaborating agencies' institutional interests and the actions that they motivate. Specifically, the model suggests that:

***Collaborating agencies' institutional interest in retaining or regaining their autonomy induces cost growth on joint programs.***

As in the case study data discussed above, the medium through which agency actions induce cost growth is a joint program's technical and organizational architecture. Figure 50 maps both actions—retaining and regaining autonomy—to the types of complexity that they induce. As shown, retaining autonomy primarily induces technical (design and architectural) complexity whereas regaining autonomy primarily induces organizational complexity by misaligning authority, responsibility, budget, and expertise. The links between agency actions and complexity mechanisms shown in Figure 50 are consistent with the instances observed in my case studies.

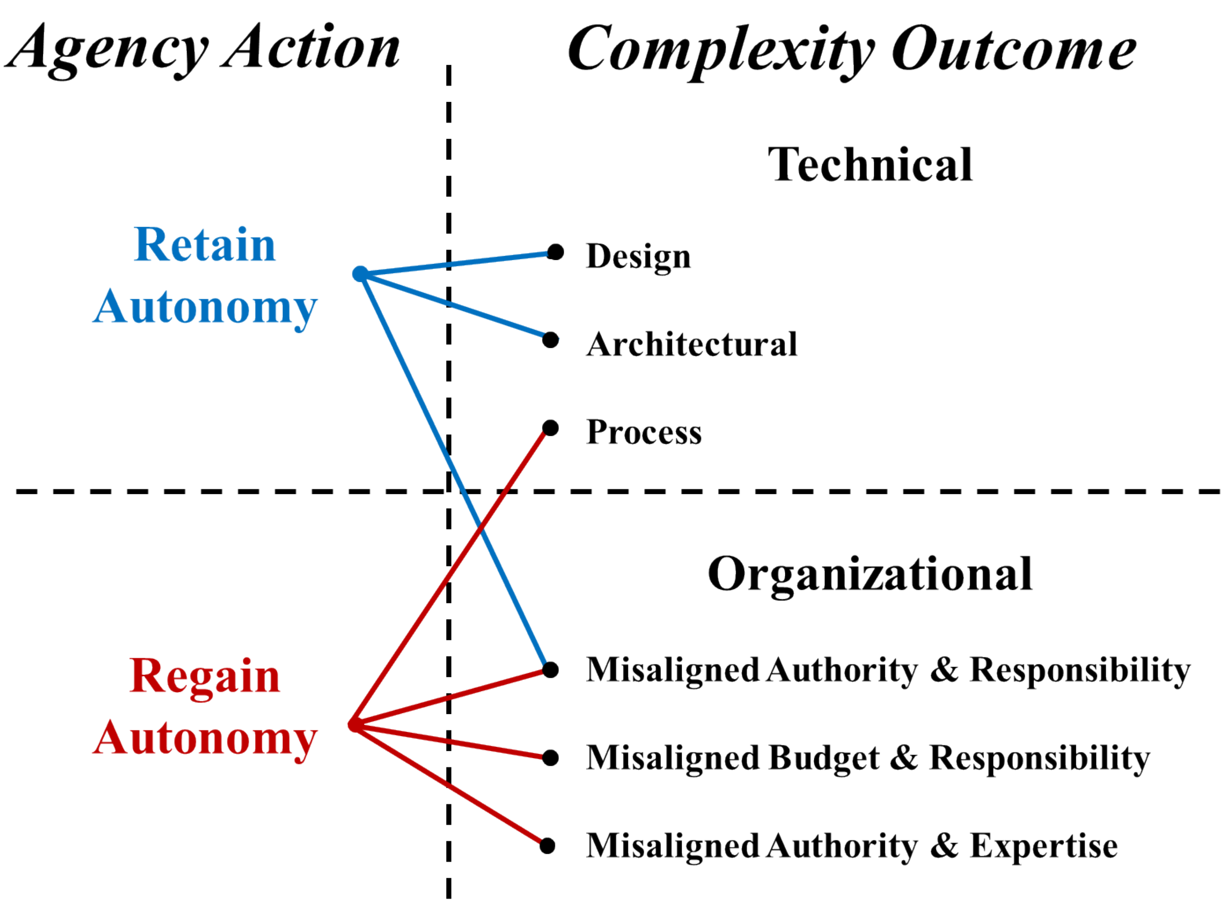


**Figure 50: Agency Actions Inducing Complexity**

In this section, I abstract my data and use it to propose a general Agency Action Model to explain cost growth on joint programs. After discussing the basics of the model, I introduce principles for architecting joint programs. The purpose of the principles is to define joint program forms (i.e. joint program technical *and* organizational architectures) that provide checks and balances against cost inducing agency actions and to identify the cost risks associated with all forms of jointness.

### 8.2.1 The Agency Action Model

The Agency Action Model describes cost growth on joint programs in terms of collaborating government agencies, those agencies' institutional interests, and the actions that they motivate. Using these components—the agencies, the interests, and the actions—the Agency Action Model identifies two mechanisms for cost growth. The first mechanism—which induces baseline cost growth—occurs when a joint program is organized in one of the basic forms shown in Figure 51. In these forms, the agencies' actions to retain or regain their autonomy increases joint programs' costs in a predictable way: because the risk for cost growth is predictable, future joint programs can add contingency funding to their *baseline* budget to reduce this risk.

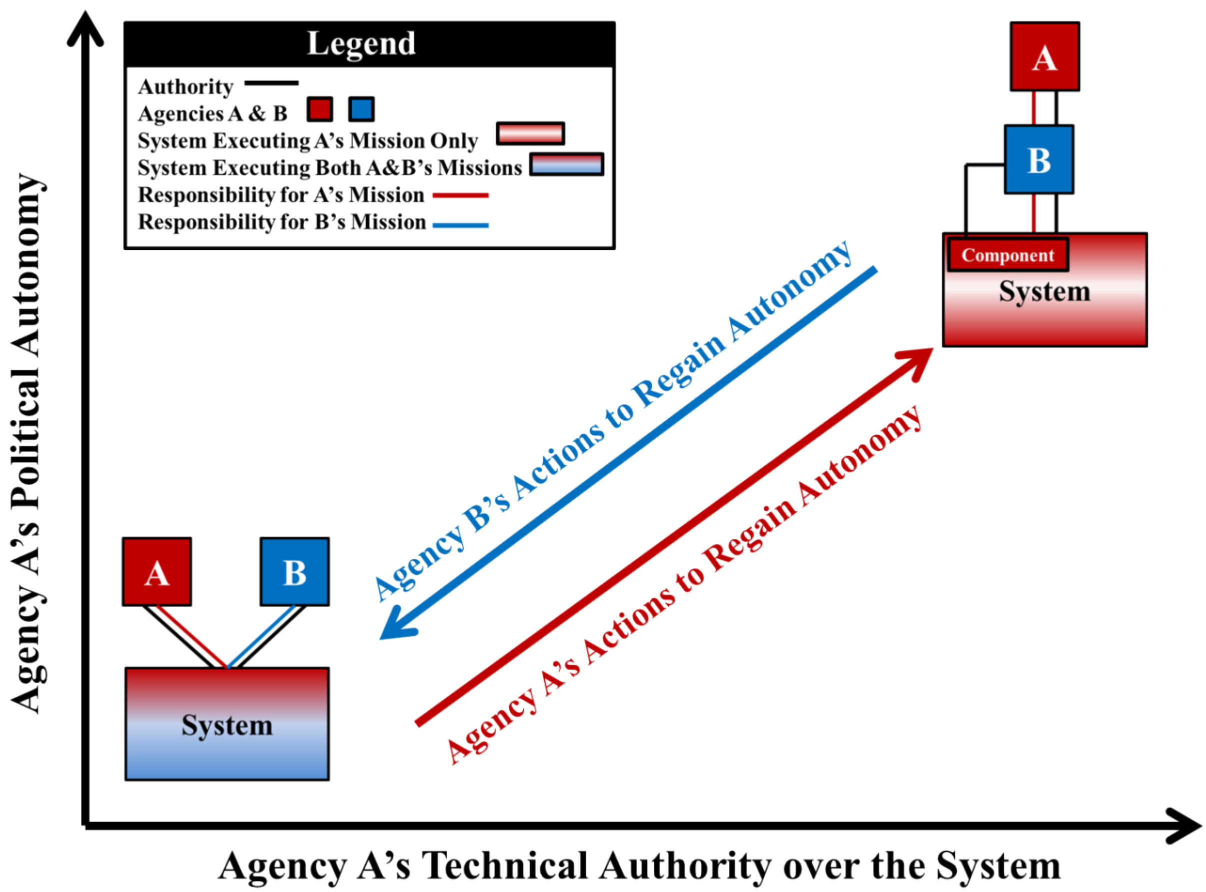


**Figure 51: Agency Actions to Regain Autonomy**

The second mechanism—which induces lifecycle cost growth—occurs when joint programs evolve away from the Figure 51's basic forms. When this happens, the agencies take opposing actions to regain their autonomy and in doing so, place their institutions and their actions in conflict with one another. Agency conflict induces cost growth in an unpredictable way by making the joint organization unstable and inefficient. Because this risk for cost growth is unpredictable, it cannot be reduced by adding contingency funding to future joint program's budgets; instead, agency actions will induce cost growth throughout a joint program's *lifecycle.*

In this section, I explain both mechanisms and their implications in terms of the agencies that take actions and the interests that motivate those actions. Finally, I review the actions that occur within the basic joint program forms and those that occur across them, when programs evolve from one form to another.

#### 8.2.1.1 The Agencies

In the Agency Action Model, the government agencies that participate in the joint program are those that have the authority to make programmatic decisions and the responsibility for developing a system to execute a mission. The agencies also contribute budget to fund the joint program and expertise to increase the quality of the program's decisions. Authority, responsibility, budget, and expertise are the same four characteristics that I used to define government agencies throughout this dissertation; as a reminder, I defined these characteristics as:

- **Authority**: When an agency has authority, it has the power to make and sustain decisions related to its mission.
- **Responsibility**: When an agency has responsibility, it is accountable for delivering a technical system that executes its mission.
- **Budget**: When an agency provides budget, it is responsible for funding the decisions that it makes and the technical system for which it is responsible.
- **Expertise**: When an agency has expertise, it has the knowledge and experience necessary to make decisions effectively.

Given these definitions, one can observe the importance of aligning responsibility, budget, and expertise with authority. Authority and responsibility should be aligned so that agencies have the power to make decisions regarding the systems that execute their missions. Authority and budget should be aligned so that agencies can consider cost when making decisions. Finally, expertise and authority should be aligned to insure that agencies make informed and effective decisions.

The government's interest in aligning authority, budget, responsibility, and expertise *across* agencies often motivates government leaders to form joint programs. For example, when two agencies lack the budget to execute their missions independently, they can share a budget and execute their missions jointly. When one agency lacks the technical expertise to develop a system to execute its mission, it may partner with another agency that houses the necessary expertise. Finally, when two agencies execute similar missions, they can reduce costs by sharing authority over a single system that executes both missions. Despite the government's interest in aligning authority, responsibility, budget and expertise, the Agency Action Model suggests that joint program costs grow because oftentimes these critical interdependencies are misaligned within joint program offices and as a result, agencies can take actions that increase programs' costs.

#### 8.2.1.2 The Interests

The Agency Action Model states that agencies' actions are motivated by institutional interests; as such, rational choice theory—which suggests exactly that (e.g. see [90, 92])—provides a theoretical backbone for my model. Within this theoretical framework, Downs' law of inter-organizational conflict states that every government agency is in partial conflict with one another over its authority, mission, budget, and relative expertise [93]. As discussed in Chapter 2, agencies perceive other organizations that have similar missions or overlapping jurisdictions (i.e. overlapping decision authority) to be their rivals [93]. By taking actions to retain their autonomy from these organizations, agencies attempt to establish a permanent claim over their mission and jurisdiction by eliminating the external threat that is posed by rival agencies [93-94].

Rival agencies pose two distinct threats. First, they threaten an agency's ability to execute its unique mission and second, they threaten an agency's ability to execute its mission independently and without interference by other agencies. Agencies are interested in eliminating these threats by maintaining autonomy; thus, in seeking autonomy, an agency has two interests:

- To execute its unique mission,
- And to do so without interference by other agencies.

When an agency participates in a joint program, by definition, it sacrifices some of its autonomy. However, even without complete autonomy, agency actions in joint programs are motivated by the same interests listed above. As such, these interests are critical to understanding how jointness itself induces cost growth.

Importantly, agency actions are not only affected by interests *within* a joint program; instead, they are affected by interests that span *across* a portfolio of missions that are executed by multiple programs. Specifically, government agencies are typically tasked to perform numerous missions for the public; to execute those missions, agencies form programs which are either joint or are contained wholly within an agency. According to executive and legislative guidance, government agencies *prioritize* their missions. When a mission has high priority, it is the focus of agency management; as a result, any programmatic decisions that require management approval are made quickly, since the program enjoys the attention of senior agency leaders. Similarly, missions with high priority receive their budget allocations first; as a result, compared to lower priority missions, missions with higher priority are more likely to receive funding at or nearer to the level that they requested. Finally, agencies tend to assign high performing employees to high priority missions; therefore, missions with high priority are executed by program offices that contain a great deal of the agency's expertise. As a program's priority decreases, it is increasingly difficult for the program to gain the attention of agency management or to receive the budget and expertise that is necessary to execute its mission.

Within joint programs, agencies' interests conflict when their priority for the joint program's mission differs. Because each collaborating agency must prioritize the joint program's mission with respect to its portfolio of other missions, the amount of management attention, budget, and expertise that each agency awards to the program may vary. Thus, agency interests can induce the misalignments in authority, responsibility, budget, and expertise that enable agency actions and result in the cost growth that is discussed below.

#### 8.2.1.3 The Forms

In the Agency Action Model, joint programs are defined by the agencies' relationships with one another and with the system under development. The primary relationships, or interdependencies, are authority and responsibility and the secondary relationships are budget and responsibility and authority and expertise. Depending on how these relationships are architected, joint programs can take on multiple different forms; therefore, to discuss the Agency Action Model and its implications, I will define and represent these forms using three dimensions:

- Agency authority relationship,
- Program modularity,
- And mission synergy.

Figure 52 illustrates how the four basic options for agency authority relationship are represented. First, agencies can *share authority* and remain equal partners. The agencies can also *delegate authority* and have one agency serve as a lead agency that has authority over the partner agency; in this case, the agencies are unequal partners because the lead agency's ultimate authority is maximized while the partner's is minimized. As shown in Figure 52, both options are identified by the following coding scheme: shared authority (S) and delegated authority (D).

Figure 52 also illustrates how the two options for program modularity and mission synergy are represented. First, a program is *integrated* (I) when only a single organization holds authority over its components. In contrast, a program is *modular* (M), when its functions are separated, the system is modularized (i.e. its functions are assigned to separate forms) so that authority over the modules can be delegated to different organizations. Finally, agencies' missions are *synergistic* (S) if their system requirements are similar and are best executed using an integrated system. Agencies' missions are *non-synergistic* (N) if their system requirements are dissimilar and they can be executed using a modular system. Restated, non-synergistic missions levy requirements on systems that are easily decoupled and that can be executed using separate components. The concept of mission synergies will be further described in Chapter 9.

As shown in Figure 53, these dimensions can be combined to create two basic joint program forms (i.e. forms that result in baseline cost growth). The first form is identified as SIS since it has the agencies *sharing authority* (S) and working in an *integrated* (I) program that executes *synergistic missions* (S). Form SIS is indistinguishable from form SIN (i.e. shard authority, integrated program, and non-synergistic missions) because as long as agencies *share authority,* an integrated program manages synergistic and non-synergistic missions identically. The second form is identified as DMN since the lead agency *delegates authority* (D) to its partner agency, the program is *modular* (M), and the agencies' missions are *non-synergistic* (N), since the system executes only one agency's mission. Consistent with the symbols used throughout this dissertation, the colors represent each agency's mission (red for Agency A and blue for Agency B). The colored lines connecting the agencies to the system indicate how the agencies' delegate their mission responsibilities. The color of the system indicates which agency's mission the system executes; for example, form SIS executes both agencies' missions, while form CMN executes only Agency A's mission. Finally, the black lines indicate authority relationships between the agencies and the system.

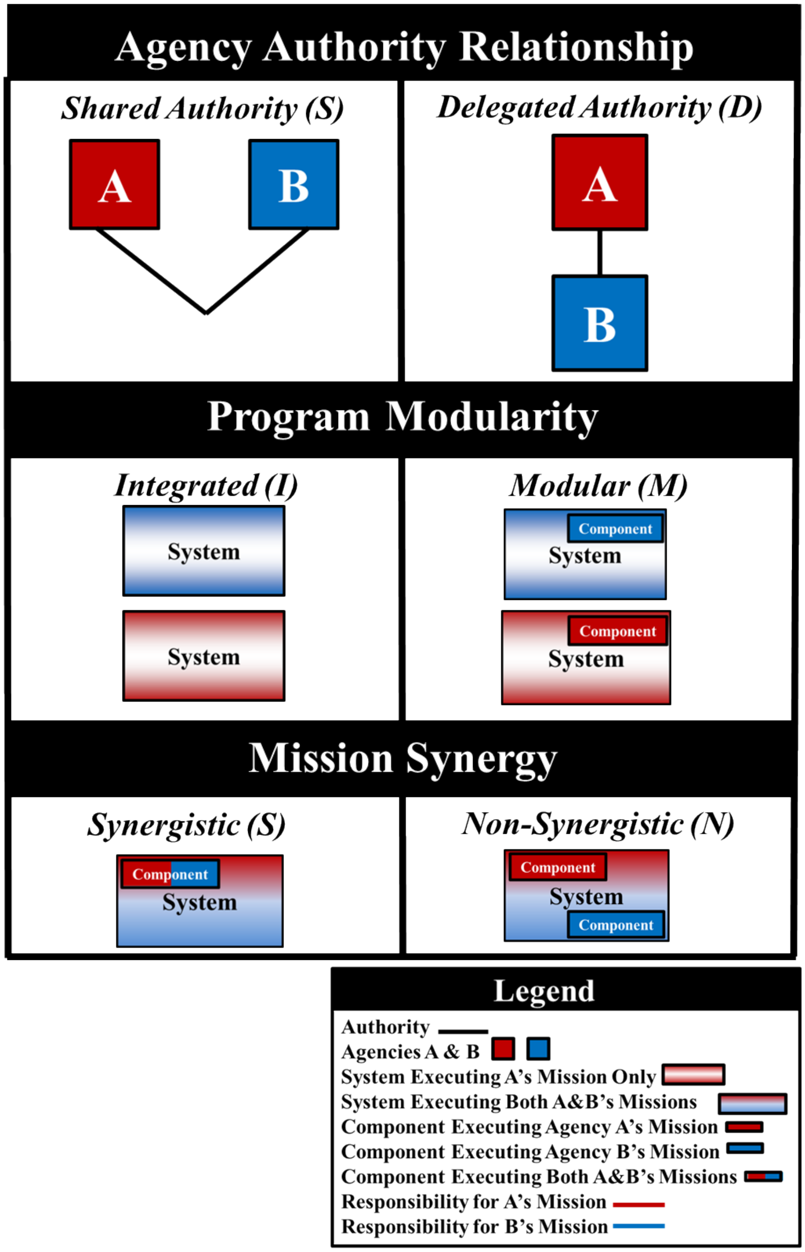


**Figure 52: Symbols Used to Represent Joint Program Forms**

In an attempt to maintain visual simplicity, budget and expertise relationships are omitted from Figure 53's (and all subsequent) joint program forms. As will be discussed later, aligning authority with expertise and budget with responsibility is critical for minimizing organizational complexity; therefore, my visual representations will focus on responsibility and authority and my discussion will highlight scenarios in which those primary interdependencies are not aligned with the secondary ones.

### 8.2.1.4 Actions Within the Basic Forms

Within Figure 53's basic joint program forms, the agencies' interests motivate two different actions. In form SIS, the agencies *retain* their autonomy by *sharing authority*. Sharing authority allows *both* agencies to retain equal autonomy because it prevents either agency from making mission execution decisions that affect the other without consulting them first. Furthermore, when making decisions, both agencies must agree on the selected option; if an agency disagrees, it has the authority to veto the other agency's selection. Using this veto power, agencies can insure that their unique missions are executed by the joint system and that their collaborators cannot interfere with that mission's execution. Again, when agencies participate in any joint program, they sacrifice some of their autonomy; however, sharing authority enables the agencies to be equal partners and for both to retain some of their autonomy.

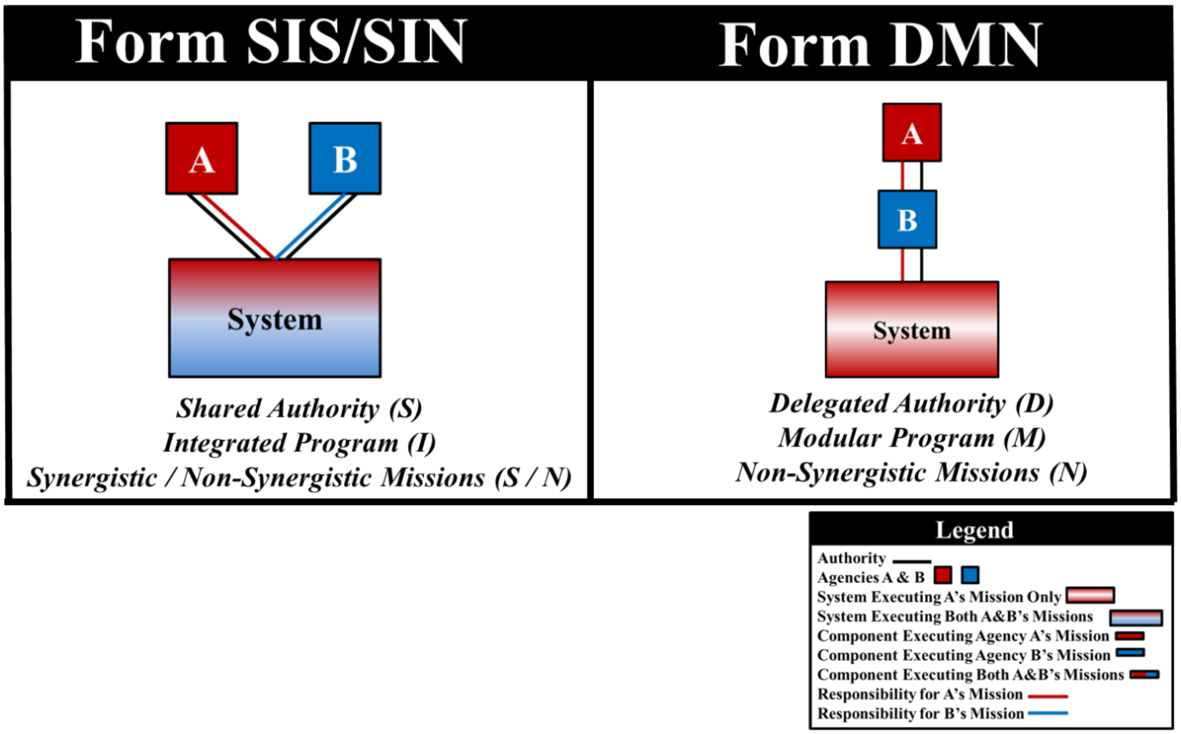


**Figure 53: Basic Joint Program Forms**

Sharing authority affects joint program costs during the requirements development process because each agency levies *all* of its requirements, regardless of whether they are shared by its partner or whether they drive the performance and configuration of the system. Neither agency vetoes its partner's requirements because each agency acts in the same way; as a result, the joint requirements set is a concatenation of each agency's unique and driving requirements. To meet these requirements, joint space programs typically develop large "Battle-star Galactica"-like [78] satellites that aggregate numerous capabilities onto single complex platforms. Thus, by sharing authority, agencies increase joint program costs by increasing the design and architectural complexity of the joint system.

In form DMN, Agency A's autonomy is maximized while Agency B's is minimized. Because the agencies are not equal partners and Agency B did not retain its autonomy, it takes actions to *regain* autonomy by *eroding Agency A's authority*. Again, Agency B's actions are motivated by its interests, which in this case, are only to execute Agency A's mission without interference. As shown in Figure 53, DNM's system does not execute Agency B's mission: as a result, Agency B cannot take any actions to execute it within the joint program.

Because Agency B has some authority to execute Agency A's mission, its remaining interest is to execute that mission without interference by Agency A. To satisfy this interest, Agency B erodes A's authority by taking actions to regain its autonomy and to maximize its ability to develop the component independently. To do this, Agency B develops a program plan that explicitly follows all of its official processes and procedures and that employs a conservative budget with more than sufficient margin. In this way, Agency B reduces the frequency with which it requires decision approval from Agency A or that it needs to request more funding in the case of unexpected cost growth.

Therefore, with this form of jointness, it is not design or architectural complexity, but rather, process complexity caused by the subordinate agency's conservative development process, that increases the joint system's cost. If a single agency held full authority over its system, it could reduce costs by deviating from official processes and procedures when doing so was in the best interests of the program; however, because the subordinate agency seeks decision making autonomy, such decisions—which require the approval of the lead agency—are rarely made.

Finally, as shown in Figure 51 *both* agency actions—to regain and retain autonomy—induce organizational complexity by creating a slight misalignment between responsibility and authority. This source of complexity is present on all joint programs because individual agencies' mission responsibilities are often derived from separate Congressional committees. Thus, in order to comply with their responsibility to Congress, agencies must individually and independently oversee and perform audits of their joint programs. Therefore, joint program oversight costs increase as a function of the number of agencies that are involved in the problem.

#### 8.2.1.5 Actions Across the Basic Forms

The basic actions described above occur in joint programs like those shown in Figure 51. In the bottom left corner (form SIS / SIN), Agency A's authority and autonomy are minimized because it shares them with Agency B. An example program of this form is the cancelled Space Radar program where the Air Force and the NRO were equal partners. In contrast, in the upper right corner (form DNM), Agency A's autonomy and authority are maximized. In this case, Agency B regains autonomy from A by eroding its authority and by executing A's mission without interference. An example program of this form is the GOES program, where NASA acquires a spacecraft on behalf of NOAA, which independently acquires and manages the ground system and its interface to the space segment.

An important characteristic of Figure 51 is that each agency's interest in executing its unique mission without interference drives its actions in opposing directions. Thus, as agencies take actions to regain their autonomy, they institgate turf wars—which depending on the agencies' relative power—drives the joint program to assume more complex configurations between Figure 51's basic joint program forms. However, regardless of where a program falls on Figure 51's spectrum of jointness, the agencies' interest in executing their missions without interference remains the same. Faced with interference, an agency will erode the authority of its partner so that it can regain autonomy to execute its mission. Absent interference, an agency will prioritize its own mission over its partner's.

An agency can erode its partner's authority directly, by second guessing its decisions or by elevating them for further arbitration. An agency can also erode its partner's authority indirectly, by attempting to sway its decisions in favor of its own interests. In both cases, actions are enabled by an agency's expertise and budget. If an agency has greater technical capability than its partner, it can use that expertise to influence the partner's decisions and to justify its own actions. If an agency is not responsible for funding a system, it can more easily prioritize its own mission, since it pays no cost for doing so.

When agencies take action and their joint program evolves away from the basic forms shown in Figure 51, organizational complexity increases because agency conflict induces instability and inefficiency. Because instability and inefficiency have an unpredictable impact on a program's lifecycle cost, joint programs should be architected to provide checks and balances that reduce agencies' ability to take actions that can induce organizational complexity. By architecting joint programs in this way, future government leaders can more reliably estimate their costs according to those predicted for the basic forms shown in Figure 51.

### 8.2.2 Checks and Balances

The principles for architecting joint programs focus on the ***alignment of responsibility, authority, budget, and expertise*** between the collaborating agencies and the system under development. ***The most important alignment is between responsibility and authority***. According to the Agency Action Model, when agencies lack autonomy, they will take actions to erode their partner's authority in order to regain the autonomy to make decisions. If, for example, Agency A is assigned the independent authority to make decisions that affect Agency B's mission, then B's authority and responsibility are misaligned and it has lost some autonomy over its mission. By taking action to regain its autonomy, B generates conflict in the joint organization that slows decision making, hinders the system development process, and ultimately induces cost growth.

Next, ***budget and responsibility must be aligned*** to insure that the agency with authority makes decisions that appropriately weigh benefit vice cost. For example, if Agency B is responsible for making decisions that affect its mission but is not responsible for funding the outcome of those decisions, B's actions will inappropriately favor its mission, rather than A's ability to fund it. In this scenario, program costs will grow because B has no incentive to consider costs when making decisions or managing A's system. Finally, ***expertise and authority must be aligned*** so that each agency can provide a check and balance on the other's interest in prioritizing its unique mission over the shared mission of the joint program.

Using these simple principles, one can evaluate the potential for cost growth in any joint program form. Figure 54 illustrates some additional forms that were constructed using the three dimensions—agency authority relationship, program modularity, and mission synergy—that were discussed above; more joint program forms can be constructed using any combination of the forms that are illustrated. An important characteristic of the joint program forms shown in Figure 54 is that only the four corner forms (SIS / SIN, SMN, DMN, and DIN) completely align authority and responsibility. Form DIN is similar to basic form DMN because both system's execute only Agency A's mission (i.e. the agencies' missions are *non-synergistic*). In contrast to basic form DMN, in form DIN, Agency A delegates authority to Agency B, which manages an *integrated* program for Agency A. Form SMN is similar to form SIS / SIN because both agencies *share authority*; however, the forms differ because SMN's program is *modular* and its system executes *non-synergistic missions*.

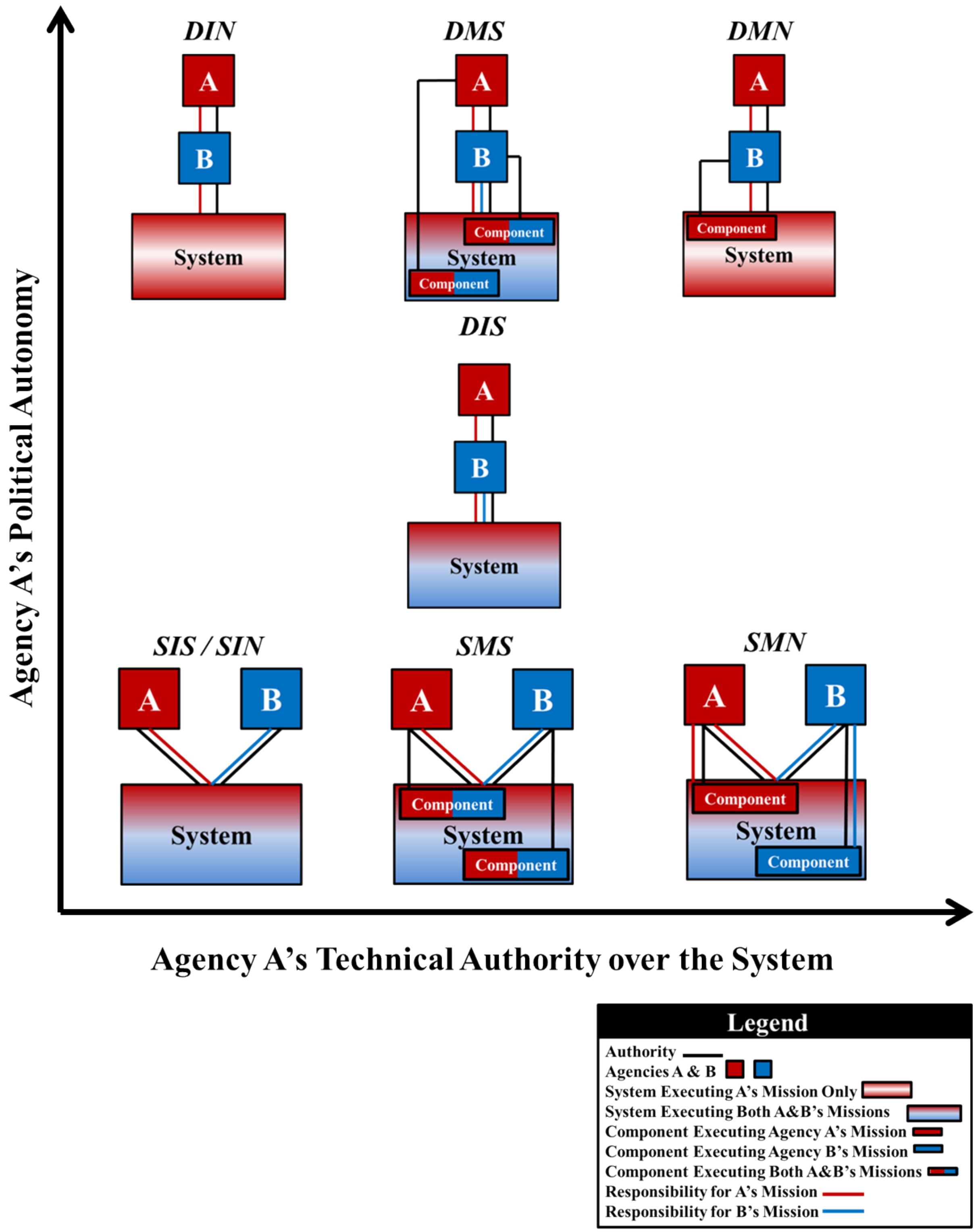


**Figure 54: Different Forms of Jointness**

The forms that transition from SIS / SIN to SMN and DIN to DMN are unstable because authority and responsibility are misaligned and the "mirror" between technical and organizational architectures has been broken. In SMS, the agencies *share authority* over the overall system, but that program is *modularized* and authority over the system's components is delegated to different agencies (i.e. Agency A in Figure 54). An example SMS-type program might use a dual-agency board for important programmatic decisions but assign only one agency authority over several component contracts. Importantly, in form SMS, Agency A has authority over a component which executes both agencies' missions; this is likely to occur when the agencies missions are *synergistic* and it is difficult to decouple the requirements that they levy on the system.

Because the component executes B's mission but B has lost its autonomy to manage that component, B will take action to regain its autonomy by eroding A's authority. Agency B can do this by monitoring the component's development and by raising any issues that it has with A's decisions to the program's joint management (i.e. the leaders of Agencies A and B). It is even easier for B to take these actions if expertise or budget are misaligned in the joint organization. For example, if B has greater expertise than A, it can second guess all of A's decisions. If B does not provide budget for the component, it can pressure A to make decisions that minimize risk and that maximize the performance of B's mission, but that ultimately increase the component's cost. Once B has sufficiently eroded A's authority, the program transitions back to form SIS / SIN, where both agencies share authority. Until that point, the program's decision making process will be slow, acrimonious, and unnecessarily costly.

In DMS, Agency A has delegated *authority* to Agency B but again, because the agencies' missions are *synergistic,* they are not easily decoupled and executed by separated modules; as a result, each agency develops a component that executes *both* agencies' missions. In this case, the agencies may seek to erodr their partners' decision authority by seeking greater involvement in the component development process since the components execute both agencies' missions. However, the agencies will not exhibit this behavior if they lack the expertise to manage their partner's component; this explains why hosted payload arrangements can remain stable (i.e. they do not transition to an alternate form) if one agency's expertise is limited to the hosted payload and does not extend to other components in the system. .

Form DMS and SMS share a common characteristic that enables the agencies to erode one another's authority: they use modular programs to execute synergistic missions. By definition, when agencies' missions are synergistic, they cannot be easily decoupled and executed by separate modules; as a result, any joint program which uses a modular program to execute synergistic missions will suffer from a misalignment of authority and responsibility. To align authority and responsibility, joint programs should modularize their programs and delegate authority over the system's modules *only* when the agencies' missions are non-synergistic, as in form SMN. Integrated programs can be used execute *either* synergistic or non-synergistic missions.

The middle joint prorgam also contains an important characteristic: delegated authority and synergistic missions. In this program, Agency A delegates its mission execution authority to Agency B, which acts as an acquisition agent for the system. However, unlike the pure acquisition agent role shown in forms DIN and DMN, in DIS, Agency A's system also execute B's mission. In these forms, Agency A is at risk that B will use its implementation authority to prioritize its own mission over Agency A's. Agency A is particularly at risk if B has greater expertise than A or if B does not contribute some of the program's budget (i.e. expertise and authority and budget and responsibility are misaligned). Therefore, the middle program form faces a risk of cost growth due to a principal-agent problem, where the agent's actions to prioritize its own mission and this increases the cost of the principal's system.

To combat the principal-agent problem that is present in joint programs with delegated authority and synergistic missions, agencies should be sure to align responsibility with budget and expertise with authority. Specifically, the subordinate agency should contribute some portion of the program's budget because doing so will balance its interest in prioritizing its own mission at the lead agency's expense. Additionally, the lead agency's expertise should be enhanced so that it can more effectively monitor the subordinate agency's actions to insure that they are consistent with its interests. Essentially, by aligning budget with responsibility and authority with expertise, the subordinate agency is transformed into a more honest broker and the lead agency is transformed into a smarter buyer.

## 8.3 The Agency Action Model Applied

Now that the Agency Action Model has been defined generally, it can be applied to understand cost growth both within my case studies and in other joint programs that were studied as part of this dissertation. I begin this section by explicitly mapping the model to my case study data and by demonstrating that it does indeed explain the dynamics of the NPOESS, JPSS, and DWSS programs. Finally, I conclude by applying the model to several other example joint programs and by doing so, illustrate its general applicability.

### 8.3.1 NPOESS, JPSS, and DWSS Actions

To represent the three agencies and the multiple program offices that were involved in the NPOESS, JPSS, and DWSS programs, several joint program forms must be added together; importantly, despite these extensions, the agency action dynamics directly apply. Figure 55 illustrates the NPOESS program's initial conditions as a cross between forms SIN and DMN. As in form SIN, NOAA and the DoD retained autonomy by sharing authority over the system's requirements. As predicted by the model, sharing authority primarily affected the program's requirements, which ended up as a concatenation of each agency's unique and driving requirements, rather than a set of requirements defined through compromise. Although both agencies shared budget responsibility, their technical expertise was misaligned, since NOAA had less space acquisition expertise than the DoD. Rather than internally supplementing NOAA's institutional capabilities, NASA was included in the collaboration and to serve as NOAA's unofficial acquisition agent and to supplement to its technical expertise; this arrangement is shown as form DMN. As also shown in Figure 55, NASA and the DoD's institutional interests drove their actions in separate and opposing directions throughout the NPOESS, JPSS, and DWSS programs.

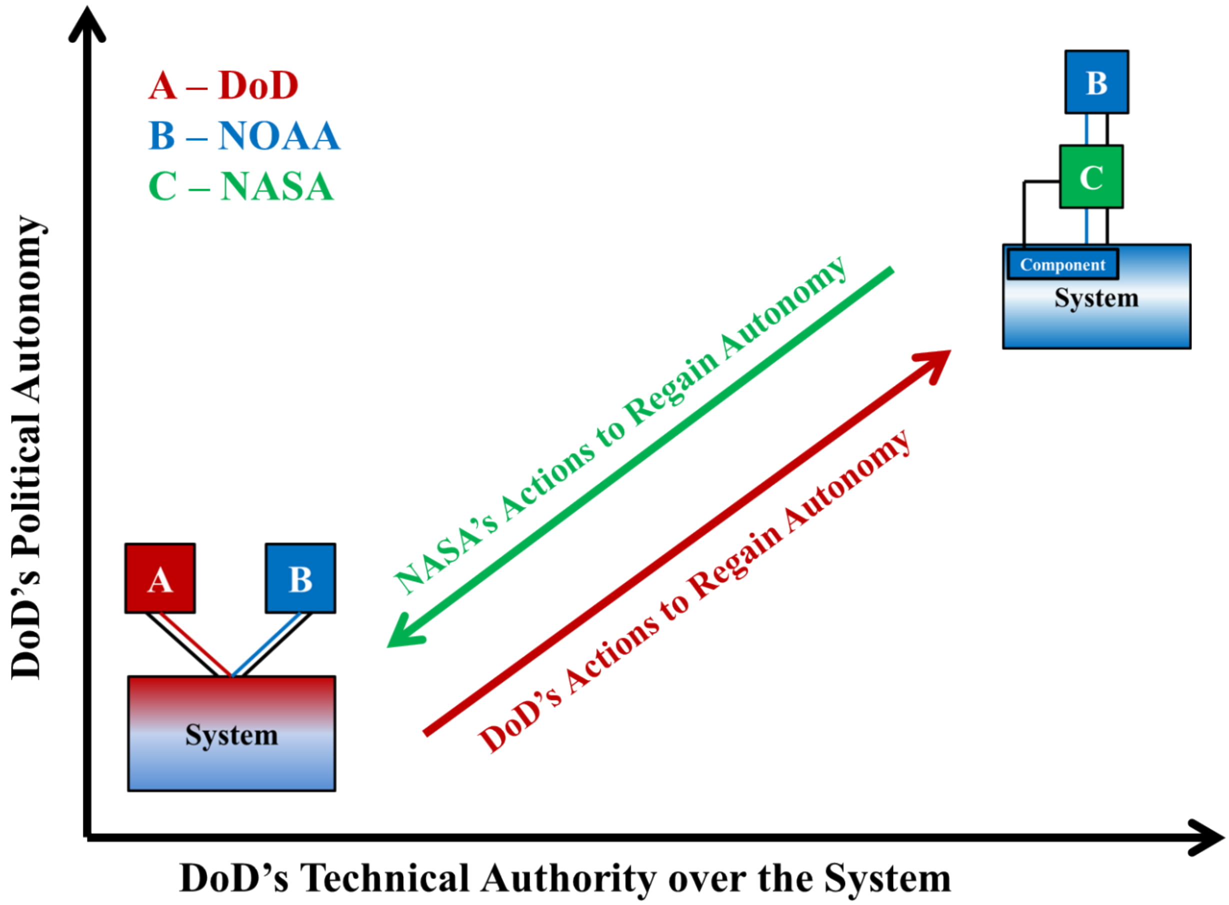


**Figure 55: Agency Action Model Applied to NPOESS, JPSS, and DWSS**

Figure 55 illustrates the starting point—Action 1—that resulted from the fundamental tension between NASA and the DoD's actions: a program form that was a cross between SIN and DMN. As shown, in addition to meeting both NOAA and the DoD's official requirements, the NPOESS system also executed NASA's mission and unofficially, met its requirements for EOS data continuity as well. Because the NPOESS system executed NASA's mission, but the agency's official role was to supplement the program's technical expertise and technology, NASA was in a position to regain more of its autonomy by using its implementation authority to prioritize its mission over the missions of its partners. The organization that was created provided no checks and balances against NASA's interests, since NASA did not contribute to the program's budget and NOAA's expertise was not commensurate with its authority over the program's requirements.

Although Action 2—the use of the "Optimized Convergence" strategy—did not affect the balance of agency power, it exacerbated the impacts of Action 1. Specifically, Action 2 induced organizational complexity that hindered the program's ability to accurately estimate and to manage the complexity of its technical system. Thus, Action 2 prevented the program from realizing the cost that had been induced by Action 1 until later in the program, when its sensor vendors and prime contractor were selected.

Action 3, which added the NPP program, reduced the DoD's autonomy by requiring it to consult not only with NOAA but now, also with NASA. In contrast, NASA gained autonomy because NPP formalized its role in the NPOESS collaboration and justified its right to share authority with the other agencies. However, the organization created to execute NPP did not foster authority sharing; instead, by misaligning NASA's mission responsibility and authority, it incentivized NASA to take actions to further regain its autonomy over its NPP mission by eroding the authority of its collaborators. NASA's actions were particularly effective because it did not have budget responsibility for NPOESS nor did the NPOESS staff have greater technical expertise than NASA's representatives to the program.

With Action 4, the Nunn-McCurdy certification, the DoD regained its autonomy in a big way: it delegated authority over NASA's NPP program to a PEO and eliminated climate instruments to better align the DoD's weather mission with its jurisdiction over NPOESS. However, as shown in Figure 56, the critical misalignment between NASA's authority and responsibility for NPP remained; as a result, as in prior epochs, NASA actions were able to erode its partners' authority.

NASA was further able to erode the DoD's authority with Action 5, which transferred NASA civil servants into NOAA NESDIS management. By taking this action, NASA formalized its alliance with NOAA and redefined the bureaucratic turf war as a battle of two agencies against one. In a sense, NASA won its battle against the DoD when NPOESS was cancelled and the President terminated the DoD's involvement in NOAA and NASA's follow-on program.

The NPOESS cancellation (Action 6) resulted in two outcomes. First, the DoD regained full autonomy and authority over its DWSS system. Second, NOAA and NASA began a struggle for autonomy and authority over the JPSS program. This resulted the brief period shown in Figure 56—where NOAA held authority over the system's ground segment—but quickly transitioned to the final form, where NOAA was the lead agency but NASA held full implementation authority. As discussed in Section 8.2, this form is unstable and will likely result in continued cost growth because NOAA lacks expertise commensurate with NASA's and NASA provides no budget for JPSS.

Thus, using the Agency Action Model, we can trace the evolution of the NPOESS, JPSS, and DWSS programs according to NASA and the DoD's actions and their institutional interest in retaining and regaining their autonomy. Importantly, as shown in Figure 49, each action can be connected to the technical and organizational complexity mechanisms that induced or enabled cost growth on each of the programs. Thus, we see that jointness induced cost growth on NPOESS, JPSS, and DWSS because the collaborating agencies' institutional interests in retaining or regaining autonomy drove complexity into the programs' architectures.

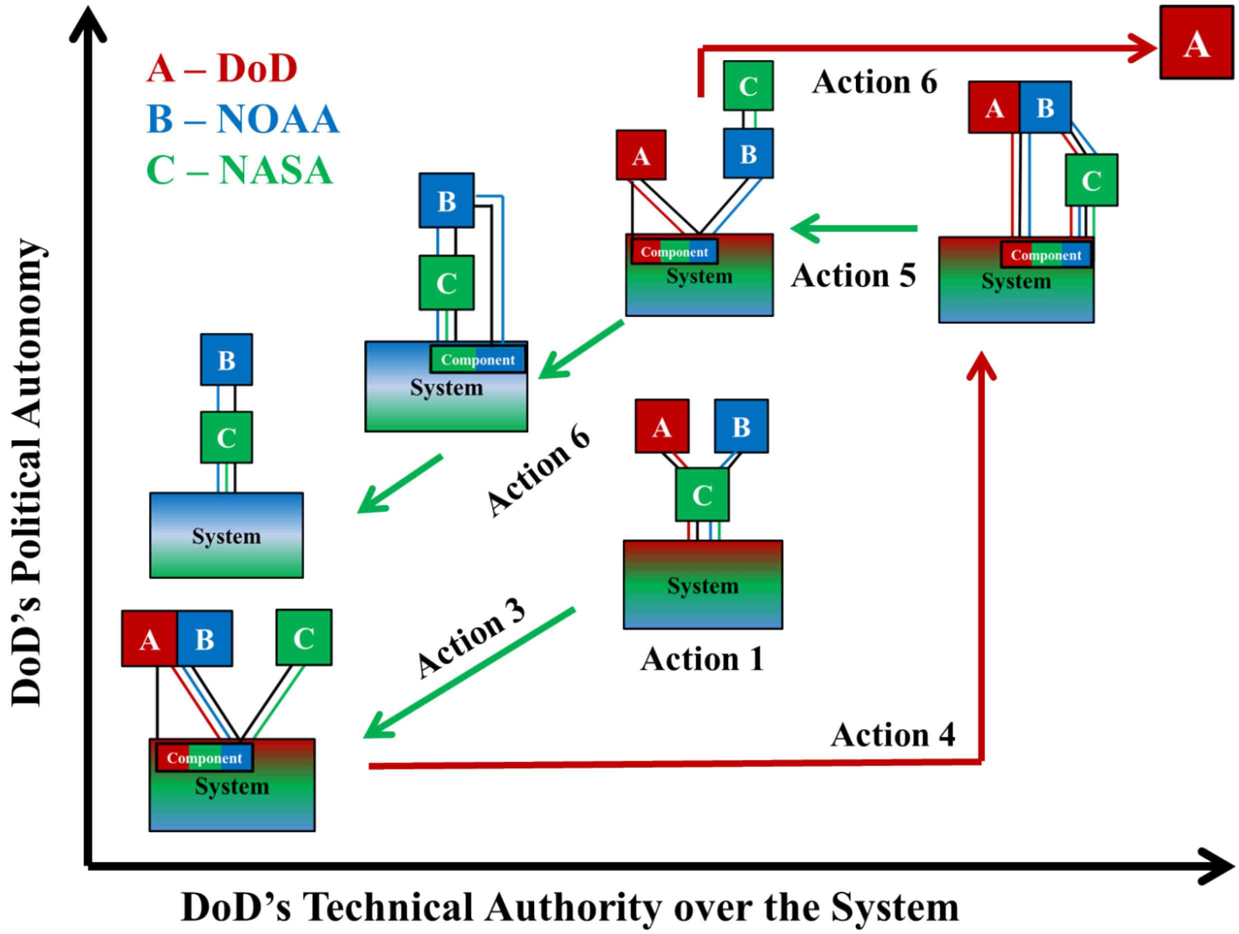


**Figure 56: NASA and the DoD's Actions**

### 8.3.2 Actions in Other Joint Programs

By defining the Agency Action Model generally, I can also apply it to explain cost growth on other programs. For example, the cancelled Space Radar program fits form SIN. As predicted by the model, because the Air Force and the intelligence community shared authority, the program's joint requirements increased the system's complexity and cost; indeed, the program's costs grew so significantly that the agencies cancelled the joint program. The cancellation actually illustrates one of the benefits of aligning mission responsibility, authority, and budget in form SIS; specifically, because the agencies shared budget responsibility, they were properly incentivized to cancel the program once the required budget exceeded the benefits that the system delivered to either agency.

In contrast, the NOAA-NASA GOES program fits form DMN, since NASA serves as NOAA's space segment acquisition agent. As predicted by the model, the GOES program's costs appear to be primarily driven by process requirements rather than by mission requirements; essentially, using NASA as an acquisition agent for the spacecraft is more costly than having NOAA directly acquire the space segment itself. That said, authority, responsibility, budget, and expertise are aligned on GOES and it is this alignment that motivated an independent review team to recommend that NOAA and NASA consider employing a GOES-like management structure on JPSS [D142].

Finally, joint programs in the defense and intelligence community are often a cross between forms SIS / SIN and DMN, where the NRO or the Air Force serve as the acquisition agent for multiple service departments or for multiple intelligence agencies. The model predicts that costs on these programs will be driven by agency actions to both regain and to retain autonomy. To retain autonomy, the user agencies that define requirements will levy their unique and driving requirements rather than compromising. To regain autonomy, the acquisition agent will request a budget with sufficient reserve so that it can execute the system development process conservatively, in full accordance with its processes and procedures, and without interference from the other agencies. Importantly, in both the defense and intelligence communities, responsibility and budget are misaligned because funding is appropriated directly to the acquisition agents rather than to the agencies that levy the requirements and use the data. As a result, unlike the Space Radar case, where the agencies cancelled the program because their requirements were too expensive, in these programs, the agencies have little incentive to reduce their requirements because they do not have to fund them. This prediction conforms with the cost growth that is commonly incurred in defense and intelligence programs like those described in Chapter 2.

With these simple examples, one can observe how the Agency Action Model is able to explain program outcomes outside of my NPOESS, JPSS, and DWSS case studies. Future research should explore how the programs mentioned above evolved over time and using a research approach similar to Chapter 3's, should seek to confirm or deny the model's ability to explain program evolution, complexity, and cost growth. Cases outside of the government space sector should also be explored.

## 8.4 Conclusion

By defining the Agency Action Model, this chapter answered my primary research question—how does jointness induce cost growth—by demonstrating that collaborating agencies' institutional interests in retaining or regaining their autonomy drives complexity into joint programs' technical and organizational architectures and thus, induces cost growth. By defining notional joint program forms, I also illustrated two key cost drivers. First, the cost of technical complexity was observed to affect costs on joint programs using forms SIS / SIN and DMN. Second, the cost of organizational complexity was observed to affect programs evolving between forms SIS / SIN and DMN or those with misaligned authority, responsibility, budget, and expertise.

This distinction highlights the two critical dimensions that must be considered when forming future joint programs: (1) the cost of a system's technical complexity and (2) the alignment of responsibility, authority, expertise, and budget within the organization that develops the system. The next chapter illustrates how government decision makers should account for both dimensions when analyzing options for future joint programs or opportunities for reforming current ones.

# 9 The Future of Jointness

*Partnerships are key to our ability to provide continuous polar-orbiting measurements. NOAA, NASA, and the DoD/Air Force have had a very productive relationship in polar observations; sharing data, coordinating user needs, and operating satellites. This cooperative relationship is essential and will continue for years to come.*

– The Presidential Decision Directive that Cancelled NPOESS, 2010 [D175]

In the years following NPOESS's cancellation, both NOAA and the DoD have struggled to define their follow-on systems. As described in Chapter 7, JPSS continues to face management challenges, cost over-runs, and schedule delays [D142] and as noted in Chapter 4, the DoD's future weather satellite capabilities remain undefined after DWSS was cancelled in 2012. While the agencies were working to define their follow-on programs, government leaders expressed an interest in disaggregation, or "the dispersion of space-based missions, functions, or sensors across multiple systems" [46]. A disaggregated approach to environmental satellite architectures is essentially the opposite of the aggregated NPOESS architecture. Disaggregated architectures have multiple potential benefits—including increased resiliency, responsiveness, and flexibility—and are also potentially less complex and costly than aggregated systems like NPOESS [46, 48-50]. Given its cost saving potential and the uncertainty of NOAA and the DoD's post-NPOESS plans, environmental monitoring satellites are top candidates for future disaggregation.

Additionally, despite recent warnings against the use of interagency collaboration for the development of space systems [17], the current space policy of the United States supports and encourages the use of partnerships to achieve cost savings and technical synergies [43]. Thus, given the continued policy support for interagency collaboration and the similarity of the environmental monitoring data that is required by NOAA, NASA, and the DoD, it is likely that these agencies will consider partnering again sometime in the future.

Therefore, in this chapter I demonstrate how future government decision makers can use the lessons learned from my case studies and the implications of the Agency Action Model to analyze future opportunities for jointness. As noted in Chapter 8, there are two critical dimensions that must be considered when forming joint programs:

- The cost of a system's technical complexity,
- And the alignment of responsibility, authority, expertise, and budget within the organization that develops the system.

In this chapter, I use a trade space analysis tool to illustrate how both dimensions can be analyzed and used to inform future decisions. The chapter begins by reviewing the tool's construction, assumptions, and evaluation metrics. It continues by analyzing the cost impacts of technical aggregation versus disaggregation for NOAA and the DoD's environmental satellite programs. Next, I define a process that the agencies can use to evaluate potential partnerships and I demonstrate this process using NOAA's system as a case study. Finally, in both my technical and organizational analyses, I make recommendations that can be used to improve current or future environmental monitoring satellite programs.

# 9.1 Overview of the Trade Space Exploration Tool

Typically, when government agencies have analyzed the cost impacts of aggregated versus disaggregated architectures, they have done so by comparing point designs for a handful of candidate systems (e.g. [D174]). To expand upon these previous analyses, I developed a trade space exploration tool that enabled me to comprehensively and quantitatively evaluate the cost impacts of aggregation. To do this, the tool generated and evaluated a broad trade space of potential system options for NOAA, NASA, and the DoD. Because the tool explored a large space rather than comparing the characteristics of a few detailed point designs, it necessarily traded model depth for breadth. As a result, the tool evaluated each option at the level of the system's *architecture*; as shown by multiple authors, this level of modeling fidelity is most useful at the very early stages of system definition, during pre-Phase A of both NASA and the DoD's acquisition timelines [41, 180-181]. In this section, I review the trade space exploration tool and its specific application to environmental monitoring systems in low Earth orbit.

## 9.1.1 Architectural Decisions

Simmons demonstrated that a system's architecture can be represented as a set of decisions and decision options [182] and Table 9 lists the decisions that were used to define my systems' architectures. First, each architecture was defined by the number and type of orbital planes that its satellites occupied; the orbital parameters that were included are consistent with previous NOAA, NASA, and DoD programs. Second, the maximum number of spacecraft per orbital plane was fixed to control the size of the trade space. Finally, each architecture was allowed three bus options. Each bus could be uniquely designed to support the instruments assigned to it. Alternatively, bus designs could be common across a train of spacecraft (i.e. spacecraft flying in the same orbital plane) or across the entire constellation of spacecraft (i.e. spacecraft flying in multiple planes).

The instrument options, with the exception of the visible / near-infrared (VIS-NIR) imager-radiometer and the conical microwave imager sounder, corresponded to instruments that are currently flying on NPP or were slated to fly on NPOESS. In addition to these instruments, three VIS-NIR imager-radiometer options were included; the first is the 22-channel VIIRS that is currently flying on NPP. The others, VIIRSLite-noocean and VIIRSLite-ocean, represent less capable candidate imager-radiometers that were considered during the NPOESS program. These instruments have less horizontal spatial resolution than VIIRS and have eight and 14 channels respectively; both instruments were assumed to have the low light imaging capability that was required by the DoD, but only VIIRSLite-ocean was able to take ocean color measurements. Three options for conical microwave imager-sounders were also included in the model. CMIS and Windsat were both developed during the NPOESS program and SSMIS-U refers to an upgraded SSMIS that the NPOESS program considered as an option to replace CMIS [D157]. Each sounder option differs in the amount and quality of the data products that it is able to collect. The instrument specifications and capabilities that were input into the model were taken from [D167] with the exception of VIIRSLite-noocean and VIIRSLite-ocean, which were taken from [D51], and SSMIS-U and Windsat, which were taken from [D157].

**Table 9: Architectural Decisions**

| Varied Architectural Decisions | |
|---|---|
| **Variable Decision** | **Decision Options** |
| Number of Orbtial Planes | 1 - 3 orbital planes |
| Orbit RAAN | Terminator, mid-morning, or afternoon orbits |
| Number of Satellites / Plane | 1 - 4 satellites / plane |
| Payload Selection | Any combination of<br>• VIS-NIR imager radiometers (VIIRS, VIIRSLite-noocean, VIIRSLite-ocean)<br>• conical microwave imager-sounders (CMIS, SSMIS-U, Windsat)<br>• cross-track microwave / IR sounders (ATMS, CrIS)<br>• earth radiation budget sensors (ERBS cross-track scanning, ERBS-biaxial scanning)<br>• ozone monitors (OMPS-Limb, OMPS-Nadir)<br>• solar irradiance monitors (TSIS)<br>• aerosol polarimetry sensors (APS) |
| Spacecraft Architecture | Any partition of instruments into spacecraft |
| Spacecraft Bus Commonality Type | Dedicated bus, common buses within train, common buses across constellation |
| **Fixed Architectural Decisions** | |
| **Fixed Decisions** | **Assumed Decision Option** |
| Mission Lifetime | 10 years |
| System Lifetime | 5 years (model accounts for spacecraft replenishment) |
| Orbital Parameters | Sun-synchronous, 800 km orbits |
| Mission Types | Weather & climate (space weather, search & rescue, data collection missions excluded) |

Finally, Table 9 also lists the decisions that were fixed in my analysis; these include lifetime, orbital parameters, and mission type. These decisions were fixed to limit the scope of the analysis but are consistent with past environmental monitoring systems. At its level of modeling fidelity, the tool was not particularly sensitive to changes in mission or system lifetime; therefore, I selected a 10 year mission and a five year mean mission duration to be consistent with NPOESS heritage [D39]. As a result, like NPOESS's acquisition plans prior to its cancellation, all system concepts that were evaluated by the tool consisted of one initial constellation of satellites and one replacement constellation.

Orbital parameters were fixed so that the instruments used in the analysis could be based directly on heritage sensors; this minimized the cost of sensor redesign. If future systems occupy orbits other than the standard 800km sun-synchronous ones considered here, new instruments will need to be designed and more satellites will be necessary to achieve the agencies' temporal resolution requirements. It is likely that these systems will also impact the ground architecture and require new concepts of operation. Since there is already limited quantitative understanding of how disaggregation will affect the cost of ground systems [47], I focused my analysis on the disaggregation of the space segment (where cost estimating relationships are widely available) and limited my focus to satellites in heritage orbits using heritage sensor designs.

Mission type was also fixed to include only weather and climate. As a result, my analysis did not consider options for hosting instruments like SARSAT, DCS, or SESS. These missions were omitted because their requirements were not as clearly defined as the weather and climate missions. Furthermore, the technical impact of assigning space weather sensors to any of the climate or weather systems was assumed to be minimal, so the decision to host these sensors on weather/climate systems can take place after their architectures are defined.

### 9.1.2 Trade Space Explorer and Architecture Evaluator

The trade space of potential architectures included all possible combinations of decision options where each architecture was defined by selecting one option for each of the decisions in listed in Table 9. To explore this trade space, the model followed the process depicted in Figure 57 and used two major components: a trade space explorer and an architecture evaluator. The trade space explorer began by generating a semi-random population of architectures to be evaluated. The architecture evaluator then executed three evaluation steps. First, the evaluator performed a preliminary design of every spacecraft in the architecture. To execute the spacecraft design process, the tool translated the architecture from the set of selected decision options to the physical components that those options represented: spacecraft buses and a set of payload instruments. Physical information about each of the instruments—its mass, power, and data-rate—were used as the primary input to the iterative spacecraft design process, which developed a mass budget for each bus. Additional description of the spacecraft design portion of the tool is provided in the Appendix.

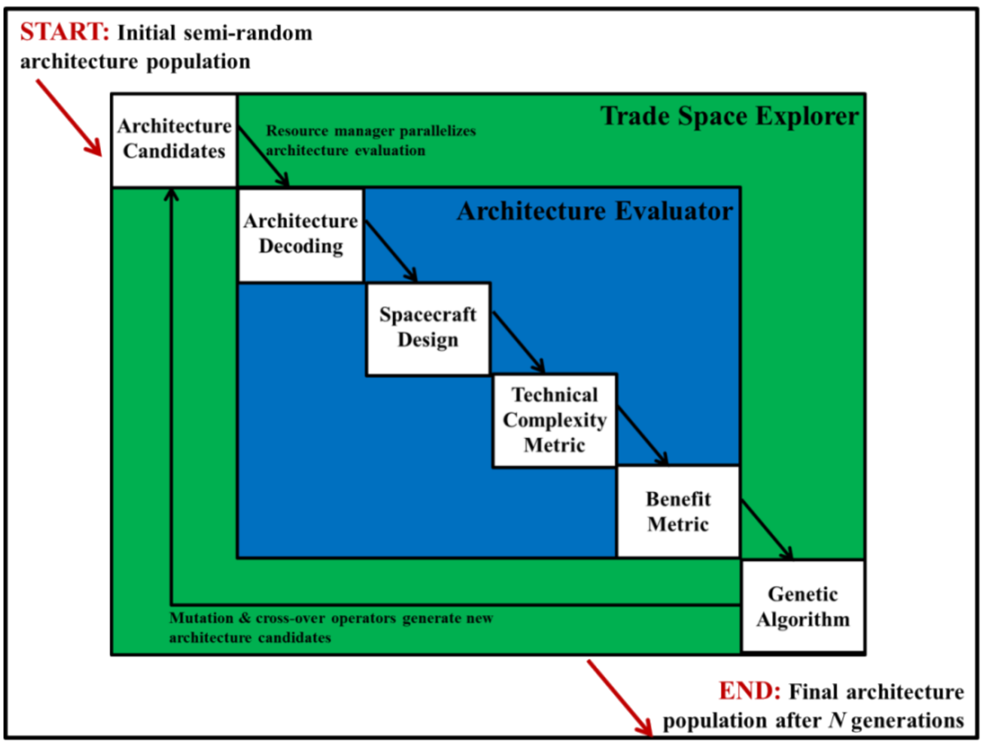


**Figure 57: Exploration & Evaluation Process**

Next, the tool used the preliminary spacecraft design to evaluate each architecture's benefit and cost. Once all of a population's architectures were evaluated, the results were passed back to the trade space explorer, which selected the highest performing architectures and used them to seed the next population of architectures. New generations were created using a genetic algorithm, which applied mutation and cross-over operators to the highest performing architectures in each population. As shown in Figure 57, once the new population was generated, the process repeated for a specified number of iterations.

For this particular analysis, I used an initial semi-random population of approximately 2,500 architectures and allowed that population to evolve for 500 generations. The trade space exploration process was executed using a Java-based source code that was originally developed to explore a trade space of communication satellite architectures [181]. Finally, the architectures were evaluated using a rule based expert system [183] and a methodology developed by Selva [41].

## 9.2 Metrics

Two basic metrics—cost and benefit—were used to evaluate the architectures. Both metrics were constructed to capture the key trade-offs associated with aggregation and disaggregation. As shown in Figure 58, aggregating multiple instruments onto the same spacecraft or within the same orbital plane allows different types of data to be cross-registered. When different data types are combined, new data products can be formed or existing products' quality can be enhanced [41]. Alternatively, by disaggregating spacecraft and distributing instruments across multiple orbital planes, systems can increase the temporal resolution of their data products.

As also shown in Figure 58, in terms of cost, the trade-offs of aggregation and disaggregation are less clear. Traditionally, the government has employed aggregated architectures because they require fewer launches and fewer components. However, recent studies have suggested that despite having fewer components, aggregated architectures are more complex, and therefore more costly, than disaggregated ones [16-17, 48].

These findings suggest that as architectures become increasingly aggregated, the cost saving benefit of aggregation is out weighed by the growing cost of complexity. Furthermore, although disaggregated architectures require more components, by doing so, they may be able to capitalize on the cost saving benefits of mass production [46]. Finally, as the government begins to use new, less costly launch vehicles, the cost to launch a disaggregated constellation may decrease and become comparable to the cost of launching only a few aggregated satellites. The metrics that I used to evaluate architectures were designed to capture each of these trade-offs.

### 9.2.1 Cost Metric

The cost metric calculated the space segment development, production, and launch costs but excluded ground system and operations costs. Importantly, the cost metric *did* capture many of the costs associated with aggregation and disaggregation, including the cost of complexity, the cost saving benefits of large-scale production, and the cost of multiple launch vehicle options. Because my analysis focused on pre-Phase A, when systems' costs are notoriously uncertain, my cost metric was not an absolute measure of cost. Instead, I calculated cost using traditional cost-estimating relationships but normalized my estimates with respect to a baseline system. This allowed my analysis to focus on alternative architectures' *relative* costs. The cost metric was calculated using the following process:

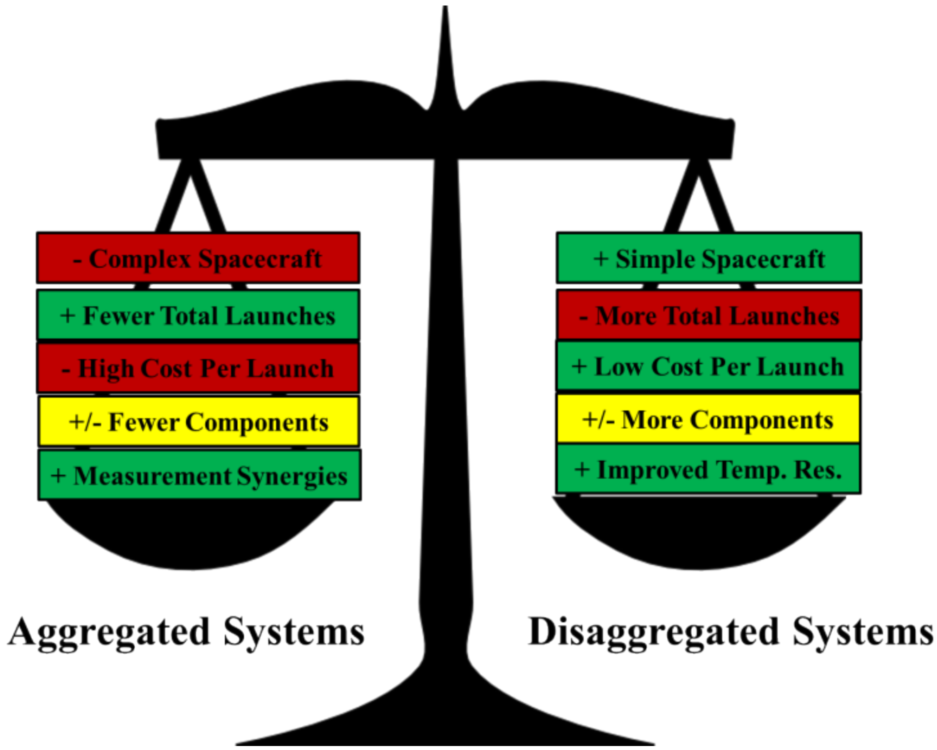


**Figure 58: Trade-offs of Aggregation versus Disaggregation**

- Instrument mass and power was adjusted for TRL according to the recommendations given in [174].
- Payload non-recurring costs were estimated using the NASA Instrument Cost Model given in [184].
- Bus non-recurring costs were estimated using either the Unmanned Space Vehicle Cost Model Version 8 (USCOM) or the Small Satellite Cost Model (SSCM); both sets of parametric equations were taken from [184]. The cost metric used the SSCM when a spacecraft's dry mass was less than 500 kg [184], otherwise, USCOM was applied.
- Payload and bus non-recurring costs were corrected to account for the cost of complexity.
- Recurring costs for both the spacecraft and the instruments were calculated using the corresponding NASA Instrument, USCOM, or SSCM cost models and discounted using a 90% learning curve as recommended by [185].
- Launch costs were calculated by assigning each spacecraft to the lowest cost launch vehicle with the necessary performance and volume accommodations. Because my analysis focused on systems that are developed by U.S. government agencies, only domestic launch vehicles were used; however, I included both traditional launch vehicles (i.e. Atlas and Delta) and new, less traditional systems including the Taurus-XL, the Minotaur-IV, and Space-X's Falcon-9.
- Finally, each system's cost was normalized by the cost of an NPOESS-like architecture, which served as my reference system in this analysis.

To account for the cost of complexity, I added cost penalties to systems that contained sources of design or architectural complexity. Table 10 lists the complexity sources and penalties that were included in the cost metric; each of source of complexity that was included in the cost metric was observed to impact cost in my case studies. Furthermore, the process for calculating complexity penalties and system cost is identical to the process that I used in my analysis of the NPOESS, JPSS, and DWSS programs; the Appendix provides additional description of this process.

**Table 10: Complexity Penalties Included in Metric**

| Complexity Type | Condition | Penalty | Penalty Applied To |
|---|---|---|---|
| Instrument Design Complexity | 1 (i.e. TRL = 7) | 3% | Instrument mass & power |
| Instrument Design Complexity | 2 (i.e. TRL = 6) | 5% | Instrument mass & power |
| Instrument Design Complexity | 3 (i.e. TRL = 5) | 25% & 10% | Instrument mass & power |
| Instrument Design Complexity | 4 (i.e. TRL = 4) | 30% & 20% | Instrument mass & power |
| Instrument Design Complexity | 5 (i.e. TRL = 3) | 50% & 25% | Instrument mass & power |
| Bus Design Complexity - Commonality | Common bus capability needs to be increased to host additional instruments | 5% | Bus non-recurring cost estimate |
| Bus Design Complexity - Commonality | Common bus capability needs to be adapted to fly in multiple orbital planes | 5% | Bus non-recurring cost estimate |
| Bus Design Complexity - High Data - Rate | Data-Rate > 7Mbps | 2% | Bus non-recurring cost estimate |
| Bus Design Complexity - High Mass | Satellite Dry Mass > 3000kg | 5% | Bus non-recurring cost estimate |
| Bus Design Complexity - Pointing Requirements | Bus hosts instruments with high pointing requirements | 5% | Bus non-recurring cost estimate |
| Architectural - Mechanical Interaction | Jitter inducing instrument hosted with sensitive instruments | 5% | Disturbed instrument & bus non-recurring cost estimates |
| Architectural - Optical interaction | Instruments with conflicting fields of view hosted on same bus | 5% | Non-recurring cost estimate of instrument requiring accomodation |
| Architectural - Programmatic | Multiple instruments managed by same program | 5% | Instrument non-recurring cost estimate |
| Architectural - Reliability | Multiple "critical" instruments hosted on same bus | 5% | Instrument non-recurring cost estimate; critical instruments are VIS-NIR sensor, conical microwave imager-sounder, CrIS, ATMS |

Finally—for reference—by accounting for complexity, the cost metric estimated NPOESS and JPSS costs' to be 20% and 12% greater than the estimates produced by mass based parametrics alone. In this way, one can think of the complexity penalties as budget reserve that accounts for the uncertain costs of developing complex systems. This reserve should be included early in a system's lifecycle while the cost of complexity is uncertain and as a system's design matures and its cost estimates stabilize, the amount of reserve that it requires should decrease. This approach to accounting for the cost of complexity was inspired by the Jet Propulsion Laboratory (JPL)'s concept of cost-risk sub-factors [175-176]. Unlike JPL's process, which added a uniform level of budget reserve to each system and a single complexity penalty for each type of complexity mechanism, my metric did not include a baseline budget reserve and instead, assigned complexity penalties for each *instance* of complexity in an architecture. This approach allowed me to better distinguish between candidate systems and resulted in penalties of the same order of magnitude as those used by JPL [176].

### 9.2.2 Benefit Metric

In order to inform cost-benefit trades, each architecture was also evaluated for benefit, which was assessed with respect to the NPOESS IORD-II. Benefit was defined as a function of *which* EDRs the architecture collected, *how many* EDRs the architecture collected, and *how well* the architecture collected those EDRs. To quantitatively assess benefit, the model employed the VASSAR (Value Assessment of System Architectures Using Rules) methodology [186]. A schematic depicting this methodology is given in Figure 59, which shows that the process began with a set of decomposed stakeholder requirements that were input into the tool. Next, the tool matched each architectures' capabilities to the set of decomposed requirements and aggregated requirement satisfaction to obtain a final benefit score.

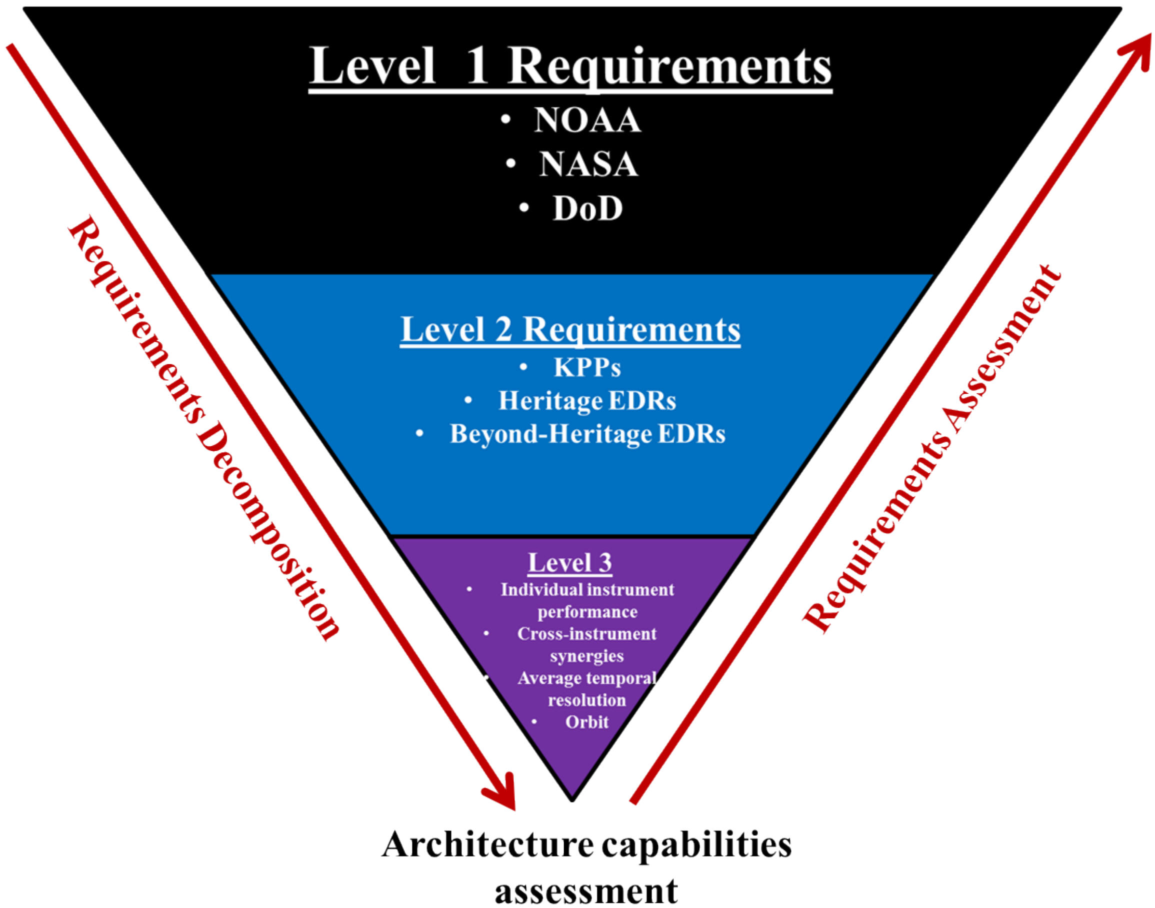


**Figure 59: Benefit Metric Illustrated**

Stakeholder requirements decomposition occurred at two levels for each agency. First, each agency's Level 1 requirements were further decomposed into three sets of Level 2 requirements: key performance parameters (KPPs), heritage EDRs, and beyond-heritage EDRs. KPPs for NOAA and the DoD were taken directly from the IORD-II and were assigned to each agency according to the instruments that it prioritized. Specifically, the IORD-II KPPs that were generated by ATMS and CrIS were assigned to NOAA while those that were generated by VIIRS and a conical microwave sounder were assigned to the DoD; this division of KPPs is consistent with each agency's current prioritization of instruments and requirements. Although NASA did not have KPPs in the IORD-II, for this analysis, I defined NASA's KPPs to be the EDRs that contribute to the operational climate and climate science missions, rather than to NOAA or the DoD's operational weather missions.

The EDRs in the heritage EDR category are those that were collected by each agency's heritage, pre-NPOESS program. Finally, the beyond heritage category contained the EDRs that were attributed to each agency in the IORD-II but were not produced by the agency's heritage system. Table 11 contains a list the individual EDRs that contributed to each agency's Level 2 requirements satisfaction scores. Level 2 scores were then combined in a weighted average to produce each agency's Level 1 score. The KPPs, heritage EDRs, and beyond-heritage EDRs were assigned weights of 50%, 35% and 15% respectively.

When joint requirements were assessed (i.e. an architecture was evaluated with respect to more than one agencies' requirements), then the agencies' Level 1 satisfaction scores were averaged.

Several performance attributes were associated with each Level 2 requirement. If an architecture contained all of the specified attributes, it was awarded a full requirement satisfaction score; however, if some of the attributes were absent, the architecture was awarded a partial requirement satisfaction score, according to which attributes it contained. The four performance attributes that were specified for nearly every requirement were individual instrument performance, cross-instrument synergistic performance, average temporal resolution, and preferred right ascension of ascending node (RAAN). The individual instrument performance attribute was used to distinguish between the performance of individual instruments of the same type; as a result, these attributes primarily distinguished between architectures that contain different VIS-NIR imager-radiometers and microwave imager-sounders. Cross-instrument synergistic performance attributes identified cases where EDR performance was improved when data was collected by more than one *type* of instrument; for example, cross-instrument synergies can improve measurement accuracy or can create new measurement capabilities, like the ability to collect data in both cloudy and clear conditions [41].

Table 12 summarizes the cross-instrument synergies that were included in the model, which only awarded requirement satisfaction when synergistic instruments flew in the same orbital plane. Additionally, the model also specified average temporal resolution for each measurement using the values defined in the IORD-II and finally, it specified the RAAN from which each agency preferred its data to be collected. The DoD's weather mission requires data from an early morning orbit (5:30 crossing time), NOAA's weather and climate missions must be executed from orbits with afternoon (13:30) crossing times, and NASA's missions can be executed from either a mid-morning or an afternoon orbit. NOAA and the DoD could also both use the mid-morning orbit to increase the temporal resolution of their measurements.

Each architecture's ability to satisfy the Level 2 requirements was a function of the instruments assigned to it and the allocation of those instruments to orbital planes. Additional information about the process that the tool used to evaluate architectural benefit and the VASSAR methodology can be found in [41, 138, 180, 186].

## Table 11: EDR Matrix for Benefit Matrix

| Environmental Data Record (EDR) | DoD Requirements | | | NOAA Requirements | | | NASA Requirements | | |
|---|---|---|---|---|---|---|---|---|---|
| | KPPs | Heritage EDRs | Beyond Heritage EDRs | KPPs | Heritage EDRs | Beyond Heritage EDRs | KPPs | Heritage EDRs | Beyond Heritage EDRs |
| Active Fires | | | X | | | X | | X | |
| Aerosol Optical Thickness | | | X | | | | | X | |
| Aerosol Particle Size | | | | | X | | | X | |
| Aerosol Refractive Index | | | | | | X | X | | |
| Albedo | | X | | | X | | | X | |
| Atmospheric Vertical Moisture Profile | | X | | X | | | | X | |
| Atmospheric Vertical Temperature Profile | | X | | X | | | | X | |
| Cloud Base Height | | | X | | | X | | X | |
| Cloud Cover / Layers | | X | | | X | | | X | |
| Cloud Effective Particle Size | | X | | | X | | | X | |
| Cloud Ice Water Path | | | | | X | | | X | |
| Cloud Liquid Water | | X | | | X | | | X | |
| Cloud Mask | | | X | | | X | | X | |
| Cloud Optical Thickness | | | | | X | | | X | |
| Cloud Particle Distribution | | | X | | | X | X | | |
| Cloud Top Height | | X | | | X | | | X | |
| Cloud Top Pressure | | | | | X | | | X | |
| Cloud Top Temperature | | X | | | X | | | X | |
| Downward Longwave Radiation | | | | | | X | X | | |
| Downward Shortwave Radiation | | | | | | X | X | | |
| Global Sea Surface Wind Stress | | X | | | | X | | | X |
| Ice Surface Temperature | | X | | | X | | | X | |
| Imagery | X | | | X | | | | X | |
| Land Surface Temperature | | X | | | X | | | X | |
| Net Heat Flux | | X | | | | | | | |
| Net Solar Radiation at the Top of the Atmosphere | | | | | | X | X | | |
| Ocean Color | | | X | | | X | | X | |
| Outgoing Longwave Radiation | | | | | | X | X | | |
| Ozone Total Column / Profile | | | X | | X | | X | | |
| Precipitable Water / Integrated Water Vapor | | X | | | X | | | X | |
| Precipitation Type / Rate | | X | | | X | | | | X |
| Pressure (Surface / Profile) | | X | | | | | | | |
| Sea Ice Characterization | | X | | | X | | | X | |
| Sea Surface Temperature | X | | | | X | | | X | |
| Sea Surface Winds | X | | | | | X | | | X |
| Snow Cover / Depth | | X | | | X | | | X | |
| Soil Moisture | X | | | | | X | | | |
| Solar Irradiance | | | | | | X | X | | |
| Surface Type | | X | | | | | | | |
| Suspended Matter | | X | | | X | | | X | |
| Total Water Content | | X | | | | | | | |
| Vegetation Index | | | X | | X | | | | |

**Table 12: EDR Synergies**

| Synergy Type | Synergistic Instruments | Synergy Description |
|---|---|---|
| Performance Enhancement | OMPS-Nadir & OMPS-Limb | OMPS-Limb increases vertical spatial resolution of ozone measurements |
| Performance Enhancement | VIS-NIR Imager Radiometer & APS | Aerosol data products are improved when combined with cloud data products produced by VIS-NIR imager-radiometers |
| Capability Enhancement | CrIS & ATMS | ATMS enhances CrIS by providing all-weather capability |
| Performance Enhancement | ERBS cross-track scanning & ERBS-biaxial scanning | Earth radiation budget measurements collected from cross-registered instruments with biaxial & cross-track scanning profiles increases measurement accuracy |
| Capability Enhancement | VIS-NIR Imager Radiometer & Microwave Imager-Sounder | Microwave imager enhances VIS-NIR imager by providing all-weather capability |

## 9.3 Managing the Technical Costs of Jointness

As noted in Chapter 8, government agencies must analyze two dimensions when considering future opportunities for jointness: (1) the cost of a system's technical complexity and (2) the alignment of responsibility, authority, expertise, and budget within the organization that develops the joint system. In this section, I illustrate how to analyze the first dimension by using the trade space analysis tool to explore candidate systems for NOAA and the DoD's future environmental monitoring programs. The specific goals of this analysis were three-fold:

- To evaluate the cost of aggregation versus disaggregation across a broad trade space of Pareto optimal architectures and with varying levels of cost and benefit.
- To evaluate the cost of disaggregation trades currently under consideration by NOAA and the DoD with respect to this broad trade space of options.
- And to note characteristics that were shared across architectures in the trade space and which suggest best practices that can be applied for future environmental monitoring satellite programs.

To complete this analysis, two separate trade spaces—one for NOAA and one for the DoD—were explored. Before exploring Figure 60's trade spaces in greater detail, a few general characteristics are important to note. First, several reference systems were plotted to anchor the reader to my cost and benefit scales. For both NOAA and the DoD, the NPOESS architecture maximized benefit and consequently, was one of the costliest architectures in the trade space; however, for both agencies, the NPOESS architecture was either close to or on the Pareto front.

While the systems that succeeded NPOESS had significantly less benefit and cost, many lay quite far from the cost-benefit Pareto front. For example, architectures based off of the JPSS & NPP satellites, JPSS & DWSS satellites, or all three satellites (JPSS, NPP, & DWSS) were dominated because I assumed that these separate programs did not use common spacecraft buses or coordinate their instruments' development. However, when JPSS was considered as a stand-alone program (i.e. without reference to DWSS or NPP), one can observe that it lies close to the Pareto front. Finally, the current programs of record, JPSS and NPP, do not meet many of the DoD's requirements; these systems' benefit scores were low because they did not provide data from the DoD's preferred early morning orbit, nor did they provide microwave imaging and sounding data from a conically scanning instrument.

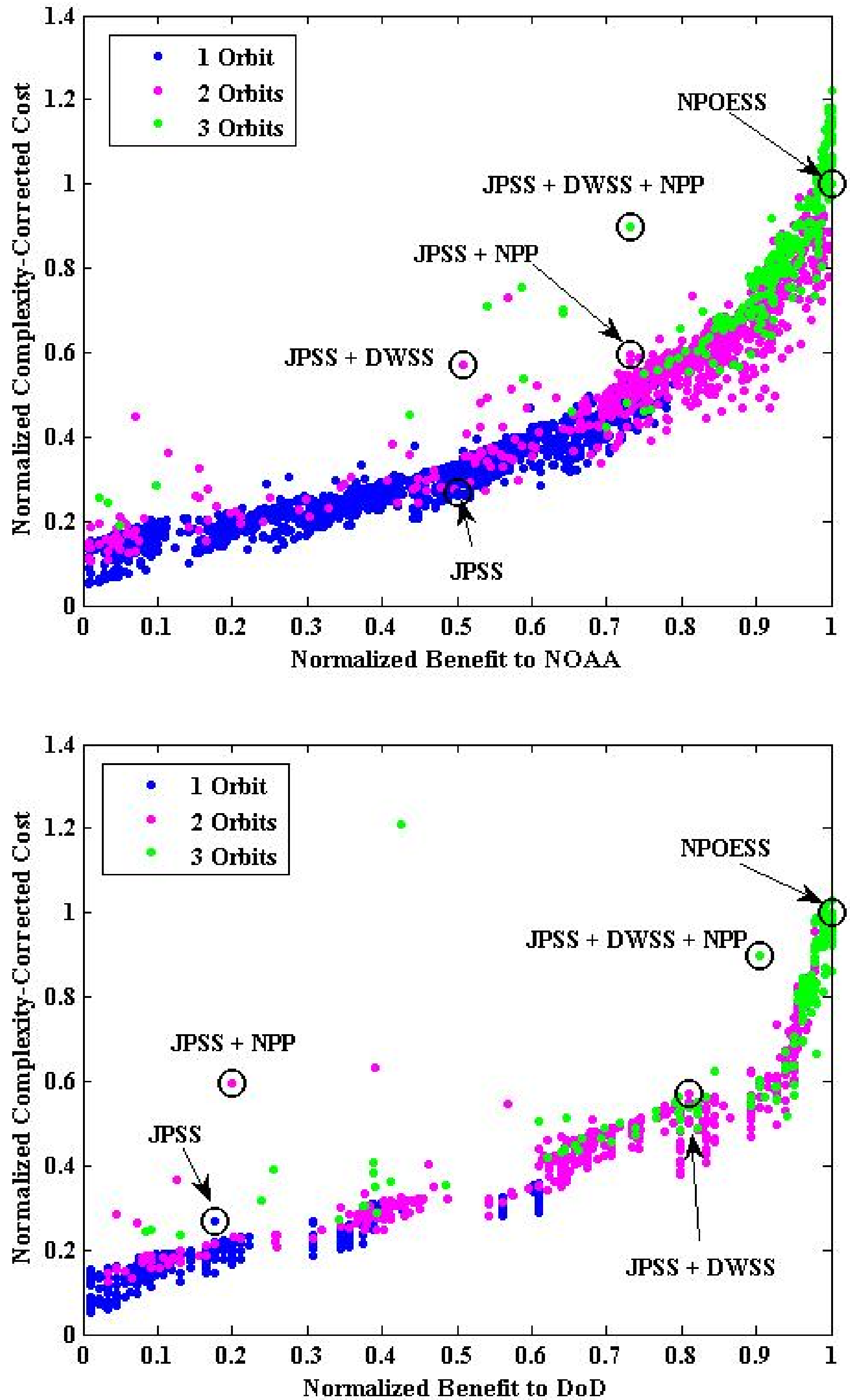


**Figure 60: Full Trade Spaces with Reference Architectures**

In the following sections, I explore these trade spaces in greater detail by focusing on the fuzzy Pareto front. To select the fuzzy Pareto front, I identified architectures on the true Pareto front and removed them from the trade space. I then identified Pareto optimal architectures in the subsequent trade space and removed them as well. I repeated this process until five successive Pareto fronts were removed and assigned to the "fuzzy" Pareto frontier that is discussed below.

### 9.3.1 The Cost Impact of Aggregation Versus Disaggregation

To assess the cost of aggregation versus disaggregation, I classified each architecture according to the average number of satellites that it contained per plane; architectures with an average of one satellite per plane, one to two satellites per plane, and more than two satellites per plane were classified as aggregated, semi-aggregated, and disaggregated, respectively. Next, I selected a fuzzy Pareto front in two ways: (1) by evaluating architectures according to traditional cost estimating relationships that were not corrected for complexity, and (2) by evaluating them using my complexity-corrected cost metric. As shown in Figure 61, when the cost metric did not account for complexity, the fuzzy Pareto fronts were largely dominated by aggregated architectures; however, when complexity costs were included in the metric, a larger number of semi-aggregated and disaggregated architectures appeared on the fuzzy Pareto front.

Figure 62 provides additional description of the composition of both Pareto fronts. For both NOAA and the DoD, when cost estimates did not account for complexity, aggregated architectures constituted the majority of the Pareto front. However, once complexity was factored into the cost equation, the proportion of semi-aggregated architectures grew while the proportion of aggregated architectures shrank; in contrast, even when complexity was included in the cost estimate, the proportion of disaggregated architectures on the Pareto front did not change significantly. The poor performance of the fully disaggregated architectures is important to note since these architectures constituted the majority of the full trade space. Specifically, the full trade space contained approximately 5e11 architectures, 99%, 9e-6% and 0.07% of which are disaggregated, aggregated, and semi-aggregated, respectively. Thus, I concluded that:

- Even when cost estimates accounted for complexity, on average, aggregated architectures containing one satellite per plane performed better than disaggregated architectures that contained greater than two satellites per plane.
- However, when I accounted for complexity, I observed that semi-aggregated architectures provided a possible alternative to fully aggregated ones. Semi-aggregated architectures reduced spacecraft complexity by breaking up complex satellites into two simpler satellites that flew in a train.

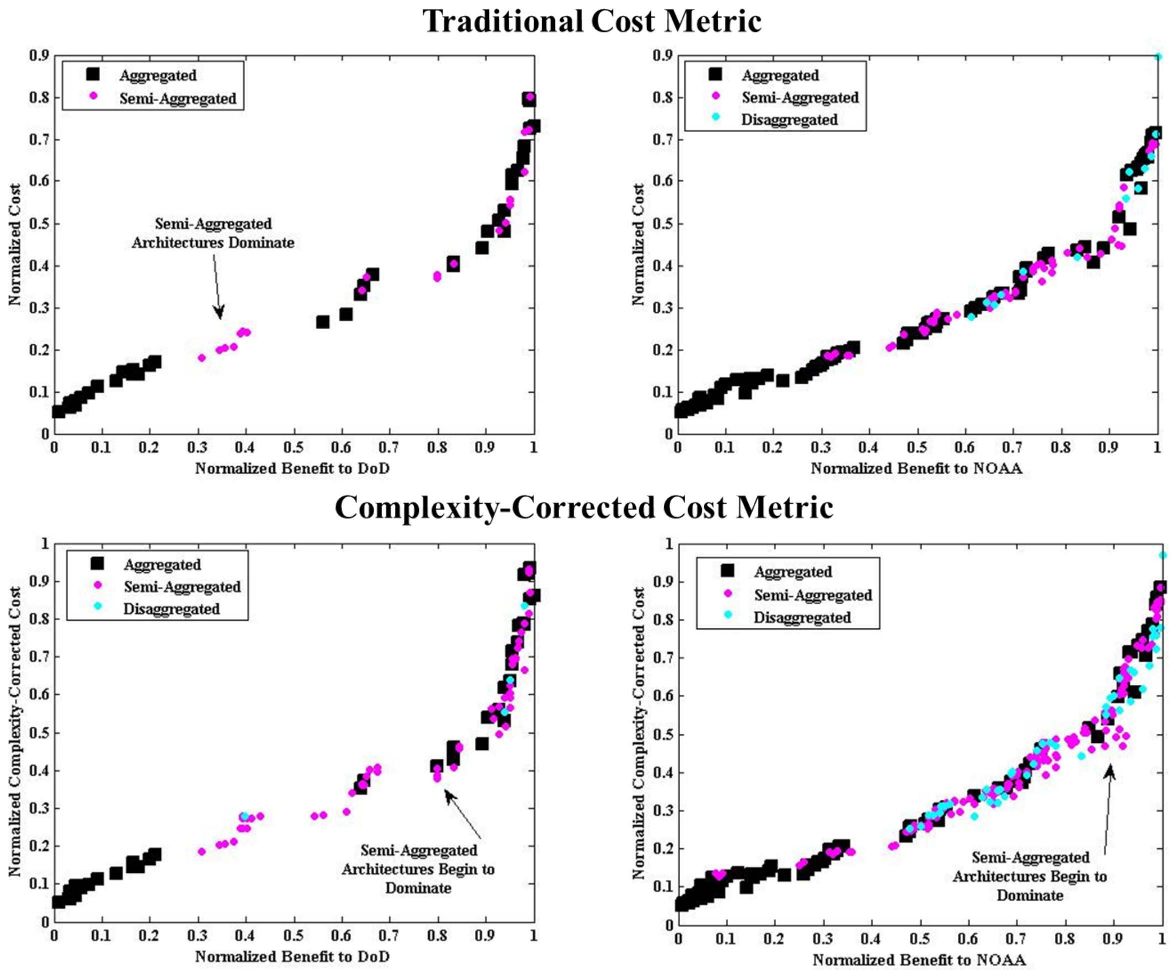


**Figure 61: Fuzzy Pareto Fronts with Both Cost Metrics**

As shown in Figure 61, there were several regions of both NOAA and the DoD's Pareto front where semi-aggregated architectures dominated aggregated ones. General characteristics of these semi-aggregated architectures include:

- For NOAA, the dominant semi-aggregated architectures each contained at least one plane with VIIRS, one plane with a conical microwave imager-sounder, and one plane with CrIS and two planes with ATMS. Different sets of climate-centric sensors (i.e. TSIS, ERBS, OMPS, and APS) were co-hosted alongside these four primary instruments.
- For NOAA, all but one of the dominant semi-aggregated architectures separated VIIRS and the microwave imager-sounder and assigned them to separate spacecraft in the same orbital plane. Although VIIRS and the microwave sounder were separated from each other, they were sometimes hosted on the same satellite as the instruments listed above.
- For the DoD, regardless of the cost metric used, semi-aggregated architectures dominated at medium benefit levels (i.e. between 0.3 and 0.6). In these architectures, a VIS/NIR sensor and a conical microwave imager-sounder were assigned to separate spacecraft in the early morning orbit.

For higher benefit architectures, either the VIS/NIR or the microwave sensor was also flown alone in a second orbital plane.

- Finally, when complexity was included in the cost metric, semi-aggregated architectures began to dominate at higher levels of the DoD's Pareto front as well. These architectures assigned VIIRS and CMIS to separate spacecraft in the early morning orbit and flew VIIRS in a second orbital plane.

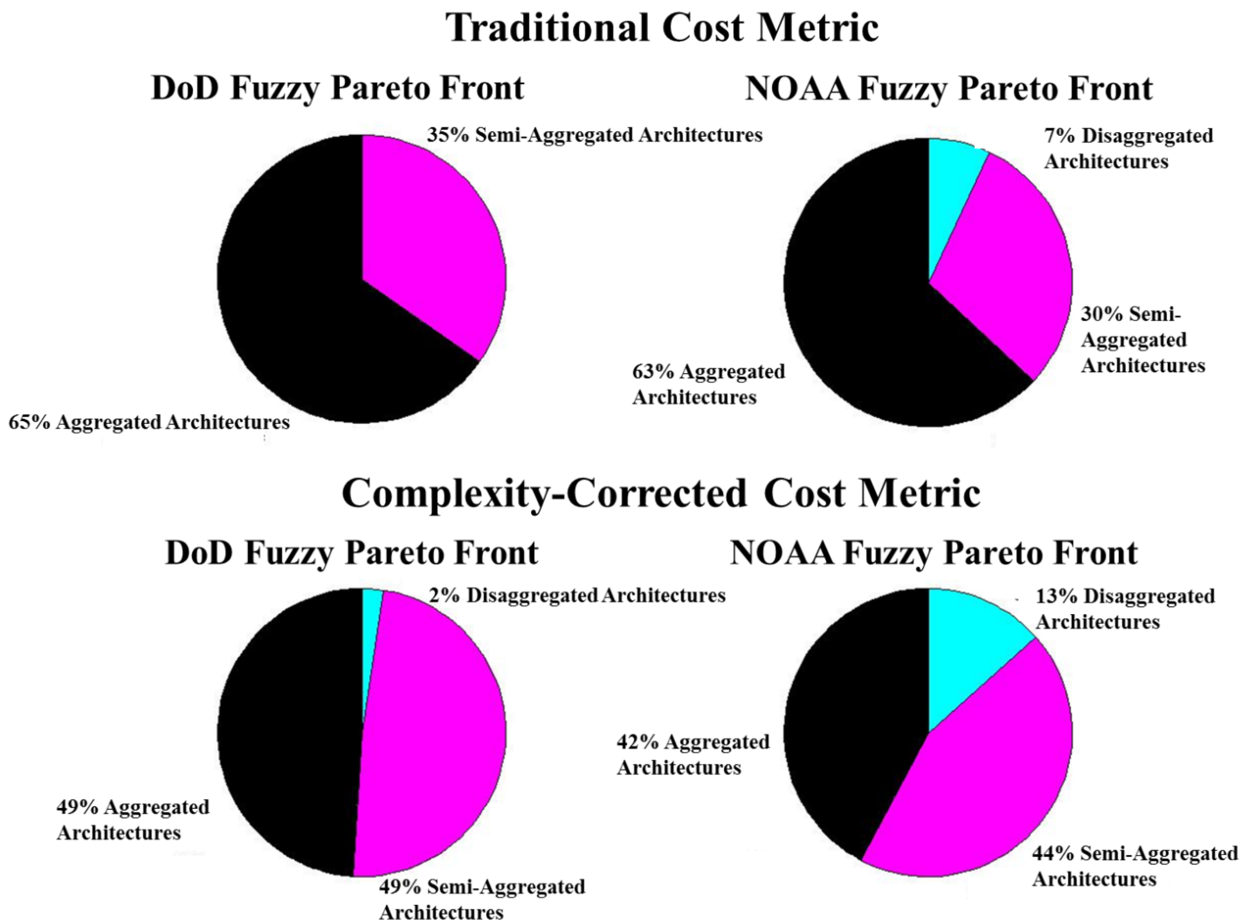


**Figure 62: Fuzzy Pareto Front Descriptive Statistics**

These results illustrate the importance of considering the cost of complexity when analyzing system architecture options: when systems' reserve budgets are increased to account for the risk of complexity-induced cost growth, different types of system architectures may dominate the Pareto front. In this case, aggregated architectures still performed well with respect to the entire trade space of options but semi-aggregated architectures also appeared as viable alternatives to more traditional aggregated systems. Because the complexity-corrected metric allowed me to observe instances where semi-aggregated or disaggregated architectures performed at levels comparable to aggregated ones, I used this metric for the remainder of my analysis. An important limitation of this metric—that it used rules-of-thumb to adjust cost estimates and that has not been calibrated—will be discussed further in my conclusions.

### 9.3.2 Current Disaggregation Trades

In response to the cost growth that occurred previously on NPOESS, JPSS, and DWSS, NOAA and the DoD began investigating options to disaggregate future systems for environmental monitoring in low Earth orbit. Currently, NOAA and the DoD are considering the following disaggregation trades:

- Disaggregating climate-centric sensors from weather-centric sensors and hosting both on separate spacecraft for future NOAA systems [D142, D143].
- Establishing a free-flyer ATMS-CrIS spacecraft by disaggregating these critical instruments from the larger JPSS spacecraft [D143].
- And disaggregating the VIS/NIR and microwave-imager sounder instruments and hosting both on separate spacecraft on future DoD systems [53].

Although there are multiple motivations for considering these trades, in this section, I discuss how each trade affects the lifecycle cost of future systems. Again, I use the complexity-corrected cost metric to account for the cost of aggregation-induced complexity. In this way, my analysis is able to assess whether the agencies' proposed disaggregation strategies effectively reduce the complexity that was previously induced by aggregation.

Figure 63 illustrates the first disaggregation trade: assigning climate-centric and weather-centric sensors to separate spacecraft. To construct this plot, I classified ERBS, OMPS-Limb, TSIS, and APS as climate-centric sensors and VIIRS, ATMS, CrIS, and OMPS-Nadir as weather-centric sensors; as will be discussed below, I refrained from assigning the microwave imager-sounders to either category. Figure 63 shows that the current JPSS program is located at a transition point in the trade space: at benefit levels below JPSS, the architectures contained *only* weather-centric sensors. However, as benefit increased above JPSS, architectures increasingly contained climate-centric sensors that were hosted on the same spacecraft as weather-centric ones. Thus, if NOAA hopes to increase JPSS's benefit in the future, it should consider architectures that aggregate climate-centric and weather-centric sensors onto the same spacecraft. If future systems plan to generate benefit at or above the level currently produced by JPSS, then there is no compelling *technical* reason to disaggregate climate and weather sensors.

While there may be little technical reason to disaggregate climate and weather sensors, there is an operational one: by limiting the scope of the JPSS project, NOAA can reduce its cost and schedule risks [D143]. The desire to reduce these risks—particularly in light of a possible gap in weather satellite data—motivated an independent review team to recommend developing an ATMS-CrIS free-flyer spacecraft [D143]. By developing a smaller free-flyer spacecraft, NOAA could accelerate its development timeline and reduce the risk of a data gap [D143]. To investigate the lifecycle cost impact of this (and related) trades, I identified all architectures that used ATMS-CrIS free-flyers and also those that used ATMS-CrIS-OMPS-VIS/NIR or ATMS-CrIS-VIS/NIR free-flyers. The results, shown in Figure 64, indicate that as a whole, none of the proposed disaggregation strategies dominated other architectures in the trade space. However, the tool did allow me to identify architectures with free-flyers that had similar cost and benefit to JPSS; these architectures are listed in Table 13. Of these possible free-flyers, a few characteristics are important to note:

- Most architectures with a CrIS-ATMS free-flyer also had a VIS/NIR free-flyer or both a VIS/NIR and a microwave imager-sounder free-flyer. By disaggregating the sensors in this way, the architectures were able to use similarly sized common buses and to capitalize on the cost saving benefits of a block buy of those buses.
- Most architectures with a CrIS-ATMS-VIS/NIR free-flyer either flew two copies of the same spacecraft in different orbital planes or had a single orbital plane but an additional spacecraft that hosted a microwave imager-sounder and several climate-centric instruments.

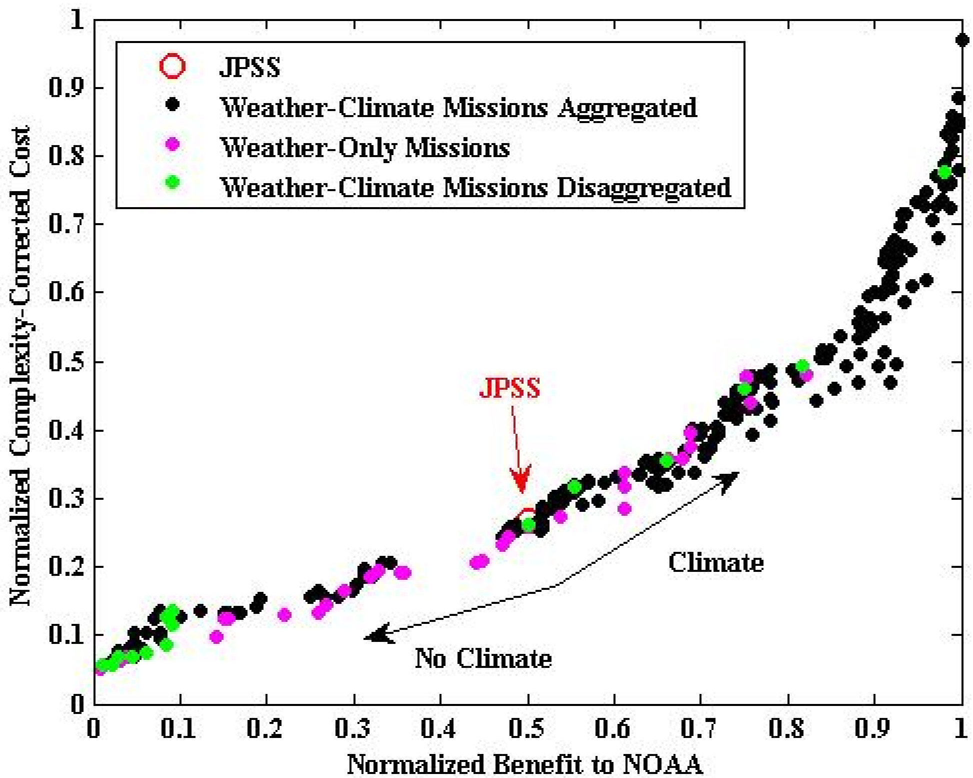


**Figure 63: NOAA's Climate-Weather Trades**

The architecture with a CrIS-ATMS-VIS/NIR free-flyer and a second spacecraft with a microwave imager-sounder and climate-centric instruments provides a potential compromise between the two trades considered above. Specifically, by limiting the scope of future projects to include only CrIS, ATMS, and VIIRS, NOAA could gain some of the operational benefits of a free-flyer mission. By establishing a second project that includes a microwave imager-sounder and climate-centric instruments, NOAA could continue collecting climate data without interfering with its operational weather mission. It may also be possible to transfer full responsibility for funding and managing the second project to NASA, which could explore additional opportunities for cost savings by seeking an international partner to contribute the microwave imager-sounder. As will be discussed in Section 9.4, transferring full authority and responsibility for the second mission to NASA is also consistent with the recommendations of Agency Action Model and the principles for architecting joint programs.

Figure 65 illustrates the technical logic behind this recommendation. As benefit increased beyond JPSS, NOAA's systems contained both a VIS-NIR sensor and a microwave-imager sounder. However, at medium-high benefit levels (i.e. 0.4 < benefit < 0.8), most Pareto optimal architectures disaggregated these instruments and it was only at the highest benefit levels (i.e. benefit > 0.8) where architectures co-hosted the instruments on the same spacecraft. Thus, it seems advisable to "anchor" two spacecraft around these sensors and to separate the climate-centric and the weather-centric sensors accordingly.

Figure 65 also illustrates a similar finding for the DoD: that at medium-high benefit levels, disaggregating the VIS-NIR and microwave imager-sounders was optimal, while at the highest benefit levels aggregating them onto the same spacecraft was. Unlike NOAA's architectures, at medium-high benefit levels, the DoD's architectures contained the VIS-NIR and microwave imager-sounders *only* and it is not until the very highest benefit levels (i.e. benefit > 0.9) that the DoD's architectures began to include other instruments and to aggregate them onto the same spacecraft as VIIRS and CMIS.

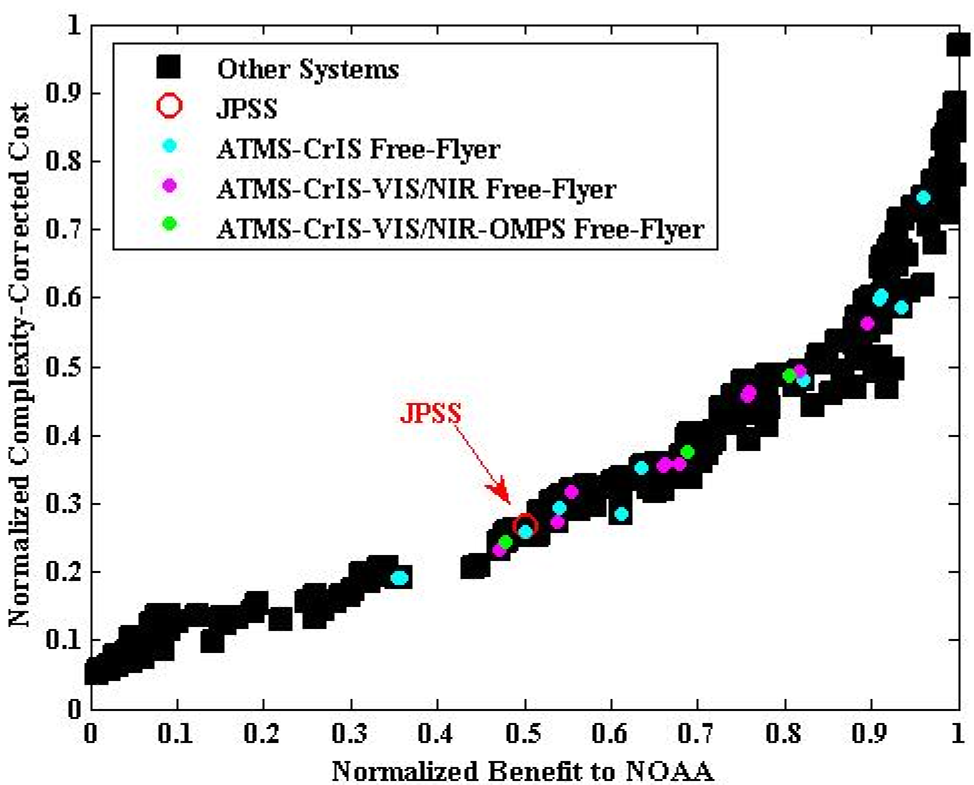


**Figure 64: NOAA's Free-Flyer Trades**

### 9.3.3 Strategies for Reducing Cost through Disaggregation

Now that I have analyzed specific trades under consideration by NOAA and the DoD, I review several of my assumptions in the context of these results. Key assumptions that affected the cost of aggregated versus disaggregated architectures include:

- The system's capabilities,

- The cost savings enabled by commonality,
- Launch costs,
- And the cost of complexity.

The discussion above suggests an important relationship between aggregation, disaggregation, and a system's capabilities. For example, medium-high benefit DoD architectures disaggregated the VIS/NIR and microwave imager-sounders whereas higher benefit architectures aggregated them onto the same spacecraft. Thus, the cost of aggregation versus disaggregation seems closely related to the capabilities that a program decides to field and the requirements that those capabilities meet. In this analysis, I only considered capabilities that were derived from the NPOESS program; therefore, the options for the VIS/NIR sensor and microwave-imager sounder were all high performing and resource intensive (i.e. they had large mass and power requirements). If NOAA or the DoD reduces the size and performance of these sensors in the future, then the above analysis should to be repeated.

Next, the fuzzy Pareto front for both agencies was composed entirely of architectures that used common spacecraft buses. Importantly, in order to achieve commonality's potential savings, programs need to make both the upfront investment to develop a common bus and the commitment to procure copies of that bus within a short period of time; as noted by Burch [48], the learning curve savings included in my cost metric are only applicable if systems are delivered six to twelve months apart. As a result, to capitalize on the cost savings potential of commonality, future programs may need more upfront funding to enable systems to be procured more efficiently. This statement is also true for the instruments in each architecture: to enable the learning curve cost savings that are assumed in the metric, future programs need to procure multiple copies of each instrument at the same time.

I also investigated whether the dominant semi-aggregated or disaggregated architectures in Figure 60 would remain dominant if they had to launch on traditional launch vehicles. I found that even when these architectures were limited to launch only on traditional launch vehicles, they still performed well with respect to the aggregated architectures. The primary reason for this appears to be the cost and benefit of the microwave imager-sounders that were included in the trade space. Specifically, these sensors were necessary to obtain a high benefit score but they appeared to drive architectures' cost and configuration. Future research could examine the specific impacts of these instruments by including less capable options with higher TRLs and by adjusting agency requirements accordingly.

Finally, as discussed previously, my results are contingent on the cost of complexity that was included in the cost metric. The metric used rules-of-thumb to develop a complexity budget for each system and thus, could benefit from improved calibration in the future. However, I stress that during a pre-Phase A analysis of potential system architectures, any means for accounting for complexity is valuable, since it enables the system architect to gain insight into potential cost growth risks that could affect the system in the future.

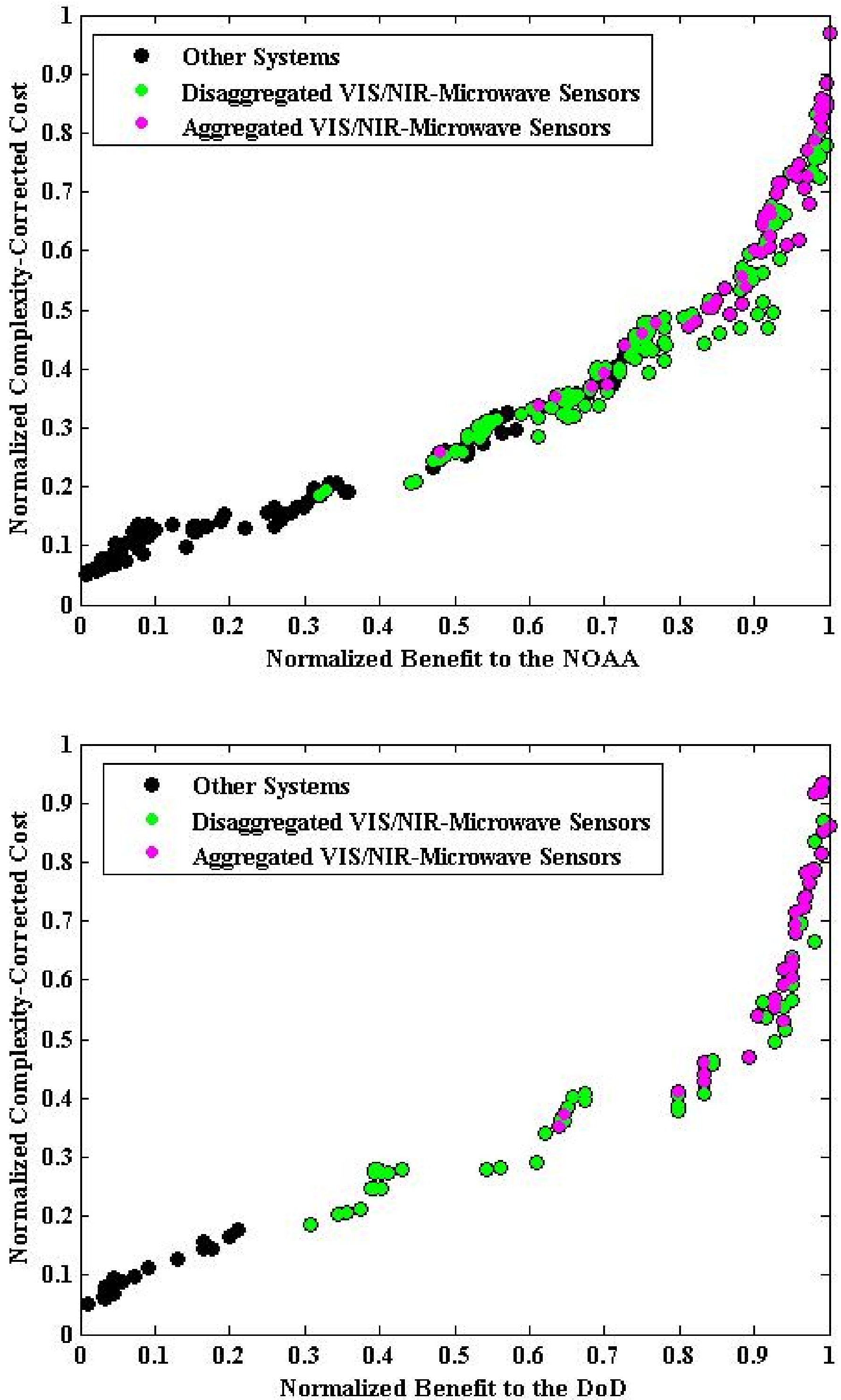


Figure 65: VIS/NIR-Microwave Imager Sounder Disaggregation Trades

**Table 13: Alternative Free-Flyer Spacecraft**

| Normalized Complexity Corrected Cost | Normalized Benefit | Terminator Orbit | Afternoon Orbit | Mid-Morning Orbit |
|---|---|---|---|---|
| **ATMS - CrIS-VIS/NIR Free-Flyer** | | | | |
| 0.49 | 0.82 | none | SC1 = {VIIRSLite-noocean, CrIS, ATMS}<br>SC2 = {CMIS, ERBS2, TSIS, APS} | SC1 = {ATMS} |
| 0.46 | 0.76 | SC1 = {ATMS} | SC1 = {VIIRS, CrIS, ATMS}<br>SC2 = {Windsat, OMPS-Nadir, OMPS-Limb} | SC1 = {OMPS-Nadir} |
| 0.46 | 0.76 | none | SC1 = {VIIRS, CrIS, ATMS}<br>SC2 = {CMIS, OMPS-Nadir, ERBS2, TSIS, APS} | none |
| 0.36 | 0.68 | none | SC1 = {VIIRS, CrIS, ATMS} | SC1 ={VIIRS, CrIS, ATMS} |
| 0.36 | 0.66 | SC1 = {VIIRS, CrIS, ATMS} | SC1 = {VIIRS, CrIS, ATMS} | none |
| 0.36 | 0.66 | none | SC1 = {VIIRS, CrIS, ATMS}<br>SC2 = {SSMIS-U, TSIS, APS} | none |
| 0.32 | 0.55 | none | SC1 = {VIIRS, CrIS, ATMS}<br>SC1 = {ERBS1, ERBS2, APS} | none |
| 0.27 | 0.54 | none | SC1 = {VIIRSLite-noocean, CrIS, ATMS} | SC1 = {ATMS} |
| 0.23 | 0.47 | none | SC1 = {VIIRS, CrIS, ATMS} | none |
| **ATMS - CrIS Free-Flyer** | | | | |
| 0.48 | 0.82 | none | SC1 = {VIIRS, SSMIS-U}<br>SC2 = {CrIS, ATMS} | SC1 = {VIIRS, OMPS-Nadir}<br>SC2 = {ATMS} |
| 0.35 | 0.63 | none | SC1 = {VIIRS, SSMIS-U, ERBS2}<br>SC2 = {ATMS, CrIS} | none |
| 0.29 | 0.61 | none | SC1 = {VIIRS}<br>SC2 = {ATMS, CrIS}<br>SC3 = {SSMIS-U} | none |
| 0.29 | 0.54 | none | SC1 = {VIIRSLite-ocean, APS}<br>SC2 = {SSMIS-U}<br>SC3 = {CrIS, ATMS} | none |
| 0.26 | 0.50 | none | SC1 = {VIIRSLite-ocean}<br>SC2 = {SSMIS-U}<br>SC3 = {CrIS, ATMS} | none |
| 0.19 | 0.36 | none | SC1 = {VIIRSLite-ocean}<br>SC2 = {CrIS, ATMS} | none |
| 0.19 | 0.35 | none | SC1 = {VIIRSLite-noocean}<br>SC2 = {CrIS, ATMS} | none |
| 0.48 | 0.82 | none | SC1 == {VIIRS, SSMIS-U}<br>SC2 = {CrIS, ATMS} | SC1 = {VIIRS, OMPS-Nadir}<br>SC2 = {ATMS} |
| **ATMS - CrIS - VIS/NIR - OMPS Free-Flyer** | | | | |
| 0.49 | 0.80 | none | SC1 = {VIIRS, CrIS}<br>SC 2 = {Windsat, ATMS, APS} | SC1 = {VIIRS, CrIS, OMPS-Nadir, ATMS} |
| 0.25 | 0.48 | none | SC1 = {VIIRS, CrIS, OMPS-Nadir, ATMS} | none |

### 9.3.4 Analysis Conclusions

The above analysis motivated several conclusions about the cost of aggregation versus disaggregation. First, I demonstrated that when complexity costs are included in a cost metric, aggregated architectures do not necessarily dominate the Pareto front. Although aggregated architectures *do* appear to consistently outperform disaggregated architectures, semi-aggregated architectures have the potential to be less costly than aggregated ones. I also noted that for all architectures except the highest performers, disaggregating the VIS/NIR sensor from the microwave-imager sounder appeared to be an optimal trade. Finally, I used this finding to motivate a recommendation that NOAA consider architectures with a VIS/NIR, CrIS, and ATMS free-flyer and a separate spacecraft that is anchored around a microwave imager-sounder and that contains other climate-centric instruments.

There are many opportunities to refine the above analysis and conclusions in the future. First, my conclusions were contingent on my initial assumptions and the evaluation metrics that were used. While the cost and benefit metrics were derived from detailed case studies of past programs, their accuracy could be improved through further calibration. Second, additional metrics that assess the risks inherent to both architectures could also be added; for example, disaggregated architectures may be more susceptible to launch failures (because the probability of experiencing no launch failures decreases with the number of launches) but more capable of responding to on-orbit failures (since smaller common spacecraft are more easily reconfigured and used as spares). Third, the cost of aggregation and disaggregation may be contingent on the mission length, on each system's lifetime, and on the capabilities fielded by each system; future work should analyze cases other than what I considered here.

Finally, although this analysis did identify alternatives to NPOESS, JPSS, and DWSS's aggregated architectures that had the potential to reduce future lifecycle costs, I still observed that—even when I accounted for the cost of technical complexity—aggregated architectures still performed well with respect to the entire trade space. Thus, as noted in Chapter 8, it is incomplete to attribute past programs' cost growth to their systems' technical architectures *only.* Instead, in order to reduce future program costs, government agencies not only need to consider technical costs, but also must consider the organizational costs that can be induced by their programs' management structures. The section that follows explores these organizational issues in greater detail.

## 9.4 Managing the Organizational Costs of Jointness

The above analysis illustrated the importance of analyzing two dimensions—technical and organizational—when evaluating future opportunities for jointness. In this section, I outline a process that government agencies can use to identify costs that may be induced by organizational jointness and to select a joint program form to minimize them. This process was directly derived from the Agency Action Model and the principles for architecting joint programs that were presented in Chapter 8. Next, I illustrate how to apply this process using the trade space analysis tool and NOAA's low Earth orbiting environmental monitoring program as a case study.

### 9.4.1 Applying the Principles for Architecting Joint Programs

To apply the Agency Action Model and principles for architecting joint programs, I suggest that government decision makers should follow a three step process for assessing the costs and risks of establishing a joint program and for selecting a program form that minimizes both. The process begins with an assessment of interagency mission synergies and continues with an assessment of the cost of sharing or delegating authority. At each step of the process, key risks should be identified and mitigation plans developed.

#### 9.4.1.1 Step 1: Assess Mission Synergies

The first step of the process is to assess mission synergies between potential partners. Two partnership types are possible:

- A ***synergistic partnership*** is one where the agencies' missions are well-aligned; in such cases, as a system's benefit to one agency increases, so does its benefit to the other.
- Alternatively, a ***non-synergistic partnership*** is one where the agencies' missions are poorly aligned; in such cases, as a system's benefit to one agency increases, its benefit does not necessarily increase for the other.

To evaluate mission synergies, I recommend that agencies *independently* determine their requirements. Once these requirements have been established, each agency should develop and evaluate multiple conceptual designs. Finally, the agencies should evaluate each other's designs with respect to their own requirements.

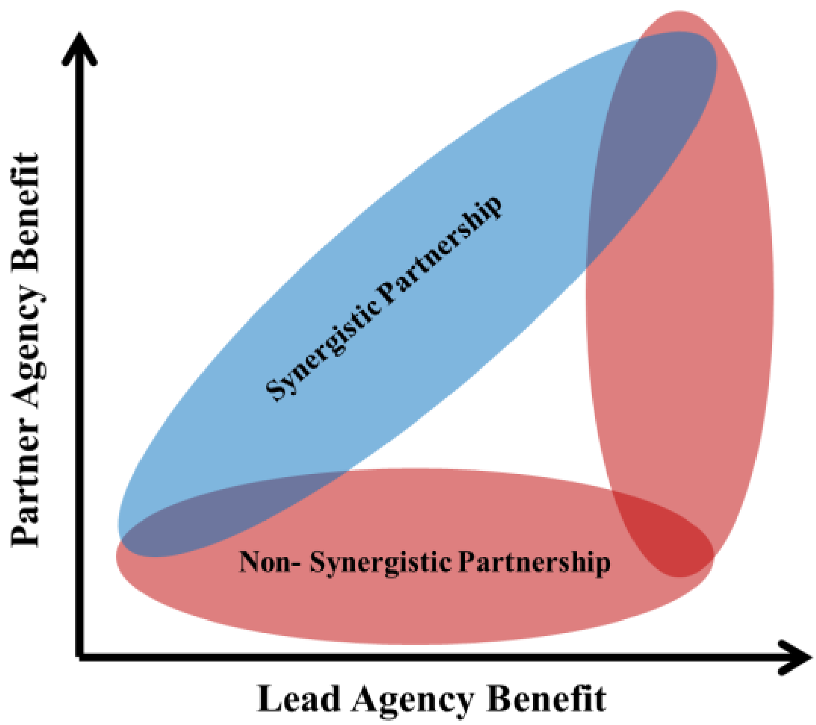


**Figure 66: Partnership Types**

Figure 66 illustrates a notional trade space of conceptual designs and how designs for agencies with synergistic or non-synergistic missions compare. As shown, if the designs are evaluated with respect to both agencies' requirements and plotted against the benefit that they deliver to each agency, synergistic partnerships will fall towards the central region of the trade space. Alternatively, non-synergistic partnerships will result in systems that perform very well with respect to one set of requirements but very poorly with respect to another's. As will be discussed below, understanding whether agencies' missions are synergistic is critical for selecting a joint program form and for actively mitigating its risks.

#### 9.4.1.2 Step 2: Assess the Cost of Sharing Authority

Regardless of whether their missions are synergistic, agencies can share authority over their joint system. According to the principles, an agency's authority must be aligned with its mission responsibility; therefore, if agencies share authority over a system, the system should equally execute both agencies' missions. Figure 67 illustrates this principle on a notional trade space and shows that when agencies share authority, they must select a system that delivers approximately equal mission benefit to both partners. If the agencies select a system outside of this zone, one agency's authority will be misaligned with its mission responsibility. According to the Agency Action Model, cost growth will result when that agency attempts reprioritize its mission's execution by the joint system. Therefore, to assess the cost of sharing authority, the agencies should generate multiple conceptual designs that equally meet both of their requirements. These designs should be compared to designs that the agencies generated independently, a cost differential determined, and additional risks identified.

Generally, sharing authority carries two key risks. First, in order to meet the joint requirements set, new technology will need to be developed since it is unlikely that either agency's heritage technology will be capable of meeting joint requirements. Developing technology is a slow and uncertain process [84] that can induce unexpected cost growth, particularly if a program undertakes multiple concurrent technology development projects. Second, once joint requirements are established, it is unlikely that the agencies will be willing to trade those requirements against cost later, since doing so poses a threat to their autonomy. Therefore, once a program establishes joint requirements, it is locked into those requirements and the complex system that meets them. To mitigate these risks, joint programs should budget for technology development and should include a large margin in their budgets since they will be unable to reduce their system's capabilities to cut costs later.

If authority is shared, the joint program can take form SIS, SMS, or SMN from Figure 54. If agencies have synergistic missions, I recommend that they use form SIS, since decoupling their individual requirements into components may be impossible and using form SMS would result in unnecessary conflict. If the agencies have non-synergistic missions, form SMN can be used, if the system can be modularized such that the agencies' missions can be decoupled. If form SMN is used, agencies should be sure to develop components to the same sets of engineering and mission assurance standards; however, if this is impossible, the joint program should allocate some budget so that engineers can reconcile the different requirements standards that were levied on each component. Finally, in all cases, the partnering agencies should have equal expertise so that one agency cannot use an expertise differential to erode the authority of the other.

#### 9.4.1.3 Step 3: Assess the Cost of Delegating Authority

After assessing the costs of sharing authority in a joint program, agencies should consider the costs and risks of delegating it. If agencies have non-synergistic missions, then one agency can serve as an acquisition agent for the other (i.e. forms FIN and CMN), as long as the system that is developed delivers benefit to one agency only. Of course, acquisition agent arrangements only make sense when one agency lacks the expertise to develop a system or its components independently. As discussed in Chapter 8, the lead agency should contribute the full budget for the program and should account for the fact that its acquisition agent will execute the system development process conservatively and in strict accordance with its policies and procedures, even if those processes unnecessarily increase the cost of the system.

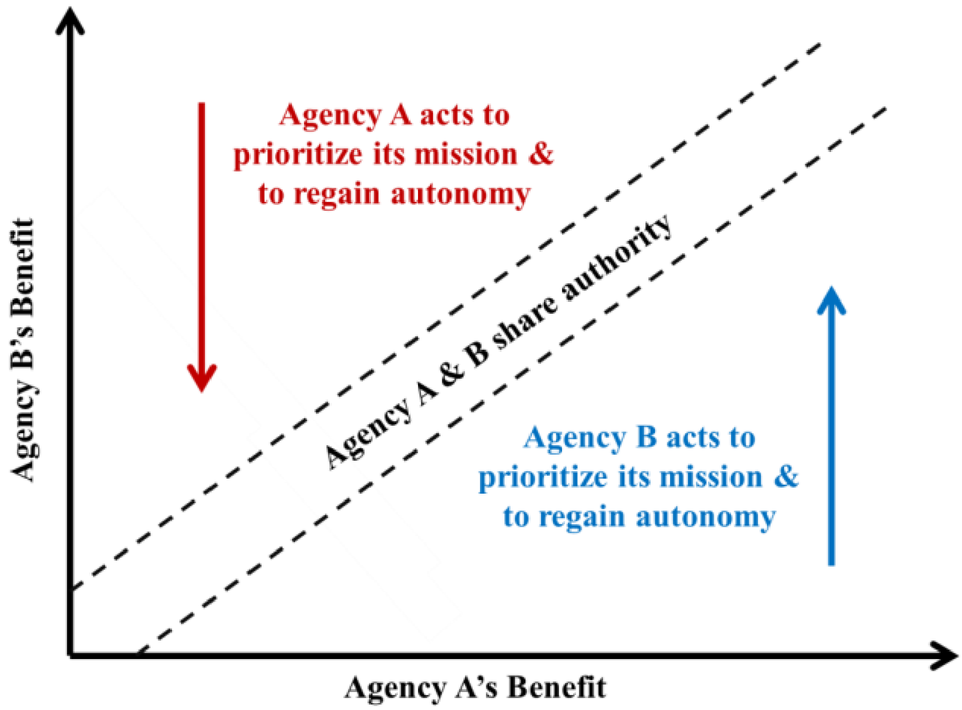


**Figure 67: Cost of Sharing Authority**

If the agencies have synergistic missions or if they chose to develop a system that executes both agencies' non-synergistic missions, a pure acquisition agent model is impossible, since both agencies' missions are satisfied by the system. In this case, there is a risk that the acquisition agent will prioritize its own mission over the mission of the lead agency. To mitigate this risk, the lead agency can attempt to select a design that minimizes benefit to its partner. The lead agency also needs to have sufficient technical expertise to monitor its partners' actions and should require the partner to contribute some portion of the program's budget. Again, form PMS is not recommended and unless the agencies' missions can be completely decoupled (a challenge when their requirements are synergistic) and neither is form PMN; this leaves form FIS as the only viable option.

### 9.4.2 Case Study: Applying the Principles to Architect NOAA's Program

To illustrate how to apply the principles presented in Chapter 8 and the process outlined above, I used a case study of NOAA's low Earth orbit environmental monitoring program. I limited this analysis to NOAA because this particular agency lacks the in-house technical expertise that is necessary to develop satellites independently. Therefore, unless NOAA gains that expertise in the future, it is likely that it will continue to partner with either NASA or the DoD. This section illustrates how NOAA leaders can apply the lessons learned from this dissertation to reason through the process of finding an agency partner for NOAA, of selecting a joint program form that is appropriate for the partnership, and of mitigating that form's risks.

Specifically, in this section, I use the process outlined above to identify joint program forms that satisfy the principles and to identify each partnership's inherent risks. To create the conceptual system designs that are required by the process, I used the trade space analysis tool that was described above. In the analysis that follows, I use concept designs that fell on the "fuzzy" Pareto front of complexity-corrected cost and benefit, or were three layers of Pareto dominance deep.

#### 9.4.2.1 Step 1: Assess Mission Synergies

NOAA, NASA, and the DoD each require similar environmental data to be collected from low Earth orbit; however, despite the similarity of their data requirements, the agencies' requirements for *implementation* differ. As shown in Figure 68, these differences were readily visible when the Pareto optimal systems for each agency were evaluated with respect to the other agencies' requirements. Figure 68 clearly shows that NOAA and the DoD are non-synergistic partners. The primary reasons for their lack of mission synergy include:

- The DoD requires data to be collected from an early morning orbit (i.e. 5:30 RAAN) whereas NOAA requires data to be collected in an afternoon orbit (i.e. 13:30 RAAN).
- The DoD prioritizes data generated by a visible-infrared (VIS-NIR) imager-radiometer and a conical microwave imager-sounder whereas NOAA's highest priority data is generated by cross-track infrared and microwave sounders. However, like the DoD, NOAA also places high priority on data collected from a VIS-NIR sensor.
- The DoD has only one mission: weather prediction. NOAA's primary mission is also weather prediction but it has an additional climate mission which the DoD does not share.

Anyone familiar with either NOAA or the DoD's heritage satellite programs could have generated the above list; however, by following my process of generating concept systems for each agency and of evaluating them against other agencies' requirements, government decision makers can observe how significantly the agencies' requirements differ and how those differences manifest themselves in the systems that each agency prefers. In this case, NOAA and the DoD's missions were so divergent that the only systems that generated benefit to both agencies were those that also maximized it.

In contrast, NOAA and NASA's missions are synergistic: as one agency's benefit increases, so does the other's. Again, the reasons for this synergism are well known within the environmental monitoring community:

- Both agencies require data that is collected from afternoon orbits.
- The instruments that execute NOAA's primary weather mission are derived from instruments that were developed previously by NASA to execute its climate science mission. Therefore, NOAA's weather instruments serve dual purposes of contributing to weather forecasting and to climate observation.
- NOAA's secondary climate mission is NASA's primary mission; importantly though, NASA does not share NOAA's weather mission.

As will be discussed below, understanding that NOAA and the DoD are non-synergistic partners and that NOAA and NASA are synergistic partners is critical for identifying which joint program forms the partners should use.

#### 9.4.2.2 Step 2: Assess the Cost of Sharing Authority

Regardless of their mission synergies, NOAA could form a joint program by sharing authority with either the DoD or NASA. Figure 69 illustrates the technical cost impact of sharing authority by identifying candidate joint systems and plotting them alongside NOAA's Pareto front. Candidate joint systems were those that equally met both partners' requirements (with a +/- 0.05 benefit score margin) and that were located on the joint Pareto front. The joint Pareto front was identified by averaging both agencies' individual benefit scores to obtain a joint benefit score. This joint benefit score and the complexity-corrected cost metric were then used to calculate each system's Pareto rank.

Figure 69 shows that the relationship between cost and benefit on NOAA's Pareto front was linear and constant until a knee in the curve after which the slope increased. Importantly, nearly all of the candidate joint systems lied *above* this point, where cost increased faster than benefit. Exceptions to this general statement included the set of systems that performed poorly with respect to both agencies' requirements (shown at the lower left corner of the trade space) and two candidate systems that met approximately 50% and 70% of both NOAA and NASA's requirements.

Important characteristics of these two systems include:

- Both systems contained a train of satellites in a single orbital plane with a 13:30 RAAN.
- Both systems contained a VIS-NIR sensor, cross-track infrared and microwave sounders, and an Earth radiation budget sensor.
- The higher performing system also included an ozone monitor, a total solar irradiance monitor, and a conical microwave imager-sounder.
- Both systems disaggregated the VIS-NIR sensor from NOAA's highest priority cross-track infrared and microwave sounders.

Figure 69 also illustrates the two costs of sharing authority. The first cost is induced by limiting the size of the trade space. As shown, if NOAA did not share authority, it would have the autonomy to select any of the systems on its Pareto front, including those with lower levels of benefit and cost. However, by sharing authority, NOAA confines its trade space to a region that maximizes both of these metrics. As discussed previously, when agencies share authority, it is unlikely that they will accept capability reductions later in the program, even if their programs' costs grow significantly. Thus, by sharing authority with either NASA or the DoD, NOAA locks its system into a costly configuration that it will be forced to preserve for the remainder of the program.

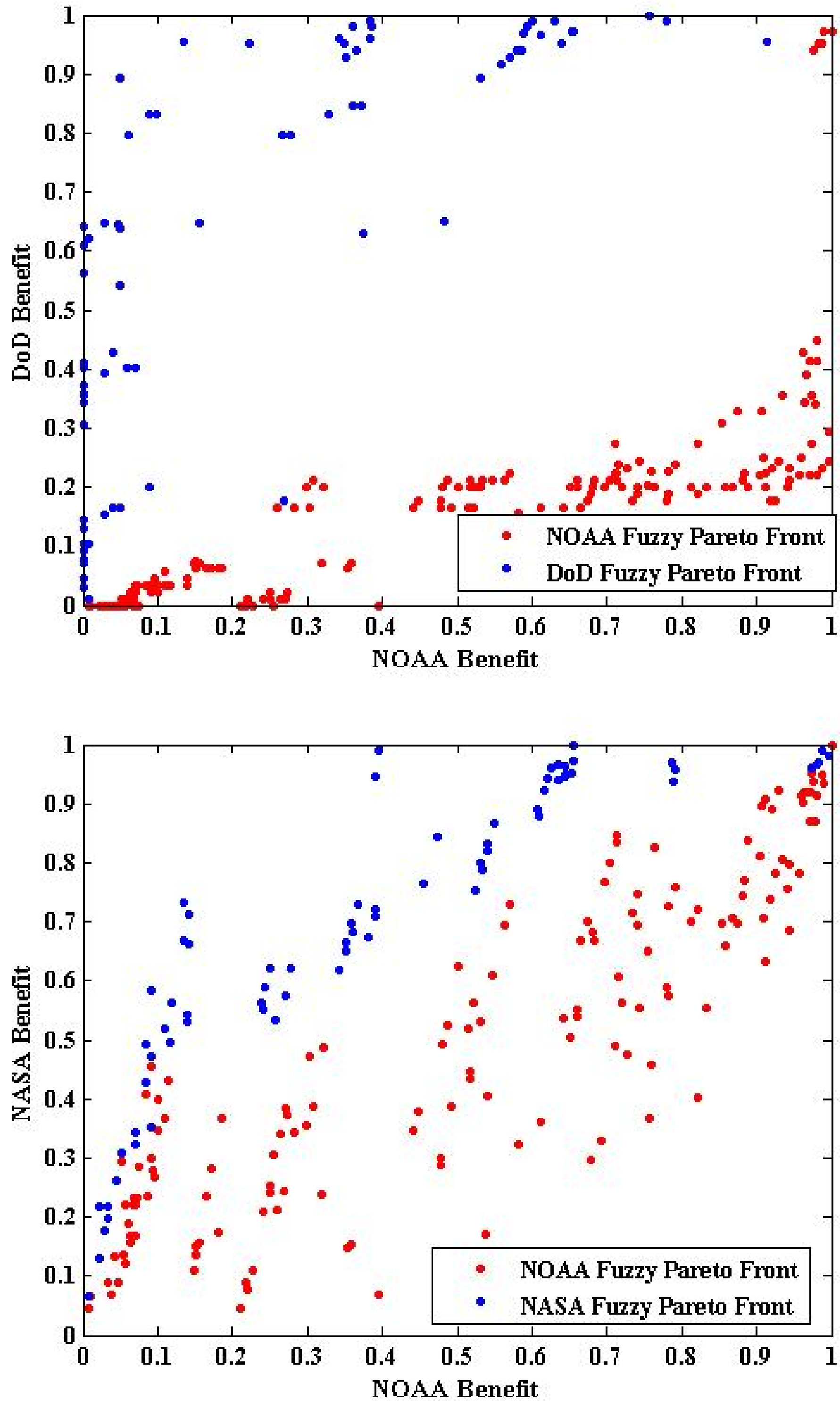


**Figure 68: NOAA, NASA, and DoD Mission Synergies**

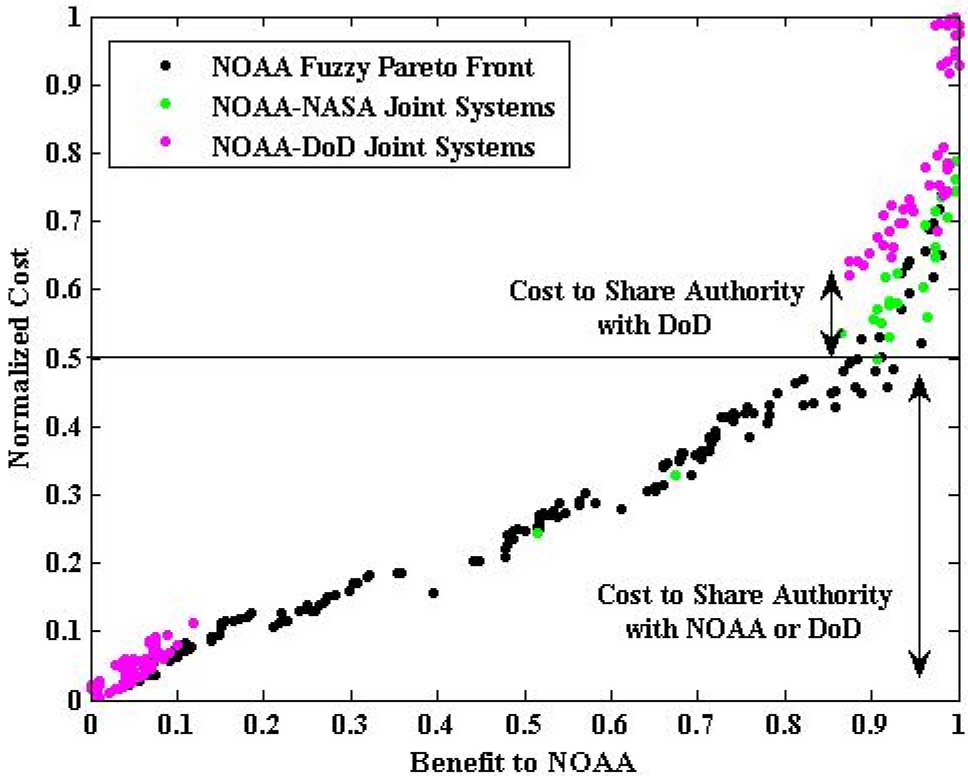


**Figure 69: Cost of Sharing Authority with NASA or the DoD**

The second cost is induced specifically by sharing authority with the DoD, since the joint NOAA-DoD systems were costlier than even the most expensive systems on NOAA's Pareto front. The cost differential was induced by the agencies' non-synergistic missions, which drove the configuration of their potential joint systems to differ from NOAA's high-benefit systems in the following ways:

- Almost all systems with high benefit (i.e. benefit > 0.9) on NOAA's Pareto front contained two orbital planes whereas only half of the high benefit joint NOAA-DoD systems contained two orbital planes and the remainder contained three planes.
- High benefit NOAA systems tended to fly multiple satellites in a train formation in a 13:30 orbit. In contrast, a larger number of the Pareto optimal joint systems flew monolithic (i.e. aggregated) satellites in each orbital plane.
- Joint NOAA-DoD systems with aggregated architectures flew VIIRS, CMIS, CrIS, and ATMS in both orbital planes. Aggregated joint systems varied according to which climate-centric sensors that they assigned to each orbit. Interestingly, these systems were similar to NPOESS prior to the program's cancellation; this suggests that given the agencies' interests and the joint program form that defined their relationship, the NPOESS program's technical architecture was optimal.

Although sharing authority with either NASA or the DoD increased the overall cost of NOAA's system, if the agencies shared budget responsibility (as recommended by the principles), the joint system's cost to

NOAA would be reduced. In addition to aligning budget and mission responsibility, the principles recommend that each agency's expertise be commensurate with its authority. Regardless of whether NOAA partners with NASA or the DoD, it is at risk for violating this principle because it lacks the technical expertise that resides in the other organizations, which have considerable experience developing space systems. To insure that potential partners do not exploit this expertise differential in order to prioritize their unique missions, NOAA could supplement its in-house expertise with greater support from external organizations such as FFRDCs.

Finally, when selecting a joint program form, NOAA should only consider form SIS if it partners with the NASA, since the agencies' missions are synergistic and harder to decouple into components that can be managed separately. Because NOAA and the DoD's missions are non-synergistic, it could consider using form SMN in addition to form SIS. For example, NOAA could assume authority and responsibility for developing the cross-track infrared and microwave sounders while the DoD could take the conical microwave imager-sounder. Because both agencies' missions use the VIS-NIR sensor, they should manage it jointly or consider strategies to modularize the instrument into components that separate the agencies' missions and can be managed independently. Again, using form SMS is not recommended.

#### 9.4.2.3 Step 3: Assess the Cost of Delegating Authority

If NOAA shares authority with either NASA or the DoD, it accepts the cost of developing a system that meets both agencies' requirements and the risk that if the program's costs grow, it will be unable to reduce the joint system's capabilities to cut costs. If these costs and risks are unacceptable to NOAA, it could consider delegating authority to either agency; by doing so, NOAA could select a lower benefit, lower cost system, and maintain the option of changing that system's capabilities later in the program.

As discussed above, when selecting a joint program form that delegates authority, government decision makers need to understand the relationship between agencies' missions. Since NOAA and the DoD have non-synergistic missions, as long as NOAA selects a system that does not maximize both agencies' benefit, the DoD can serve as a pure acquisition agent, because it derives little benefit from NOAA's system. As a result, NOAA should hold full budget responsibility for the system and both forms FIN and CMN can both be used. NOAA will not need to enhance its in-house technical expertise significantly because it is unlikely that its acquisition agent will use an expertise differential to prioritize its own mission, since its mission will not be executed by NOAA's system. Of course, given the DoD's myriad of other missions, it is also unlikely that it will be willing to serve as an acquisition agent. As an alternative, NOAA could consider using an FFRDC to fill that role.

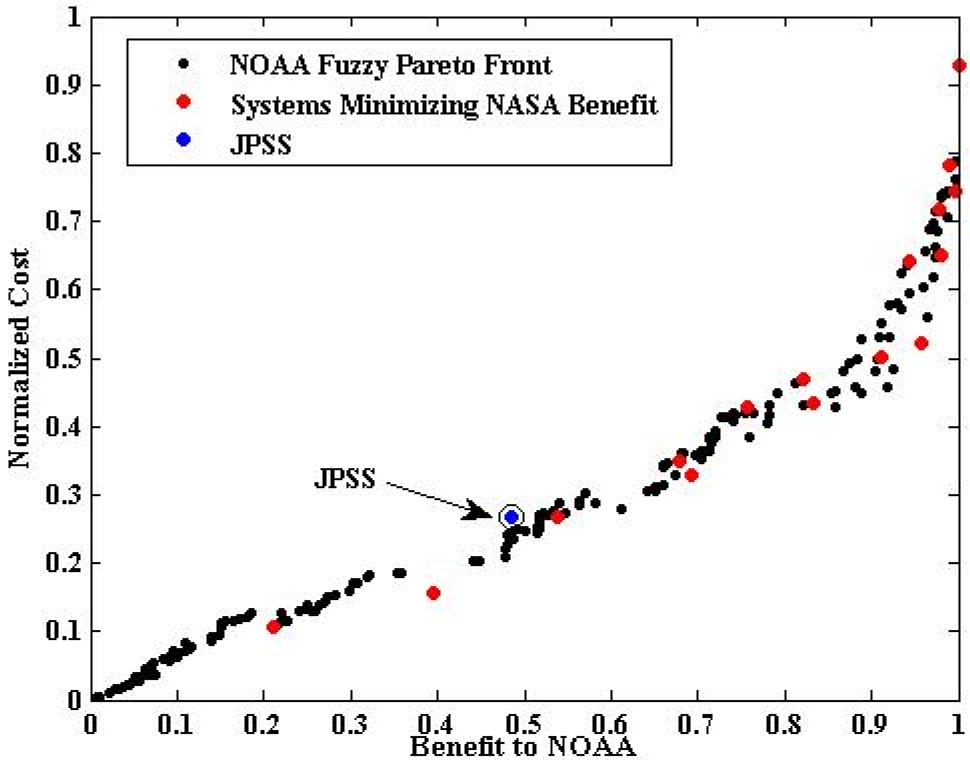


**Figure 70: System Options when Delegating Authority to NASA**

Since NOAA and NASA have synergistic missions, NASA cannot serve as a pure acquisition agent because it derives benefit from NOAA's systems. To guard against NASA taking action to prioritize its mission over NOAA's, NOAA could select a system that minimizes benefit to NASA: although this seems counterintuitive, doing so will help NOAA maintain organizational stability and will reduce NASA's ability to take actions that prioritize its mission over NOAA's.

However, because the agencies have synergistic missions, finding systems that minimize one agency's benefit while maximizing the other's is a challenge; Figure 70 identifies candidate systems on NOAA's fuzzy cost-benefit Pareto front that are also on a secondary Pareto front that minimizes NASA's benefit while maximizing NOAA's. While none of these systems include the current JPSS architectures, alternative systems that provide < 0.9 benefit to NOAA have the following characteristics:

- Each system includes the cross-track microwave sounder and the infrared sounder.
- Most systems also include the VIS/NIR sensor, although several select a sensor that is less capable than NOAA's current sensor (i.e. VIIRS).
- The systems include, at most, only one sensor which has the primary purpose of contributing to NOAA and NASA's climate mission.

The suggestion put forth in Section 9.3—that NOAA anchor a separate climate-centric system around a microwave imager sounder—could also achieve the goal of defining a weather program that simultaneously minimizes benefit to NASA while maximizing benefit to NOAA. In accordance the principles, NASA should assume full authority and responsibility for the climate mission, while NOAA should retain authority and responsibility for weather. The programs' could then be decoupled and managed separately.

Regardless of the system that NOAA selects, in accordance with the principles, NOAA should require NASA to contribute some funding so that the agency's budget and mission responsibilities are aligned. For example, Figure 70 also identifies the current JPSS architecture. JPSS generates a benefit score of 0.49 to NOAA and 0.39 to NASA. To align the agencies' mission and budget responsibilities, NOAA could contribute approximately 55% of the budget, while NASA contributes 44%: currently, NOAA funds 100% of the program. Furthermore, it is critical that NOAA enhance its current technical expertise so that it can effectively oversee NASA and ensure that its missions are appropriately prioritized. With regards to joint program forms, form FIS is recommended, while form PMS and PMN are not. Finally, regardless of whether NOAA decides to partner with NOAA or the DoD, as discussed above, it should budget for the conservative development process that each agency will execute in an attempt to regain some of their autonomy from NOAA.

### 9.4.3 Analysis Conclusions

By applying the principles for architecting joint systems to NOAA's low Earth orbiting weather satellite program, I identified the costs and risks of each potential partnership and recommended appropriate joint program forms. In doing so, I noted several misalignments that exist in NOAA's current JPSS program and made the recommendation that if NOAA continues its partnership with NASA, it should select a system that minimizes benefit to NASA, should require NASA to contribute budget, and should enhance its own technical expertise. Thus, applying the principles allowed me to gain new insight into the structure of a current joint program and most importantly, to identify strategies to reform it. I hope that by following this example, government agencies will be able to more effectively structure other joint programs in the future.

Past studies of joint programs have generated excellent lessons learned and guidelines for future programs (e.g. [12, 17]) and the above process does not replace these resources. Instead, the process should be applied *before* establishing a joint program and used to help decision makers reason through the costs and risks of each potential partnership and joint program form. Once a partner and form have been selected, I encourage the joint program to capitalize on the resources cited above. Finally, even if current joint programs are applying best practices, the process can be used as a tool to identify reforms that can improve the alignment of responsibility, authority, budget, and expertise between partners and thus, can reduce the potential for joint program cost growth in the future.

## 9.5 Conclusions

Until this chapter, my analysis was largely retrospective and focused on identifying the underlying mechanisms for cost growth on past programs. This chapter illustrated how, armed with an understanding of those cost growth mechanisms, government decision makers can make more informed decisions to use aggregated technical or organizational architectures. Specifically, I presented a trade space analysis tool that captured critical cost-benefit trade-offs of aggregated versus disaggregated technical architectures and used that tool to explore a large trade space of architectures that spanned the spectrum from aggregated to disaggregated systems.

Using this tool, I found that generally, aggregated technical architectures perform well with respect to the entire trade space but that when complexity costs are included in a cost estimate, semi-aggregated architectures may be less costly than fully aggregated ones. This finding stresses the importance of identifying technical complexity mechanisms and of accounting for the cost risk that they present to systems. Additionally, I was also able use the Agency Action Model and the principles for architecting joint systems to evaluate potential partnerships between NOAA, NASA, and the DoD, to recommend appropriate technical and organizational architectures for each partnership and to identify potential risks in each.

Thus, ultimately, this chapter illustrated the utility of dissertation's research approach and the applicability of its findings. By performing an in depth study of past programs, inductively generating definitions of complexity, and using a quantitative framework to observe the evolution of complexity over time, I was able to generate new policy recommendations that can be implemented on future programs. In particular, I illustrated how trade-offs between aggregated and disaggregated architectures should be evaluated and identified situations where government decision makers should consider using semi-aggregated, rather than aggregated technical architectures. I also illustrated how, when one applies the process motivated by the Agency Action Model and evaluates potential partnerships for NOAA, one can observe that the principles for architecting joint programs are violated by the current JPSS program. Therefore, I not only generated policy guidance for future joint programs, but I also identified opportunities to reform current ones.

# 10 Conclusions

*This guy's walking down a street, when he falls in a hole. The walls are so steep, he can't get out. A doctor passes by, and the guy shouts up "Hey you! Can you help me out?" The doctor writes him a prescription, throws it down the hole and moves on. Then a priest comes along and the guy shouts up "Father, I'm down in this hole, can you help me out?" The priest writes out a prayer, throws it down in the hole and moves on. Then a friend walks by. "Hey Joe, it's me, can you help me out?" And the friend jumps in the hole! Our guy says "Are you stupid? Now we're both down here!" and the friend says, "Yeah, but I've been down here before, and I know the way out."*

–Leo McGarry, *The West Wing,* Season 2 Episode 10 [187]

Studying cost growth on government programs requires the researcher to be overly critical of past programs' performance. What were the inefficiencies? What were the bad decisions? And with the wonderful gift of hindsight, what should have been done differently? This dissertation contains no shortage of criticism of the NPOESS, JPSS, and DWSS programs and of the agencies tasked with their management. However, the goal of this work was not to find fault with the government's acquisition of these systems but rather, to understand *why* they were more costly than expected and to identify strategies to more effectively manage program costs in the future. Were it not for a page limit to this dissertation, I could have matched every criticism of the NPOESS, JPSS, and DWSS programs with praise, since the components of those systems that are flying today are performing at or above their already stringent specifications.

The technical success of these systems is a testament to the skill of the engineers and scientists who were responsible for their development. Despite all of the unnecessary technical and organizational complexity that was present in these programs, their technical staff persevered and remained committed to delivering quality systems. And it for this reason that my research—and I hope future research—is so important. Government decision makers, agency leaders, and program managers owe it to their technical staff to create programs that make the system development process easier—or at the very least, that do not hinder it by making it unnecessarily complex. This was certainly not the case with the NPOESS, JPSS, or DWSS programs; however, with the insights gained from this dissertation and using its specific recommendations, I hope that environmental monitoring programs can be architected differently—and more cost effectively—in the future.

My dissertation was able to produce a new understanding of cost growth on joint programs and to generate unique policy recommendations because of the research approach that I employed. To use the undeniable wisdom of *The West Wing's* Chief of Staff Leo McGarry as a metaphor, I "jumped into the hole" with the technical staff of the NPOESS, JPSS, and DWSS programs. Using their expertise and incredible knowledge of their systems and organizations, I was able to weave together a set of diverse perspectives from all levels and functional roles within the programs' organizational hierarchy. By integrating these perspectives, first within my framework for studying cost growth on acquisition programs and second, within the Agency Action Model, I began the process of climbing out of the joint program "hole" and hopefully motivated other "friends" of the acquisition system to do the same in future research.

In this final chapter, I summarize my dissertation's key findings and contributions. I continue by describing opportunities for future research and finally, I close the dissertation with some final conclusions and thoughts on the concept of jointness.

# 10.1 Dissertation Summary

This dissertation began by reviewing the history of jointness in operations and acquisition both within the military and across government agencies. I then focused on joint system acquisition and reviewed several studies which concluded that, during the acquisition process, joint programs experience higher rates of cost growth than non-joint programs. These studies motivated my research question, which asked: *How does jointness induce cost growth?* To address this research question, I focused on joint space programs and specifically, on environmental monitoring systems in low Earth orbit. I also defined joint programs in terms of their aggregated technical and organizational architectures and used the hypothesis that aggregated architectures induce complexity and cost growth to guide my subsequent analysis.

In Chapter 2, I summarized past root cause analyses of cost growth on government space programs. I then argued that to better understand the underlying mechanisms for cost growth on government programs, researchers should explore how government actions affect a program's technical and organizational architectures and the relationship between them. To facilitate this type of study, I reviewed literature from public administration theory, organizational theory, and system architecture theory. Using this literature, I defined the key characteristics of the government bureaucracies that are tasked with managing system acquisition as authority, responsibility, expertise, and budget. I also used the literature to suggest that misaligned interdependencies between a program's components can induce organizational complexity, which hinders the program's ability to make effective and efficient decisions. Finally, I stated that technical complexity has three components—design, process, and architectural—and that these complexity mechanisms induce cost growth by making the system cost more than originally estimated.

In Chapter 3, I outlined a new approach for studying complex acquisition programs. To implement the approach, I advised researchers to collect a broad but detailed qualitative data set by interviewing program staff from all levels and functional roles within a program's organizational hierarchy. Using this data, researchers inductively define complexity in the context of the program and identify specific complexity mechanisms that affected program costs at any point in time. Next, I recommended that researchers organize their data using a quantitative framework that represents program architectures in DSMs, quantifies each architecture's complexity, and observes the evolution of complexity over time. I also defined two metrics for technical and organizational complexity that were directly motivated by the literature discussed in Chapter 2.

In Chapters 4-7, I used my proposed approach to study the cost of jointness on the NPOESS, JPSS, and DWSS programs. Chapter 4 presented a descriptive history of the programs and identified the key characteristics of their technical and organizational architectures that were captured in the DSMs and the metrics that were used in my subsequent analysis. Chapters 5-7 presented analytic histories of the programs by using the quantitative framework to identify agency actions and program decisions that induced organizational and technical complexity. Each chapter also reviewed the qualitative evidence that was used to construct the DSMs and to generate my final conclusions.

First, Chapter 5 identified the decisions that induced technical complexity on the NPOESS program and illustrated that although the program's costs did not increase substantially until after its prime contractor was selected, complexity was injected into its technical architecture much earlier. Chapter 5 also presented evidence to suggest that early cost estimates were able to remain low because the program both underestimated the cost of complexity and under managed complexity early in the system development process. Next, in Chapter 6, I illustrated how—by hindering the decision making process—organizational complexity enabled the program to underestimate and under manage its technical architecture's complexity. I also illustrated how organizational complexity induced additional cost growth by making the program's decision making processes less efficient. Finally, I identified the agency actions that injected complexity into the program's organizational architecture and in doing so, increased the program's technical and non-technical costs.

Then, in Chapter 7, I discussed the complexity that was observed on the JPSS and DWSS programs and compared it to NPOESS. I found that technical complexity mechanisms were present on all three programs and that, in particular, NPOESS and JPSS contained design, process, and architectural complexity mechanisms while DWSS contained only design and architectural. I concluded that three types of aggregation—requirements, mission, and system—affected program cost and I mapped each type of aggregation to the type of complexity (design, process, and architectural) that it induced. Next, I found that organizational complexity mechanisms affected both NPOESS and JPSS and that instead of *aggregation* inducing this complexity, disaggregation—or the misalignment of key interdependencies between the organizations' components—was responsible for it. In particular, I found that misalignments between authority, responsibility, expertise, and budget hindered the quality and efficiency of the organizations' decisions.

These findings motivated me to propose the Agency Action Model in Chapter 8, which explained joint program cost growth in terms of agency actions. Specifically, the Agency Action Model states that collaborating agencies' institutional interests in retaining or regaining their autonomy drives complexity into joint program architectures and induces cost growth. I grounded my model in my case study data by connecting the basic actions of retaining and regaining autonomy to the agency actions and program decisions that were observed to induce complexity and cost growth on the NPOESS, JPSS, and DWSS programs. I then used the model to propose principles for architecting joint programs that aim to create checks and balances that prevent agency actions from inducing cost growth.

Finally, in Chapter 9, I presented a trade space analysis tool that explored numerous candidate environmental monitoring systems for NOAA, NASA, and the DoD and evaluated those systems using metrics that were specifically designed to capture the costs and benefits of aggregation versus disaggregation. Using this tool, I identified options to reduce cost using semi-aggregated architectures but also concluded that, despite their complexity, aggregated technical architectures still performed well with respect to an entire trade space of system architecture options. Finally, using the trade space analysis tool, the Agency Action Model, and the principles for architecting joint programs, I defined a process that government decision makers can use to assess potential partnerships and to identify their inherent costs and risks. I applied this process to evaluate potential partnerships for NOAA and in doing so, generated several policy recommendations for NOAA's current JPSS program and that program's successor.

## 10.2 Key Contributions

This dissertation made six major contributions to the state of the art in studying complex acquisition programs and in understanding the cost of jointness. Specifically, this dissertation:

1) **Demonstrated** a new mixed methods, DSM-based approach for studying cost growth on long term, complex acquisition programs.
2) **Developed** a trade space analysis tool capable of assessing the costs and benefits of technical aggregation and disaggregation.
3) **Generated** practical definitions of technical and organizational complexity in government acquisition programs and defined metrics to assess both.
4) **Proposed** a generalizable Agency Action Model and principles for architecting joint programs.
5) **Conducted** the first comprehensive, root-cause analysis of the NPOESS, JPSS, and DWSS programs.
6) **Used** the trade space analysis tool, the Agency Action Model, and the principles for architecting joint programs to create policy recommendations that are applicable to current and future environmental monitoring programs.

The first two contributions are methodological and they expand the analytical tools that are available to future researchers. The first contribution refers to the alternative approach for studying complex acquisition programs that was presented in Chapter 3. Specifically, my analysis of NPOESS was the first time that a complex acquisition program has been studied both in depth and longitudinally using a mix of qualitative and quantitative methods. Given the length and complexity of our government's major acquisition programs, my proposed approach provides a much needed strategy for studying programs both in detail at any point in time and over the course of a system's acquisition lifecycle. Although I demonstrated the approach using a particular type of system, I defined it generally so that future researchers may use it to study different types of systems that are developed by all types of government agencies.

Of course, the second contribution refers to the trade space analysis tool that was presented in Chapter 9. Although similar tools exist and were leveraged for this research, the analysis presented in this dissertation marks the first time that a trade space analysis tool was extended to explicitly consider not only the costs of an initial constellation of satellites, but also the costs of replenishing those satellites to conduct a multi-year mission. By making this extension, my metrics were better able to capture the cost of aggregation versus disaggregation, since my case study data suggested that non-recurring cost growth can hinder a program's ability to afford the replenishment systems necessary to conduct a multi-year mission.

The third and fourth contributions are theoretical. The third contribution refers to the practical and empirically grounded definitions of technical and organizational complexity that were proposed by this dissertation. Although both definitions resonated with the theoretical literature that was discussed in Chapter 2, each definition was grounded in my case study data. Most importantly, using metrics to quantity complexity, I demonstrated that on government acquisition programs, complexity is a dynamic, rather than a static, property. This finding suggests a need to shift the academic communities' perspective for studying complexity from one that is focused on static analyses that identify statistical correlations between complexity and cost to one that appreciates and incorporates the dynamic nature of complexity.

The fourth contribution, the Agency Action Model and the principles for architecting joint programs, is arguably this dissertation's most important component. Until this work, both the academic and the acquisition community has lacked an explanation for *why* joint program costs grow more significantly than non-joint program costs. This dissertation proposed an explanation and using the implications and predictions of the Agency Action Model, generated guidelines for future joint programs unlike any other prior analyses on the topic.

Finally, the fifth and sixth contributions focus specifically on the domain of environmental monitoring satellites in low Earth orbit. Although the NPOESS, DWSS, and JPSS programs have each been reviewed by the GAO and by independent review teams (IRTs), both groups' reviews were contemporaneous to the programs' execution and were responsive to requests for program assessment. As a result, the GAO and IRT reviews provided only a snapshot of the programs' financial, technical, and organizational status, predicted future performance based on current trends, and made recommendations for corrective action. Aside from predicting future performance and assessing risk, the reports did not address the evolutionary and dynamic nature of the programs' cost growth or investigate *how* its costs increased over time. Instead, they identified only the extant cost drivers that program managers, operating within the programs' *existing organizational and technical architectures,* could correct. By observing how the programs' architectures evolved and complexity increased over time, this dissertation research addressed the *how* question that was absent in previous lines of inquiry.

The Aerospace Corporation was also tasked to review the NPOESS program and because their review took place after the program's cancellation, it provided a more holistic analysis. Using this perspective, the Aerospace Corporation suggested a dynamic theory to explain the dissolution of the NPOESS interagency partnership. In their proposed "container model," the Corporation identified eight factors that are critical to motivating and sustaining a collaborative joint program [D195]. The authors then suggested that over time, forces both internal and external to the NPOESS program reduced the cohesion of these previously fortifying factors and induced the program's ultimate divergence [D195].

Given the overlap between my interview population and those surveyed by the Aerospace Corporation, it is unsurprising that many of my findings support this "container model." Despite this similarity, three critical factors differentiate this work from that conducted by the Aerospace Corporation. First, my process-centric, semi-structured interview approach uniquely allowed me to explore program events in significant technical and organizational detail, oftentimes without reference to the program's joint nature or to its ultimate cancellation. Although the Corporation's report does not detail their interview methodology, my approach is more commonly utilized in academic, rather than in corporate settings. The Corporation also failed to interview contractors and other more technical members of the program's staff that were included in my interview sample. Second, I considered cost growth from an evolutionary perspective and explored the intermediate mechanisms which drove the program from convergence to divergence; the Corporation's "container model" neglects these intermediary dynamics. Finally, unlike the Aerospace Corporation, which actively participated in the NPOESS program and remains a stakeholder in its successor programs, this work was conducted independently and without government or industry affiliation. As a result, my interview discussions, analysis, and conclusions were not constrained by organizational, financial, or political relationships to any of the government agencies or contractors involved in the program. Given these critical distinctions from both the Aerospace Corporation, and GAO and IRT reports, my research was able to present a unique and heretofore unarticulated perspective on the evolution of the NPOESS program the role that jointness played in its ultimate cancellation.

Finally, unlike these past studies, my analysis of the NPOESS, JPSS, and DWSS programs was able to motivate a generalizable understanding of the cost of jointness that could be directly applied to reform current joint programs or to improve joint programs in the future. In my sixth contribution, I applied this understanding to define a process to evaluate potential partnerships between NOAA, NASA, and the DoD by assessing their cost risks and by selecting appropriate joint program forms. By applying this process, I also generated policy recommendations that can be implemented to improve NOAA's current JPSS program.

## 10.3 Future Work

The dissertation's contributions also motivated three related streams of potential future research:

1) Applying the alternative approach for studying complex acquisition programs to study other acquisition programs.
2) Validating and expanding the Agency Action Model and the principles for architecting joint programs by studying other joint programs.
3) Exploring the expansive trade space of architectures for environmental monitoring in low Earth orbit using systematic search methods.

First, the research approach suggested in Chapter 3 and demonstrated by this dissertation can be applied to other government programs, particularly those that experienced significant cost growth. Within the government space sector, many people suggested that SBIRS and AEHF would have made good case studies for my dissertation; although I did not include them here, they make excellent candidates for future work. The F-35 Joint Strike Fighter is also a great candidate for future study. Although the F-35 has been studied by multiple researchers, none of the prior studies have used a research approach like that proposed in this dissertation. Finally, because I defined my research approach generally, I hope that it can also be applied to study systems outside of the aerospace domain.

Second, the Agency Action Model and the principles for architecting joint programs can be validated and expanded through future study of other joint programs. Within the government space sector, joint programs within the NRO and collaborations between the NRO and Air Force would make excellent case studies, as would NASA's collaboration with USGS for Landsat, and the recent DoD-DoT collaboration for GPS. Outside of the government space sector, the F-35 is an obvious candidate for future study, as is the Joint Tactical Radio System, and the U-2 reconnaissance aircraft. Outside of domestic joint programs, the Agency Action Model could be tested and expanded by studying international joint programs like the

International Space Station. Finally, outside of system acquisition altogether, the Agency Action Model could also be used to guide research on agency interactions in joint governance bodies like the National Intelligence Council.

Third, additional research can continue exploring the trade space of environmental monitoring architectures in low Earth orbit. Specifically, in developing the trade space exploration tool, I intentionally coupled two separate system architecting problems—selection of instruments and packaging instruments into spacecraft—that were previously considered separately [41]. As a result, the trade space generated by my tool is very broad and could benefit from methods that are designed to search the entire trade space systematically. Such methods would enable the researcher to gain a global understanding of trends across the trade space and would yield more generalizable results than those discussed in Chapter 9, which focused on visibly observable trends in the fuzzy Pareto front.

## 10.4 Final Conclusions

Given the opportunities for future work described above—which include the validation of my central contribution, the Agency Action Model—how truly generalizable are this dissertation's conclusions? First, by focusing on joint programs in the government space sector and specifically on environmental monitoring programs, I intentionally traded internal for external validity. Specifically, I determined that for an initial study of this type, analyzing costs across systems and mission types would require too great of a conceptual leap that would hinder the initial theory building process. However, with Agency Action Model in place, future research can anchor its analysis in the model's theoretical framework and use it to compare a more a diverse set of case studies.

So given my limited focus on environmental monitoring satellite programs, what is the chance that future research will validate, rather than reject, the Agency Action Model's predictions? First, it bears noting that, in many ways, the government space sector is unique: while there is a great demand for space-based data, only three government agencies are capable of independently developing space systems. Given this large demand for data but the limited number of agencies capable of supplying it, interagency collaboration is a necessity in the government space sector and the competition between data suppliers is probably more severe. In this way, it is possible that space programs are affected by jointness differently than programs outside of the space acquisition community.

However, it is the necessity of interagency collaboration and the intensity of the interagency turf wars that make the government space sector an ideal setting to study the cost of jointness. Unless every data user develops the capability to independently develop space systems, it is likely that the dynamics described by the Agency Action Model will continue to affect space program costs in the future. Furthermore, because the impacts of jointness are exacerbated in the government space sector, it was easier to observe them and to generate the Agency Action Model. Therefore, although the cost of agency actions outside of the government space sector may be less severe that within it, similar dynamics are likely to exist. More importantly, the Agency Action Model resonates with each of the literature streams that I described in Chapter 2; thus, it seems likely that model's applicability extends beyond the case studies that were used to generate it.

Regardless of the model's generalizability, I hope that this dissertation demonstrated the utility of studying complex acquisition programs in an academic environment. Academic researchers bring fresh eyes to the problems that plague our acquisition system and unique theoretical and methodological perspectives from which to analyze them. While no single piece of academic research will have power or impact to reform the acquisition system on its own, by supporting this type of research, government agencies and universities can create a cadre of future leaders who are armed with ability to think critically about complex socio-technical problems and who, collectively, have the greatest potential to solve them. I sincerely hope that this type of research continues in the future and that for me, working to solve the problems of system acquisition is *what's next*.

# 11 Appendix

This Appendix contains additional information on the data and analysis that was presented in the previous chapters. This includes a description of alternative sources of cost growth, additional information on the process for calculating the complexity metrics, a description of my interview process and finally, tables that list the interviewees and documents that were consulted for the case studies.

## 11.1 Other Sources of Cost Growth

When discussing cost growth in the previous chapters, I focused on costs that were induced by complexity mechanisms in the programs' organizational and technical architectures. Despite this focus, I also uncovered other sources of cost growth. These sources of included:

- A weak industrial base,
- Poor management practices by the prime contractor and program office,
- Schedule pressure,
- And transition costs.

Of the four additional sources of cost growth, a weak industrial base appeared to have the most significant cost impact. Specifically, during NPOESS, several contractors merged or were acquired. Oftentimes, this left suppliers struggling to retain corporate knowledge that was gained during the development of NPOESS's heritage systems. As a result, interviewees reported that suppliers had to relearn how to develop and test instruments [I4, I14, I23]; one interviewee described the resulting situation as: "So not only have you got a new part but you have to retrain a whole new industry, a whole new company to do space business and that's not in anybody's plans….dealing with supplier obsolesce….So all of that stuff came together to create huge technical problems with these designs" [I23]. Obviously, the unanticipated learning curve associated with "supplier obsolescence" affected costs when suppliers made amateur mistakes that caused schedule delays during the design and test of the program's instruments.

VIIRS provided a vivid example of the impacts of "supplier obsolescence." The VIIRS design was originally based on MODIS, a NASA sensor that was developed by Santa Barbara Research Center. Importantly, Santa Barbara developed MODIS in collaboration with engineers from NASA GSFC who had worked hand in hand and in plant with their industrial partners to design, develop, and test the first MODIS unit [I4, I18, I46]. Despite Santa Barbara's heritage of partnering with the government, the elevated level of government involvement on MODIS was incompatible with NPOESS's acquisition strategy. As a result, the NASA engineers who had contributed to MODIS's development were under utilized during the early years of the NPOESS program [I07, I10, I28, D195].

Further exacerbating Santa Barbara's loss of key NASA contributors was the corporate restructuring that occurred during NPOESS. In 1998, Hughes Aircraft, Santa Barbara's parent company, sold the center to Raytheon. After the acquisition, interviewees reported that Raytheon struggled to retain key personnel who had experience with MODIS and SeaWiFS (another instrument with heritage ties to VIIRS) [I4, I23]. Santa Barbara also struggled to win new business during this period; as a result, the overhead rates that were charged to VIIRS increased; as described by one interviewee: "So think of it in simple terms, the gate guard that is sitting there welcoming you at the door….if there's eight programs in there, then you are paying 1/8th of that guy's salary but when there's not, then you are paying the whole load of that guy's salary. So what happened was…the CERs [i.e. cost estimating relationships] which people assumed would work, didn't work, because that one sensor is paying for the entire facility, not 1/8th of it. So the environment changed….that's why the cost estimating relationships that had been previously used were no longer valid, because the assumptions weren't valid any longer [I13]." To combat this situation, while VIIRS hardware was in test, Raytheon moved the VIIRS development team to its larger facilities in El Segundo, California. While the move reduced the overhead rates charged to the NPOESS program and gave the VIIRS development team greater access to Raytheon and Northrop managers, Raytheon struggled to maintain core team members who were uninteresting in relocating from Santa Barbara to El Segundo [I39].

After losing members from the MODIS team, being acquired by Raytheon, and moving to El Segundo, VIIRS experienced what one interviewee described as a "tortured" development process [I4]. Not only did Santa Barbara have to redesign portions of VIIRS after CDR, but it also broke mechanisms and a cryoradiator door during vibration testing [I4, D195]. Additionally, they used the wrong paint on the instrument's rotating telescope assembly and accidentally subjected it to more EMI radiation than was specified during test [I9, I17, I21]. The Aerospace Corporation's report [D195] provides a list of all of the development issues that were encountered on VIIRS, which the same interviewee attributed to "a lot of simple, dumb, learning…. relearn[ing] how to build a complicated instrument [I4]."

A second source of cost growth related to prime contractor and program office management practices. In particular, there are reports that the prime contractor's award fee score was inflated given the contractor's poor performance [I5, I35, D120] and that the program office maintained inappropriately low budget reserves [D148, D147, D156, D195]. While both actions could have affected cost, because I was unable to obtain program or contractor budget data to verify these claims, I acknowledge them here but suggest that they had little effect on the complexity-induced cost growth that was the subject of previous chapters.

A third source of cost growth derived from NPOESS's aggressive schedule. Specifically, throughout its lifecycle, the NPOESS organization was under significant schedule pressure; for example, the Aerospace Corporation reported that the program originally planned to develop VIIRS in half the time that it had taken NASA to develop MODIS [D195]. Schedule pressure affected the quality of the organization's decisions in several ways. First, it forced the program to accept unnecessary risks in its development processes or to complete processes hastily. Interviewees cited several examples where contractors that were under schedule pressure took shortcuts that ultimately led to design, analysis, or test failures that required costly rework [I9, I4, I21]. Furthermore, the program's schedule pressure was so severe that NPP and NPOESS instruments were developed concurrently [D241]; this concurrent development placed NPOESS instruments at risk for rework if problems were encountered during NPP. While schedule pressure certainly affected the program's decisions, since it was not directly a result of the organization's architecture, I note its impact here but suggest that the organizational complexity that was discussed in Chapter 6 had a more significant impact on the program's cost.

Finally, the fourth source of cost growth was induced by cancelling NPOESS and transitioning its contracts and staff to work on the JPSS and DWSS programs. The NPOESS cancellation nullified the MOA that governed agency interactions, yet still required the agencies to collaborate on their shared ground system and JPSS; as a result, new MOAs had to be negotiated and ratified. Additionally, contracts had to be cancelled, updated, and transitioned to new ownership and significant intellectual property questions plagued this multi-year process [I8, I64, I65]. Finally, a program office had to disbanded and two new offices had to established and staffed. Interviewees noted that these transition activities impacted the cost and schedules of both JPSS and DWSS [I58, I59, I61] and therefore, represent an important source of cost growth on both programs.

# 11.2 Additional Description of Complexity Metrics

This section presents additional detail on the process that was used to calculate the technical and organizational complexity metrics in the case studies. To calculate both metrics, I used the general process described in Chapter 3, but used the system and organization specific inputs that are described below.

## 11.2.1 Technical Complexity Metric

As described in Chapter 5, the technical complexity metric specifically focused on space segment costs. To calculate the metric for each epoch, I used the following basic process:

- Adjusted instrument parameters for design complexity,
- Used instrument parameters to do a preliminary spacecraft design,
- Calculated non-recurring costs,
- Added complexity penalties to spacecraft and instrument non-recurring costs,
- Calculated recurring costs,
- And calculated launch costs.

First, instrument parameters were adjusted for design complexity. Design complexity was scored on a scale of zero to five according to the criteria shown in Table 14 and described in [174, 188].

**Table 14: Design Complexity Penalties (derived from [D61, 174]**

| Design Complexity Score | Design Maturity (from ANSI/AIAA, 1999) | Relationship to Heritage | Percent Mass Growth Allowance (from ANSI/AIAA 1999) | Percent Power Growth Allowance (from ANSI/AIAA 1999, case study data) |
|---|---|---|---|---|
| 0 | Actual Mass (measured flight hardware) | N/A | 0 | 0 |
| 1 | Existing Hardware (actual mass from another program) | Off-the-shelf heritage instrument hosted in identical spacecraft environment | 3 | 3 |
| 2 | Released Drawings (calculated value) | Heritage instrument hosted in a new spacecraft environment | 5 | 5 |
| 3 | Pre-Release Drawings (or minor modification of existing hardware) | Heritage instrument corrected for parts obsolensce | 25 | 10 |
| 4 | Layout (or major modifications of existing hardware) | New functions added to heritage or performance increase | 30 | 20 |
| 5 | Estimated (preliminary sketches) | New functions added & performance increase from heritage and/or new conflicting requirements added | 50 | 25 |

Table 15, Table 16, Table 17, and Table 18 show the instrument parameters that were used for each epoch in the case studies; Table 19 shows the instrument parameters that were used for the trade space analysis that was presented in Chapter 9. As was discussed in Chapter 5, instrument properties like mass, power, and capabilities varied throughout the NPOESS program. For this reason, parameter values changed between epochs and typically, values for mass, power, and design maturity increased over time.

**Table 15: Pre-Epoch A Inputs for the Technical Complexity Metric**

| Components | Early Morning Orbit | Mid-Morning Orbit | Afternoon Orbit | NPP | Mass [kg] | Power [W] | Data-rate [kbps] | Design Penalty | Process Penalty | Sources |
|---|---|---|---|---|---|---|---|---|---|---|
| **Pre-Epoch A DoD** | | | | | | | | | | |
| VIIRS | X | X | | | 163 | 155 | 2860 | 4 | 0 | [D44] |
| CMIS | X | X | | | 127 | 187 | 189 | 4 | 0 | [D44] |
| CrIS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ATMS | | | | | 0 | 0 | 0 | 0 | 0 | |
| SESS | X | X | | | 66 | 82 | 14 | 3 | 0 | [D44] |
| TSIS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ERBS | | | | | 0 | 0 | 0 | 0 | 0 | |
| APS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ALT | | | | | 0 | 0 | 0 | 0 | 0 | |
| OMPS | | | | | 0 | 0 | 0 | 0 | 0 | |
| DCS | | | | | 0 | 0 | 0 | 0 | 0 | |
| SARSAT | | | | | 0 | 0 | 0 | 0 | 0 | |
| **Pre-Epoch A NOAA** | | | | | | | | | | |
| VIIRS | | X | X | | 72 | 60 | 1044 | 4 | 1 | [D44] |
| CMIS | | | | | 0 | 0 | 0 | 0 | 0 | |
| CrIS | | X | X | | 66 | 72 | 3.5 | 0 | 0 | [D44] |
| ATMS | | X | X | | 207 | 292 | 6.5 | 3 | 0 | [D44] |
| SESS | | X | X | | 31 | 33 | 0.6 | 3 | 1 | [D44] |
| TSIS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ERBS | | | | | 0 | 0 | 0 | 0 | 0 | |
| APS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ALT | | | | | 0 | 0 | 0 | 0 | 0 | |
| OMPS | | X | X | | 78 | 49 | 0.9 | 3 | 1 | [D44] |
| DCS | | X | X | | 66 | 70 | 2.6 | 0 | 0 | [D44] |
| SARSAT | | X | X | | 76 | 112 | 0 | 0 | 0 | [D44] |

**Table 16: Epochs A-C Inputs to the Technical Complexity Metric**

| Components | Early Morning Orbit | Mid-Morning Orbit | Afternoon Orbit | NPP | Mass [kg] | Power [W] | Data-rate [kbps] | Design Penalty | Process Penalty | Sources |
|---|---|---|---|---|---|---|---|---|---|---|
| Epoch A | | | | | | | | | | |
| VIIRS | X | X | X | | 163 | 155 | 2860 | 5 | 0 | [D44] |
| CMIS | X | X | X | | 127 | 187 | 189 | 4 | 0 | [D44] |
| CrIS | | | X | | 66 | 72 | 3.5 | 3 | 0 | [D44] |
| ATMS | | | | | 0 | 0 | 0 | 0 | 0 | [D44] |
| SESS | X | X | X | | 66 | 82 | 14.5 | 3 | 0 | [D44] |
| TSIS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ERBS | | | | | 0 | 0 | 0 | 0 | 0 | |
| APS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ALT | | | | | 0 | 0 | 0 | 0 | 0 | |
| OMPS | | | X | | 78 | 49 | 0.9 | 3 | 0 | [D44] |
| DCS | X | X | X | | 68 | 70 | 2.6 | 0 | 0 | [D44] |
| SARSAT | X | X | X | | 46 | 67 | 0 | 0 | 0 | [D44] |
| Epoch B | | | | | | | | | | |
| VIIRS | X | X | X | | 105.5 | 173.6 | 7086 | 5 | 0 | [D61] |
| CMIS | X | X | X | | 154.6 | 189.2 | 226.8 | 4 | 0 | Mass & Power [D61], Data-rate scaled up 20% to correspond with power, based off of MISS from [D44] |
| CrIS | | | X | | 54 | 72.8 | 1229 | 5 | 0 | [D61] |
| ATMS | | X | X | | 53.6 | 70 | 2.5 | 3 | 0 | Mass & Power [D61], Data-rate estimated from 80% of AMSU-A since this was to have a slight reduction in number of channels [D167] |
| SESS | X | X | X | | 85.94 | 67.27 | 11.3 | 3 | 0 | Mass & Power [D61], Data-rate scaled down to account for power differences between SES on [D44] |
| TSIS | X | | | | 39.2 | 35.45 | 0.6 | 2 | 0 | Mass & Power [D61], Data-rate from heritage ACRIM [D167] |
| ERBS | | | X | | 45.71 | 47.62 | 10 | 3 | 0 | Mass & Power [D61], Data-rate from heritage CERES [D167] |
| APS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ALT | X | | | | 62 | 70.4 | 9.8 | 5 | 0 | Mass & Power [D61], Data-rate from heritage NASA altimeter [D44] |
| OMPS | | | X | | 30 | 30.4 | 0.9 | 5 | 0 | Mass & Power [D61], Data-rate from heritage SBUV and TOMS [D44] |
| DCS | X | X | X | | 66.02 | 67.96 | 2.6 | 0 | 0 | Mass & Power [D61], Data rate [D44] |
| SARSAT | X | | X | | 44.66 | 65.04 | 0 | 0 | 0 | Mass & Power [D61], Data-rate [D44] |
| Epoch C | | | | | | | | | | |
| VIIRS | X | X | X | X | 199 | 134 | 7086 | 4 | 3 | Mass & Power[D86], Data-rate from [D61] |
| CMIS | X | X | X | | 257 | 340 | 280 | 4 | 1 | [D86] |
| CrIS | | | X | X | 87 | 91 | 1536 | 4 | 3 | [D86] |
| ATMS | | | X | X | 66 | 85 | 50 | 4 | 1 | [D86] |
| SESS | X | X | X | | 85.94 | 67.27 | 11.3 | 3 | 0 | [D167] |
| TSIS | X | | | | 29 | 58 | 5.4 | 2 | 1 | Mass & Power [D86], Data-rate from [D167] |
| ERBS | | | X | | 45.71 | 47.62 | 47.5 | 0 | 0 | [D86] |
| APS | | X | | | 69 | 55 | 160 | 0 | 1 | [D167] |
| ALT | X | | | | 70 | 78 | 22.5 | 5 | 1 | [D167] |
| OMPS | | | X | X | 63 | 60 | 180 | 4 | 3 | [D86] |
| DCS | X | | X | | 68 | 70 | 2.6 | 0 | 0 | Mass & Power [D86], Data rate [D61] |
| SARSAT | X | X | X | | 46 | 67 | 0 | 0 | 0 | [D44] |

**Table 17: Epochs D-F Inputs into the Technical Complexity Metric**

| Components | Early Morning Orbit | Mid-Morning Orbit | Afternoon Orbit | NPP | Mass [kg] | Power [W] | Data-rate [kbps] | Design Penalty | Process Penalty | Sources |
|---|---|---|---|---|---|---|---|---|---|---|
| Epoch D | | | | | | | | | | |
| VIIRS | X | X | X | X | 266 | 198 | 7086 | 2 | 3 | Mass & Power[D157], Data-rate from [D61] |
| CMIS | X | X | X | | 475 | 354 | 280 | 2 | 1 | Mass & Power [D157], Data-rate [D86] |
| CrIS | X | | X | X | 142 | 131 | 1536 | 2 | 3 | Mass & Power[D157], Data-rate [D86] |
| ATMS | X | | X | X | 73 | 94 | 50 | 2 | 1 | Mass & Power [D157], Data-rate [D86] |
| SESS | X | X | X | | 85.94 | 67.27 | 11.3 | 3 | 0 | Mass & Power [D157] |
| TSIS | X | | | | 29 | 58 | 5.4 | 2 | 1 | Mass & Power [D86], Data-rate from [D167] |
| ERBS | | | X | | 45.71 | 47.62 | 10 | 3 | 1 | Mass & Power [D157] |
| APS | | X | | | 69 | 55 | 160 | 0 | 1 | [D167] |
| ALT | X | | | | 70 | 78 | 22.5 | 5 | 1 | [D167] |
| OMPS | | | X | X | 67 | 101 | 180 | 2 | 3 | [D86] |
| DCS | | | X | | 68 | 70 | 2.6 | 0 | 0 | Mass & Power [D157], Data rate [D61] |
| SARSAT | X | X | X | | 46 | 67 | 0 | 0 | 0 | Mass & Power [D157], Data-rate [D61] |
| Epoch E | | | | | | | | | | |
| VIIRS | X | | X | X | 266 | 198 | 7086 | 2 | 3 | Mass & Power[D157], Data-rate from [D61] |
| CMIS | X | | X | | 341 | 350 | 35 | 3 | 1 | Mass & Power [D157], Data-rate [D86] |
| CrIS | | | X | X | 142 | 131 | 1536 | 2 | 3 | Mass & Power[D157], Data-rate [D86] |
| ATMS | | | X | X | 73 | 94 | 50 | 2 | 1 | Mass & Power [D157], Data-rate [D86] |
| SESS | X | | X | | 23.9 | 18.9 | 1.1 | 3 | 0 | Mass & Power [D157] |
| TSIS | | | | | 0 | 0 | 0 | 0 | 0 | Mass & Power [D86], Data-rate from [D167] |
| ERBS | | | | | 0 | 0 | 0 | 0 | 0 | Mass & Power [D157] |
| APS | | | | | 0 | 0 | 0 | 0 | 0 | [D167] |
| ALT | | | | | 0 | 0 | 0 | 0 | 0 | [D167] |
| OMPS | | | X | X | 30.5 | 67 | 2.6 | 2 | 2 | [D86] |
| DCS | X | | X | | 30.5 | 67 | 0 | 0 | 0 | Mass & Power [D157], Data rate [D61] |
| SARSAT | X | | X | | 46 | 67 | 0 | 0 | 0 | Mass & Power [D157], Data-rate [D61] |
| Epoch F | | | | | | | | | | |
| VIIRS | X | | X | X | 275 | 240 | 6042 | 3 | 2 | [D167] |
| CMIS | X | | X | | 341 | 350 | 35 | 1 | 1 | [D167] |
| CrIS | | | X | X | 165 | 123 | 1536 | 3 | 2 | [D167] |
| ATMS | | | X | X | 75.4 | 93 | 20 | 1 | 1 | [D167] |
| SESS | X | | X | | 23.9 | 18.9 | 1.1 | 0 | 0 | [D61] for mass and power, see notes on data rate |
| TSIS | X | | | | 30 | 40 | 5.4 | 1 | 1 | [D61] |
| ERBS | | | X | X | 57 | 50 | 10 | 1 | 1 | [D61] |
| APS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ALT | | | | | 0 | 0 | 0 | 0 | 0 | |
| OMPS | | | X | X | 80.5 | 108 | 165 | 3 | 2 | [D167] |
| DCS | X | | X | | 30 | 72 | 2.5 | 0 | 0 | [D167] |
| SARSAT | X | | X | | 51.5 | 86 | 2.4 | 0 | 0 | [D167] |

Table 18: Epoch G Inputs to the Technical Complexity Metric

| Components | Early Morning Orbit | Mid-Morning Orbit | Afternoon Orbit | NPP | Mass [kg] | Power [W] | Data-rate [kbps] | Design Penalty | Process Penalty | Sources |
|---|---|---|---|---|---|---|---|---|---|---|
| Epoch G DoD | | | | | | | | | | |
| VIIRS | X | | | | 275 | 240 | 6042 | 0 | 0 | [D167] |
| CMIS | X | | | | 341 | 350 | 35 | 3 | 0 | [D167] |
| CrIS | | | | | 0 | 0 | 0 | 0 | 0 | [D167] |
| ATMS | | | | | 0 | 0 | 0 | 0 | 0 | [D167] |
| SESS | X | | | | 23.9 | 18.9 | 1.1 | 3 | 0 | [D61] |
| TSIS | | | | | 0 | 0 | 0 | 0 | 0 | [D61] |
| ERBS | | | | | 0 | 0 | 0 | 0 | 0 | [D61] |
| APS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ALT | | | | | 0 | 0 | 0 | 0 | 0 | |
| OMPS | | | | | 0 | 0 | 0 | 0 | 0 | [D61] |
| DCS | | | | | 0 | 0 | 0 | 0 | 0 | [D61] |
| SARSAT | | | | | 0 | 0 | 0 | 0 | 0 | [D167] |
| Epoch G NOAA | | | | | | | | | | |
| VIIRS | | | X | X | 275 | 240 | 6042 | 2 | 2 | [D167] |
| CMIS | | | | | 0 | 0 | 0 | 0 | 0 | [D167] |
| CrIS | | | X | X | 165 | 123 | 1536 | 2 | 2 | [D167] |
| ATMS | | | X | X | 75.4 | 93 | 20 | 2 | 2 | [D167] |
| SESS | | | | | 0 | 0 | 0 | 0 | 0 | COBRA for mass and power, estimated data-rate from Epoch B |
| TSIS | | X | | | 30 | 40 | 5.4 | 1 | 1 | [D61] |
| ERBS | | | X | X | 57 | 50 | 10 | 2 | 1 | [D61] |
| APS | | | | | 0 | 0 | 0 | 0 | 0 | |
| ALT | | | | | 0 | 0 | 0 | 0 | 0 | |
| OMPS | | | X | X | 80.5 | 103 | 165 | 2 | 2 | [D167] |
| DCS | | X | | | 30 | 72 | 2.5 | 0 | 0 | [D167] |
| SARSAT | | X | | | 51.5 | 86 | 2.4 | 0 | 0 | [D167] |

Table 19: Inputs to Trade Space Exploration Tool

| Components | Mass [kg] | Power [W] | Data-rate [kbps] | Design Penalty | Process Penalty | Sources |
|---|---|---|---|---|---|---|
| Trade Space Analysis Inputs | | | | | | |
| VIIRS | 275 | 240 | 5900 | 0 | 0 | [D167] |
| VIIRSLite-noocean | 106.1 | 192.1 | 6500 | 5 | 0 | [D61] |
| VIIRSLite-ocean | 106.1 | 176.6 | 6920 | 5 | 0 | [D61] |
| CMIS | 405 | 350 | 90 | 2 | 0 | [D157] |
| SSMIS-U | 146 | 240 | 90 | 3 | 0 | [D157] |
| Windsat | 341 | 350 | 35 | 2 | 0 | [D157] |
| CrIS | 165 | 123 | 1500 | 0 | 0 | [D167] |
| OMPS-Nadir | 12.5 | 41 | 1 | 0 | 0 | [D167] |
| OMPS-Limb | 68 | 68 | 165 | 0 | 0 | [D167] |
| ATMS | 75.4 | 93 | 20 | 0 | 0 | [D167] |
| ERBS1 (biaxial scanning) | 48 | 50 | 10 | 0 | 0 | [D167] |
| ERBS (cross-track scanning) | 48 | 50 | 10 | 0 | 0 | [D167] |
| TSIS | 41 | 65.3 | 2.5 | 0 | 0 | [D167] |
| APS | 69 | 55 | 160 | 0 | 0 | [D167] |

Once instrument parameters were adjusted for design complexity, they were used as inputs to the iterative spacecraft design process. The first iteration of the process estimated the spacecraft's dry mass using an assumed payload / spacecraft mass ratio and the payload's mass. The resulting mass estimate was then used to calculate individual subsystem masses, which were summed to generate a more accurate estimate of the spacecraft's total mass. The updated estimate of spacecraft dry mass was then used as an input for the next iteration of the calculation. This process continued until the difference between subsequent iterations' estimates was less than 10 kg.

To estimate the power subsystem's mass, the model followed the calculation process detailed in [184], which took the spacecraft's dry mass, orbital parameters, lifetime, and payload power requirements as inputs. The payload power requirement was calculated by summing the average power of each manifested instrument. Additional inputs, such as fraction of time with sunlight, worst sun angle, and maximum duration of eclipse were computed using AGI's Satellite ToolKit™ and each spacecraft's orbital parameters. Table 20 documents additional assumptions and technical variables that were inputs to the power budget calculation.

To estimate the propulsion subsystem's mass, the model calculated a delta-V budget using the process described in [189]; this budget accounts for the delta-V required for an injection burn, a deorbiting burn to enable drag-based deorbiting, and periodic burns throughout the system's lifetime that perform station keeping and attitude control. Next, the model estimates propellant mass using total delta-V, the rocket equation, and the additional input assumptions documented in Table 20. Finally, the propulsion subsystem's dry mass was estimated using the rules of thumb given in [184].

To calculate the ADCS subsystem's mass, the model calculated each spacecraft's maximum disturbance torque using the process described in [184] and accounted for gravity gradient, aerodynamic, solar pressure, and magnetic field torques. The ADCS subsystem was sized to compensate for the maximum disturbance torque, using the assumptions listed in Table 20. Finally, the remaining avionics, thermal, and structural subsystems were estimated using the rules of thumb given in [184]. Subsystem masses were totaled to obtain the final launch mass of the spacecraft and to estimate the spacecraft's volume, assuming a cube shape and uniform density as suggested by [184].

**Table 20: Assumptions Used to Design Spacecraft**

| Power Budget Assumptions | |
|---|---|
| **Parameter** | **Value** |
| Energy efficiency from solar arrays to equipment through batteries | 65% |
| Energy efficienty from solar arrays through batteries | 85% |
| Type of solar cell | GaAs |
| Power output from solar array | 253 $W/m^2$ |
| Theoretical solar array efficiency | 77% |
| Solar array performance degradation / year | 2.75% |
| Solar array specific power | 25 W/kg |
| Type of battery cell | Ni-H2 |
| Battery efficiency | 90% |
| Battery specific energy density | 40 Whr/kg |
| Duty cycle | 20% |
| Battery depth of discharge | 60% for terminator orbit, 40% otherwise |
| **Delta-V Budget / ADCS Subsystem Assumptions** | |
| **Parameter** | **Value** |
| Propellant type | Hydrazine |
| Propellent ISP | 290 s |
| ADCS-type | Three-axis |
| Pointing requirement | 0.05 degrees |
| Slew angle | 2.0 degrees |

The outputs of the spacecraft design module were fed directly into the parametric equations used to calculate the cost metric, which had three components: non-recurring space segment, recurring space segment, and launch costs. Importantly, the cost metric did not include ground segment non-recurring and production costs, nor did it include operations costs. Despite these limitations, the cost metric *did* include penalties for technical complexity that are described further below.

Space segment payload costs were estimated using the NASA Instrument Cost Model given in [184]. To account for the complexity and additional cost of developing instruments with high design complexity, the penalties given in Table 14were assigned before instrument costs were estimated. Space segment bus costs were estimated using either USCOM or SSCM; both sets of parametric equations were taken from [184]. The cost metric used the SSCM when a spacecraft's dry mass was less than 500 kg [184], otherwise, USCOM was applied. Recurring costs for both the spacecraft and the instruments were calculated using the corresponding NASA Instrument, USCOM, or SSCM cost models and discounted using a 90% learning curve as recommended by [185].

Next, spacecraft and instrument non-recurring costs were all corrected for complexity using the process described in Chapter 3. Specifically, for each complexity mechanism that affected a component, a penalty ($W_A$) was applied to its costs. The value for $W_A$ was taken from [175-176] and typically ranged between 3-5%. The following assumptions were made to account for interferences in the complexity metric:

- All interferences between instruments were assumed to be bi-directional (i.e. to affect both instruments) with the following exceptions:
    - TSIS optically interfered with all other nadir-facing instruments, but I assumed that only TSIS's design would be modified to fly on a nadir-pointing spacecraft. Therefore, complexity penalties were levied on TSIS only.
    - SARSAT and DCS electromagnetically interfered with all other instruments, but I assumed since these were leveraged payloads, their designs would not be augmented. Therefore, complexity penalties were only levied on the other instruments.
- All VIS/NIR and conical microwave imager-sounder instruments, as well as CrIS and ATMS, were considered to be mission critical instruments. Therefore, if these instruments were placed on the same spacecraft bus, then they interacted with one another through the system's reliability budget.
- For the analysis of the NPOESS program, I assumed that components did not interfere programmatically until Epoch D, when the program's costs grew but it did not receive extra funding. All components were assumed to interfere programmatically in the trade space analysis that was presented in Chapter 9.
- In addition to interfering with other instruments, the conical microwave imager-sounder and SARSAT also interfered with the spacecraft bus because the bus had to be specifically designed to accommodate them.
- The conical microwave imager-sounder was assumed to mechanically interact with all instruments except for SESS.
- The radar altimeter, SARSAT, and DCS were assumed to interact electromagnetically with all instruments except each other and SESS.
-

To account for design relationships between components, the following assumptions were made:

- One design relationship penalty was added to a component cost for each additional environment in which the component had to function. For example, VIIRS was assigned to three different operational orbits plus the NPP orbit. To account for the cost of verifying that the VIIRS design worked in all four systems, three penalties were added to VIIRS's non-recurring cost.
- Design relationships for common spacecraft buses were calculated similarly. For example, the NPOESS bus had to fly in three orbits with different manifests of instruments in each. To account for the complexity of using a common design to complete this task, I designed each spacecraft bus independently and selected the driving design (i.e. the most costly) to serve as the common design. Two complexity penalties were added to account for the cost of adjusting that design to fly in two other orbits and penalties were also added for each additional instrument that needed to fly on the common bus but that did not fly in the orbit that contained the driving design.

Finally, launch costs were included in each complexity metric. For complexity metrics used in the case study, an EELV was assumed for all epochs during the NPOESS program. The reference architectures (i.e. POES O, P, Q and DSMP Block 6) were assumed to use a Delta-II and EELV, respectively. Finally, DWSS and JPSS were assumed to launch on an EELV and Delta-II, respectively. Initial NPOESS documents show that the program assumed that it would use a Delta-II launch vehicle [D61] but that an EELV was baselined later [D192]. However, because the change from a Delta-II to the EELV coincided with the Air Force's new EELV program, which was created to establish a common launch vehicle to be used across Air Force missions, I used an EELV throughout my analysis so that the metrics captured cost growth that was internal to the program and to exclude cost growth that was caused by external directives.

For the trade space analysis in Chapter 9, I assigned spacecraft to launch on the lowest cost launch vehicle with sufficient performance. Launch vehicles that were included in the analysis were taken from [184, 190] and are shown in Table 21 below.

**Table 21: Launch Vehicle Performance and Cost**

| Launch Vehicle | Performance to Desired Orbit | Cost / Launch [FY10] |
|---|---|---|
| Atlas-5 | 10,000 kg | $138 M |
| Space-X | 7,162 kg | $53 M |
| SLS | 70,000 kg | $627 M |
| Delta-7320 | 1,620 kg | $56 M |
| Delta-7420 | 1989 kg | $69 M |
| Delta-7920 | 3200 kg | $81 M |
| Taurus-XL | 870 kg | $37 M |
| Minotaur-IV | 1050 kg | $44 M |

The remaining assumptions that were used to calculate the technical complexity metric in the case studies included:

- The cost of the NPP spacecraft and launch vehicle were not included; however, the cost of the NPP instruments (with the exception of ATMS) were included in the technical complexity metric.
- The architectural complexity costs induced by NPP's interference with NPOESS were included in all epochs after NPP was established.
- All NPOESS systems were assumed to be duplicated throughout the program's lifetime. In other words, I assumed that second spacecraft to fly in the early morning orbit would be the same as the first. As the program's costs began to grow in later years, they began taking one or two instruments off copies of spacecraft; however, my metrics do not account for these smaller details.
- Costs for SARSAT and DCS were not included in the cost metric although the cost of the architectural complexity they induced was included.

## 11.2.2 Organizational Complexity Metric

The organizational architecture for each epoch was created by mapping the responsibility and authority relationships between components of the NPOESS, JPSS, and DWSS organizational architectures. All authority and responsibility relationships were assumed to be bi-directional and each relationship was mapped using +1 to indicate the presence of a relationship. The authority links were augmented to account for authority erosion and +1 was added to each relationship that was affected by an authority erosion factor. These authority erosion factors included:

- Ineffective delegation eroded authority in the NPOESS user community. This was captured by adding +1 to the authority relationship between the JARC and the SUAG and the SUAG and the JARG. This did not affect POES, DMSP, DWSS, or JPSS.
- NOAA's authority over the EXCOM was misaligned with its expertise (since it is not a space acquisition organization) so +1 was added to the authority link between NOAA and the EXCOM.
- The IPO's authority over its contractors was weakened by its acquisition strategy so +1 was added to all authority links between the IPO and its contractors.
- The IPO's authority over its contractors was also weakened by the misalignment of budget and responsibility that occurred due to the "Optimized Convergence" strategy's extended competition period. This misalignment added +1 to the IPO's authority over its contractors during Epoch B and C.
- The IPO's expertise was not commensurate with its authority over its contractors so +1 was added to each of these relationships throughout the NPOESS program.
- After the NPP program was added, two sources of expertise converged on the instrument contractors. This misalignment of authority and expertise eroded prime contractor's authority over its instrument subcontractors and +1 was added to capture this effect. This also affected the IPO's authority over the contractors in Epoch C (before the prime contractor was selected).
- The authority relationship between the IPO and the EXCOM and later, between the EXCOM, TSC, and the IPO all suffered from ineffective delegation so +1was added to each authority link.
- When the PEO's authority was eroded in Epoch F, +1 was added to its authority link between the IPO and NPP and a responsibility link was also added between the PEO and NOAA and NASA.
- On JPSS, the NASA JPSS office's authority over its contractors was affected by a misalignment of responsibility and budget, so +1 was added to each link.
- An additional +1 was added to the link between the JPSS program office and the ground system to account for the misalignment of responsibility and budget that was induced by DWSS using the Common Ground System but not managing or funding it.
- Also on JPSS, NOAA's expertise was not commensurate with its authority, so +1 was added to the authority link between NOAA and the NJO.

Additional links between components that are important to note include:

- A responsibility link existed between the EXCOM and the JARC and the IPO and the SUAG.
- Since NASA did not formally levy requirements on the NPOESS program, there was not initially a responsibility link between the agency and the EXCOM. When climate science requirements were added in Epoch C, a responsibility link was added between NASA and NOAA. Finally, when the PEO was added in Epoch E, NASA delegated its responsibility for NPP through the EXCOM.
- NASA's responsibility on JPSS flowed from the agency, to NASA Goddard, to the NASA program office. NASA's responsibility was represented separately from NOAA's responsibility which it delegated through JASD.
- When NPP was added, responsibility links connected NPP to NASA, the IPO to NPP, and NPP to the contractors.

In the interest of space, neither the organizational architecture DSMs—nor the sketches of the organizations themselves—are included here. However, they may be requested from the author if necessary by emailing morgan.dwyer@aya.yale.edu.

## 11.3 Additional Description of Interviews

This section provides additional description of the interview process and the interviews that were conducted. Interviewees were recruited using an email similar to the form email copied below:

**EXAMPLE SUBJECT INTRODUCTORY/RECRUITMENT EMAIL**

> *Dear Mr./Mrs. [Insert Interviewee Name],*
>
> *The MIT Systems Architecture Group is currently studying historic cases of joint space systems development and we believe that your knowledge on [Topic of Interest] is an important perspective that should be included in our study. [Reference] suggested that you would be a good person to speak with about this topic.*
>
> *Would you be interested in discussing your experiences? The conversation should last roughly one hour; your participation is voluntary, you may decline to answer any or all questions, or decline further participation at any time, without adverse consequences. We will not identify your participation.*
>
> *Thank you and I look forward to hearing from you soon.*
>
> *Best,*
>
> *Morgan Dwyer*

If potential interviewees responded, an interview was scheduled, either in person or over the phone. Prior to beginning the interview, interviewees were given the following consent form to review. Interviewees were then allowed time to review the form and to ask questions. As approved by MIT's Committee On the Use of Human Subjects (COUHES) board, once interviewees reviewed the form, I collected their verbal consent. The consent form contained the following text:

**CONSET TO PARTICIPATE IN INTERVIEW**

**Systems Architecting of Joint Space Systems**

> *You have been asked to participate in a research study conducted by Morgan Dwyer from the Engineering Systems Division at the Massachusetts Institute of Technology (M.I.T.). The purpose of this study is to identify impediments and enablers to joint space systems development. The results of this study will be included in Morgan Dwyer's PhD thesis. You were selected as a possible participant in this study because of your position and/or experience with joint space systems. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.*

- *This interview is voluntary. You have the right not to answer any question, and to stop the interview at any time or for any reason. We expect that the interview will take about an hour.*

- *You will not be compensated for this interview.*

- *Unless you give us permission to use your name, title, and/or quote you in any publications that may result from this research, the information you tell us will be confidential.*

- *We would like to take notes and make an audio recording of this interview so we can use it for reference while proceeding with this study. We will not take notes or record this interview without your permission. If you do grant permission for us to take notes and/or record the interview, you have the right to revoke permission and/or end the interview at any time.*

*This project will be completed by 1 September 2016. All interview notes and recordings will be stored in a secure work space until 1 September 2017. Then these records will be destroyed.*

*I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.*

*Please contact Morgan Dwyer (mdwyer@mit.edu) with any questions or concerns.*

*If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143b, 77 Massachusetts Ave., Cambridge, MA 02139, phone 617-253-6787.*

As described in Chapter 3, interviews were semi-structured and questions were tailored to focus on the unique experiences and perspectives of each interviewee. Interviews approximately used the following outline:

1. After obtaining verbal consent, the interview began with introductions, an explanation of study goals, and interview procedures. I then provided the interviewee with the opportunity to ask questions or make requests.
2. Early questions focused on the subject's professional background. This information was used to gather information on the subject's position in the program. I also asked about related work that the subject had performed because this information was often helpful for understanding the subject's frame of reference or interpretation of program events. These questions included:
    a. What was your role on [insert program name] and during what time frame?
    b. What were your primary responsibilities?
    c. What other positions on the program did you interface with on a regular basis?

d. What related work have you done?

3. Central interview questions focused on the decision making processes used in program under study. Questions focused on the organizational processes, values, personnel, and technical competencies that affected the program's decisions and how these factors evolved over time. These questions were tailored for each program and for the subject's particular experience or role. Example questions are listed below.
   a. Who were the key decision makers on the program?
   b. Describe the process by which technical decisions were made. How were the issues that needed decisions communicated to decision makers?
   c. Evaluate the process by which technical decisions were made. How effective was it? What were its strenghts and weakness? How could it have been improved?
   d. When technical issues arose during the system's development? How were they communicated to program management? How often did this happen? How effective was program management at resolving issues in a way that satisfied both technical and management concerns?
   e. What was the program's requriements development process? How were trades negotiated between the agencies?
   f. What system architecture options were considered during the system's early development and what motivated the ulimate selection?
   g. Did the collaborative environment alter individual agencies' stated preferences or needs? How?
   h. Did the collaborative environment alter individual agencies' tolerance for technical or programmatic risk?
   i. How well did the program understand the technology that they selected to use? What were known risks or uncertainties? How did these inform the decision making process?
   j. What technology or programmatic risks were not realized during the program's early decisions? Why?
   k. How were cost and risk estimates formulated on the program? What were the strengths and weakness of this approach?
   l. What was the progam's strategy for risk management? What were its strengths and weaknesses?
   m. If 100% requirement satisfaction was not possible, how did the program determine what capabilities to degrade?
   n. How did the interagency nature of the program cause organizational or technical difficulties? How could this be avoided in the future?
4. The subject was then be given the opportunity to share additional insights or information on the general research topic or on their experience working on the program under study.
5. The interview concluded by asking the subject if he/she could recommend additional interviewees or provide program documents. The subject was also given the opportunity to ask additional questions about my research.
6. Finally, I offered to follow-up with the subject on my results and asked permission to contact him/her with any follow-up questions.

Table 22 provides additional description of the interviews that were conducted and limited information about the identity of the interviewees. Please note that the codes protecting the agency identities change between NPOESS and the two plausibility probe cases (i.e. Case 1 and Case 2). The intent of this change is to prevent agency identities from being discovered. Interviewees who were consulted for more than one case (i.e. NPOESS and a plausibility probe case) are also assigned new numbers so that identifying information cannot be inferred from their association with more than one program. Finally, group interviews are identified in the length column which notes when interviews were joint (i.e. conducted in a group). Note that people from group interviews were also sometimes interviewed individually as well.

**Table 22: Case Study Interviewee List**

| Interview ID | Case | Interview Details | Length (minutes) | Organizational Affiliation | Role |
|---|---|---|---|---|---|
| I1 | NPOESS | Remote | 60 | Agency C | Oversight |
| I2 | NPOESS | Remote | 46 | Contractor | Technical--System |
| I3 | NPOESS | In Person | 50 | Agency A | Technical--System |
| I4 | NPOESS | In Person | 150 | Agency B | Technical--System |
| I5, I15 | NPOESS | Remote | 101 (individual), 325 (joint) | Agency B | Technical--System |
| I6 | NPOESS | In Person | 35 | Agency B | Oversight |
| I7 | NPOESS | In Person | 86 | Agency B | Oversight |
| I8 | NPOESS | In Person | 96 | Agency B | Oversight |
| I9 | NPOESS | In Person | 103 | Agency B | Technical--Components |
| I10 | NPOESS | Remote | 66 | Agency B | Technical--System |
| I11, I15 | NPOESS | In Person, Remote | 209 (individual), 325 (joint) | Agency B | Management |
| I12 | NPOESS | Remote | 67 | Agency A | Management |
| I13 | NPOESS | Remote | 87 | Agency C | Oversight |
| I14 | NPOESS | Remote | 70 | Agency A | Technical--System |
| I16 | NPOESS | Remote | 122 | Agency C | Management |
| I17 | NPOESS | In Person | 54 | Agency B | Technical--System |
| I18 | NPOESS | In Person | 94 | Agency B | Technical--System |
| I19 | NPOESS | In Person | 34 | Agency B | Oversight |
| I20 | NPOESS | In Person | 54 | Contractor | Technical--Components |
| I21 | NPOESS | In Person | 150 | Agency A | Technical--Components |
| I22 | NPOESS | In Person | 88 | Contractor | Technical--Components |
| I23 | NPOESS | In Person | 129 (joint) | Agency A | Technical--System |
| I23 | NPOESS | In Person | 129 (joint) | Agency A | Technical--System |
| I24 | NPOESS | In Person | 56 | Agency B | Technical--System |
| I25 | NPOESS | In Person | 66 | Agency C | Non-Technical |
| I26 | NPOESS | In Person | 127 | Agency C | Technical--System |
| I27 | NPOESS | In Person | 53 | Agency C | Technical--Components |
| I28 | NPOESS | In Person | 44 | Agency B | Management |
| I29 | NPOESS | Remote | 64 | Agency C | Technical--Components |
| I30 | NPOESS | Remote | 63 | Contractor | Technical--Components |
| I31 | NPOESS | Remote | 42 | Agency C | Technical--Components |
| I31 | NPOESS | Remote | 42 (joint) | Agency A | Technical--Components |
| I32 | NPOESS | Remote | 47 | External Review | Oversight |
| I33 | NPOESS | In Person | 160 | Agency C | Management |

| Interview ID | Case | Interview Details | Length (minutes) | Organizational Affiliation | Role |
|---|---|---|---|---|---|
| I34 | NPOESS | In Person | 106 | Agency A | Technical--Components |
| I35 | NPOESS | In Person | 153 | Agency A | Technical--System |
| I36 | NPOESS | Remote | 62 | Agency A | Oversight |
| I37 | NPOESS | In Person | 104 | Agency C | Technical--System |
| I38 | NPOESS | In Person | 82 | Agency B | Oversight |
| I39 | NPOESS | In Person | 264 | Agency B | Technical--Components |
| I40 | NPOESS | In Person, Remote | 91 (individual), 325 (joint) | Agency C | Technical--System |
| I41 | NPOESS | Remote | 51 | External Review | Oversight |
| I42 | NPOESS | Remote | 25 | External Review | Oversight |
| I43 | NPOESS | Remote | 38 | Contractor | Technical--Components |
| I44 | NPOESS | In Person | 64 | Agency C | Technical--System |
| I45 | NPOESS | Remote | 60 | Agency C | Technical--System |
| I46 | NPOESS | In Person | 211 (joint) | Contractor | Management |
| I46 | NPOESS | In Person | 211 (joint) | Contractor | Management |
| I46 | NPOESS | In Person | 211 (joint) | External Review | Oversight |
| I46, I50 | NPOESS | In Person | 44 (individual), 211 (joint) | External Review | Oversight |
| I47 | NPOESS | Remote | 76 | Contractor | Technical--Components |
| I48 | NPOESS | Remote | 74 | Contractor | Technical--System |
| I49 | NPOESS | In Person | 130 | Agency C | Technical--System |
| I51 | NPOESS | In Person | 95 | Contractor | Non-Technical |
| I52 | NPOESS | In Person | 106 | Agency C | Non-Technical |
| I53 | NPOESS | Remote | 58 | Contractor | Technical--Components |
| I54 | NPOESS | Remote | 65 | Contractor | Technical--Components |
| I55 | Case 2 | Remote | 51 | External Review | Oversight |
| I56 | Case 2 | Remote | 57 | Agency E | Technical--System |
| I57 | Case 2 | Remote | 55 | Agency F | Technical--System |
| I58 | NPOESS | Remote | 143 | Agency A | Technical--Components |
| I59 | Case 2 | Remote | 88 | Agency E | Technical--System |
| I60 | Case 2 | Remote | 57 | Agency F | Technical--System |
| I61 | NPOESS | Remote | 77 | Contractor | Technical--Components |
| I62 | Case 1 | Remote | 66 | Agency D | Technical--System |
| I63 | Case 2 | Remote | 75 | Agency E | Technical--System |
| I64 | NPOESS | Remote | 78 | Agency C | Oversight |
| I65 | Case 1 | Remote | 51 | Agency D | Management |
| I66 | Case 2 | Remote | 52 | Agency F | Technical--System |
| I67 | Case 1 | Remote | 40 | Agency D | Technical--System |
| I68 | Case 1 | Remote | also interviewed for NPOESS | Agency D | Technical--System |

| Interview ID | Case | Interview Details | Length (minutes) | Organizational Affiliation | Role |
|---|---|---|---|---|---|
| I69 | Case 2 | Remote | also interviewed for NPOESS | Agency F | Technical--Components |
| I70 | Case 2 | Remote | also interviewed for NPOESS | Contractor | Technical--Components |
| I71 | Case 1 | Remote | also interviewed for NPOESS | Agency D | Oversight |
| I72 | Case 2 | Remote | also interviewed for NPOESS | Agency E | Management |

## 11.4 Case Study Document List

The table below lists the documents that were consulted in each of the case studies.

**Table 23: Case Study Document List**

| Code | Case Study | Document Type | Document Description |
|---|---|---|---|
| D1 | NPOESS | Internal Program Document | "Distributed Satellite Formation Alternatives." *Aerospace Technical Report, TOR-96(8511)-1.* March 1999. |
| D2 | NPOESS | Internal Program Document | "Reliability Considerations for Satellites with More than One Critical Payload." *Aerospace Technical Report, TOR-97(8511)-4.* |
| D3 | DWSS | Internal Program Document | "US Army Research, Development, and Engineering Command: Review of JPSS and DWSS." *Land Surface Dynamics Workshop.* Tucson, AZ, March 2011. (briefing) |
| D4 | DWSS | News article | (2010, February 8). Weathering the Breakup. *Air Force Magazine: Online Journal of the Air Force Association.* Retrieved from http://www.airforcemag.com/Features/newtech/Pages/box020810npoess.aspx. Accessed March 16, 2014. |
| D5 | JPSS | News article | (2010, September 23). NASA Awards Contract for JPSS-1 Spacecraft." *NASA.* Retrieved from http://www.nasa.gov/home/hqnews/2010/sep/HQ_C10-058_JPSS-1_Spacecraft.html. Accessed Aug. 6, 2014. |
| D6 | DWSS | News article | (2011, May 31). Northrop Grumman to Begin Work on Defense Weather Satellite System. *Space Daily.* Retrieved from http://www.spacedaily.com/reports/Northrop_Grumman_to_Begin_Work_on_Defense_Weather_Satellite_System_999.html. Accessed March 16, 2014. |
| D7 | DWSS | News article | (2011, November 24). Northrop Grumman Creates Significant Efficiencies for Defense Weather Satellite System" *Space Daily.* Retrieved from http://www.spacedaily.com/reports/Northrop_Grumman_Creates_Significant_Efficiencies_For_Defense_Weather_Satellite_System_999.html. Accessed March 16, 214. |
| D8 | DWSS | News article | (2011, October 11). Northrop Grumman-led Team Advances Defense Weather Satellite System With Spacecraft Flight Hardware Deliveries Ahead of Schedule. *Bloomberg News.* Retrieved from http://www.bloomberg.com/apps/news?pid=newsarchive&sid=a6mwBZwIxCfU. Accessed Aug. 5, 2014. |

| Code | Case Study | Document Type | Document Description |
|---|---|---|---|
| D9 | JPSS | Website | (2012, April 17). Chairwoman Mikulski Demands More Frugal and Efficient Satellite Procurement: Spending Bill Transfers Operational Satellite Acquisition from NOAA to NASA. Retrieved from http://www.mikulski.senate.gov/media/pressrelease/4-17-2012-3.cfm. Accessed Aug. 6, 2014. |
| D10 | JPSS | News Article | (2012, August 16). Ball Aerospace Incorporates Enhanced Data Communications for JPSS-1 Satellite. *Space Mart.* Retrieved from http://www.spacemart.com/reports/Ball_Aerospace_Incorporates_Enhanced_Data_Communication_for_JPSS_1_Satellite_999.html. Accessed March 25, 2014. |
| D11 | JPSS | Website | (2013, August 12). JPSS Program, JPSS-1 Mission Reach Key Milestones. *NASA.* Retrieved from http://www.nasa.gov/content/goddard/jpss-program-jpss-1-mission-reach-key-milestones/#.Uyo5xvldXN4. Accessed March 19, 2014. |
| D12 | JPSS | News article | (2013, August 26). U.S. Weather Satellites: From NPOESS' Hairy Crises, to DWSS/JPSS Split Ends. Retrieved from http://www.defenseindustrydaily.com/major-shifts-flow-from-npoess-polar-satellite-program-crisis-01557/. Accessed Aug. 6, 2014. |
| D13 | DWSS | News Article | (2013, January 7). ATK Awarded Study Contract from USAF Network Centric Weather Satellite Program. *Bloomberg.* Retrieved from http://www.bloomberg.com/article/2013-01-07/ayOanAZwgEbU.html. Accessed Aug. 6, 2014. |
| D14 | NPOESS | Government Study | Allison, L.J., Schnapf, A., Diesen, B.C. IIII, Martin, P.S., Schwalb, A., Bandeen, W.R. (1980, June). *NASA Technical Memorandum 80704: Meteorological Satellite.* (Publication No. NASA-TM-80704). Goddard, MD: Goddard Spaceflight Center National Aeronautics and Space Administration. |
| D15 | NPOESS | Congressional Hearing | *An Insecure Forecast for Continuity of Climate and Weather Data, The NPOESS Weather Satellite Program: Hearing before the Subcommittee on Energy and the Environment, Committee on Science and Technology of the House of Representatives*, 110th Congress, 2nd Session, 1 (2008). Retrieved from http://www.gpo.gov/fdsys/pkg/CHRG-110hhrg43349/html/CHRG-110hhrg43349.htm |
| D16 | NPOESS | Journal Article | Anderson, D.E., Cahalan, R.F. (2005). The Solar Radiation and Climate Experiment (SORCE) Mission for the NASA Earth Observing System (EOS).*Solar Physics,* Vol. 230, p 3-5. |
| D17 | NPOESS | Conference Paper / Presentation | Andreoli, L., Coyle, K. (January 2005). Payload Accommodations on Future Environmental Sensing Spacecraft--Lessons Learned from EOS and the future with NPOESS. In Komar, G., Wang, J., Kimura, T. *Proceedings of SPIE Vol. 5659.* Paper presented at Enabling Sensor and Platform Technologies for Space borne Remote Sensing. Doi: 10.1117/12.578384 |
| D18 | NPOESS | Journal Article | Ardanuy, P.E., Schueler, C.F., Miller, S.W., Kealy, P.S., Cota, S.A., Haas, J.M., Welsch, C. (2002) NPOESS VIIRS Design Process. *Proceedings of SPIE Vol. 4483 Earth Observing Systems VI.* doi:10.1117/12.453461 |
| D19 | NPOESS | Conference Paper / Presentation | Asbury, S., Cass, S., Farwell, L., Eastman, K., Remund, Q., Rodriguez, J. (January 2007). OMPS - The Next Generation Sensor Suite for Global Ozone Monitoring. Poster presented at Third Symposium on Future National Operational Environmental Satellites, San Antonio, TX. |
| D20 | DWSS | Government Study | Bennett, Michael. (2012, September). *Options for Modernizing Military Weather Satellites.* Washington, D.C.: Congressional Budget Office. Retrieved from http://www.cbo.gov/sites/default/files/cbofiles/attachments/09-20-WeatherSatellites.pdf |
| D21 | JPSS | News Article | Betz, Laura. (2012, August 14). NASA Finalizes Contracts for NOAA's JPSS-1 Mission. *Space Daily.* Retrieved from http://www.spacedaily.com/reports/NASA_Finalizes_Contracts_for_NOAAs_JPSS_1_Mission_999.html. Accessed March 19, 2014. |

| Code | Case Study | Document Type | Document Description |
|---|---|---|---|
| D22 | NPOESS | Conference Paper / Presentation | Bingham, G.A., Fish, C., Zavyalov, V., Esplin, M.P., Pougatchev, N.S., Blackwell, W.J., Barnet, C.D. (January, 2010). The NPOESS CrIS and ATMS as a Companion to the New Generation AIRS/AMSU and IASI/AMSU Sounder Suites. Paper presented at 6th Annual Symposium on Future National Operational Environmental Satellite Systems-NPOESS and GOES-R, Atlanta, GA. |
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