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Precision Pointing System Development

Robert M. Bugos, Editor

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Precision Pointing System Development

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ABSTRACT

The development of precision pointing systems has been underway in Sandia's Electronic Systems Center for over thirty years. Important areas of emphasis are synthetic aperture radars and optical reconnaissance systems. Most applications are in the aerospace arena, with host vehicles including rockets, satellites, and manned and unmanned aircraft. Systems have been used on defense-related missions throughout the world. Presently in development are pointing systems with accuracy goals in the nanoradian regime. Future activity will include efforts to dramatically reduce system size and weight through measures such as the incorporation of advanced materials and MEMS inertial sensors.

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Contributors to this report at Sandia National Laboratories include: Arnold Muyshondt, Manager, Rob Bugos, Pete Stromberg, and Sharlene McLane of the Mechanical Design and Analysis Department; Armin Doerry and Tom Cordaro of the Radar and Signal Analysis Department; and Andrew B. Cox, Manager, and Stew Kohler of the Inertial Systems Department.

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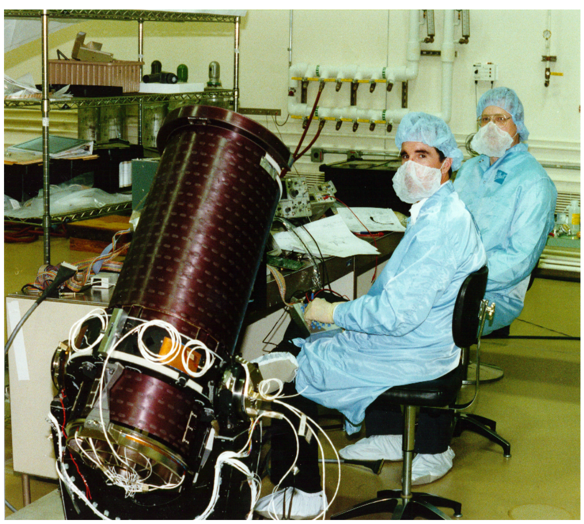
I. INTRODUCTION

Inertial measurement may be defined as the application of collections of inertial sensors, (i.e. gyroscopes and accelerometers) to the determination of location and/or orientation. Historically, the initial objectives of inertial measurement, at Sandia and elsewhere, were the navigation, guidance, and control of aerospace vehicles such as rockets. However, beginning about thirty years ago and accelerating in the last decade, precision pointing has evolved into a major application area for inertial measurement technology.

Pointing, in the context of this report, refers to the act of controlling the orientation of an object relative to specific directions such as north, east, and down. A pointing system generally requires gyros or other angle sensors attached to the item to be pointed, and a supporting structure with a system of rotary bearings, motors, and electronics to enable and control angular motion.

At Sandia, the majority of the recent rapid increase in pointing system development activity has occurred in two areas: synthetic aperture radars (SARs) and optical sensing. In the case of a SAR, the radar antenna is the object to be pointed. In an optical sensing system, a collection of optical elements, generally classified as a telescope, is pointed. Most of the pointing system development at Sandia occurs in the Electronic Systems Center. Figure 1 is a table of the pointing systems developed by the Center.

Sandia pointing systems are being used by a variety of customers including branches of the U.S. military, agencies of the U.S. government, and U.S. corporate suppliers of high-technology defense products. Host vehicles (Figure 2) have included rockets, satellites, and manned and unmanned aircraft. Although most missions are categorized as intelligence-gathering in nature, some involve combat operations. Details are necessarily classified in most cases. However, it is clear from the success of these systems, and the rapid increase in funding for new projects that Sandia-developed pointing system technology will continue to grow in importance to U.S. national security.



Flight Telescope pointing system
under development, circa 1995

	Pointing Systems developed by the Electronic Systems Center							
Use codes: OS=Optical Surveillance, SAR=Synthetic Aperture Radar, IFSAR =Interferometric SAR,								
	GC=Guidance and Control, EXP=Experimental (no specific use or host vehicle)							
Host Vehicle Codes: A=Aircraft, R=Rocket, SA=Space App., SH=Ship, B=Bomb, UAV=Unmanned								
	Aerial Vehicle, RV=Reentry Vehicle, LV=Land vehicle, NA=Not applicable							
IMU Codes: RIG=Single axis rate integrating gyros, RG=Single axis rate gyros, DTG=Dynamically tuned gyros,								
	DMARS=Digital Miniature Attitude Reference System (DTGs), LN200=Northrop Grumman							
	LN200 IMU (Fiber Optic Gyros), HAIMS=High Accuracy Inertial Measurement							
	System (Ring Laser Gyros), RLGA=Ring Laser Gyro Assembly, IAS =Inertial Angle							
	Sensor, HRG=Hemispherical Resonator Gyro, H423= Honeywell H423 INS							
System	Date	Use	IMU	Host	Accuracy	Application Notes		
TAR	1970	GC	RIGs (2)	RV	1.0 degree	Two-axis Attitude Reference		
HEOMS	1972	OS	RGs(3)	SH	0.1degree	High Expl. Output Measur. Sys.		
LPS	1985	EXP	DTG	NA	20 micro-rad	Laser Pointing System		
DAPS	1986	EXP	DTG	NA	0.01 degree	Directional Antenna Point. Sys.		
TFS	1987	SAR	H423	A	0.1 degree	Terminal Fix System		
Thorny Merit	1989	GC	RGs(2)	R	0.1 degree	Rocket homing system		
Strip	1989-1999	SAR	RLGA	A	0.01 degree	Data collection system		
AMPS	1992-1994	SAR	RLGA	A	0.01 degree	Airborne Modular Pod System		
ITAG	1995	SAR	DMARS	B	0.02 degree	Inertial Terrain-aided Guidance		
FT	1998	OS	IAS(2)	SA	2 micro-rad	Flight Telescope		
Lynx	1999	SAR	LN200	UAV	0.05 degree	In military operations		
SARFS	2001	SAR	LN200	A	0.05 degree	In military operations		
RTV	2002	SAR	HAIMS	A	0.005 degree	Interferometric SAR (IFSAR)		
AURA	2002	OS	LN200	UAV	0.05 degree	Adv. Ultraviolet Remote-sens. Appl.		
Ares *	2003	OS	IAS(2)	LV	0.01 degree	Terrestrial optical recon.		
ST *	2004	OS	HRG	SA	nanoradians	Space Telescope		
JTM *	2004	SAR	HAIMS	UAV	0.005 degree	Joint Tactical Mapper (IFSAR)		
* under development								

Figure 1: Pointing systems developed by the Electronic Systems Center

Figure 2: Hosts for Sandia-developed pointing systems encompass a wide variety of aerospace vehicles

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II. HISTORY OF POINTING SYSTEM DEVELOPMENT

Several pointing systems listed in Figure 1 are discussed in more detail below because they represent important milestones in the progression to the capabilities embodied in today's systems.

Two-axis Attitude Reference (1970-1972)

Work on pointing systems began in the Electronic Systems Center around 1969. Initial systems were developed to provide an inertial attitude reference for reentry vehicles (RVs) and were referred to as two-axis, inertial platforms. The item to be pointed, an instrument cluster containing two single-axis gyros, was arranged so that the gyro input axes were perpendicular to each other and to a vector pointing out the side of the re-entry vehicle (RV). The gyros were supported on a nested pair of gimbals: an outer gimbal surrounding an inner gimbal. The gimbals and associated bearings and motors enabled angular freedom between the RV and the instrument cluster. The motors on each gimbal were driven by servo electronics to null the gyro outputs. Thus the direction of the vector pointing out the side of the vehicle, and defined by the cross-product of the gyro input axes, was inertially stabilized (remained pointing in a fixed direction). The outer gimbal axis was collinear with the RV roll (or spin) axis. An angle transducer on the gimbal provided a measurement of the RV roll angle. Similarly, an inner gimbal transducer measured pitch angle. Rotation in yaw, about the pointing axis, was not controlled or measured. A two-axis attitude reference was tested in the laboratory at accelerations up to 150 gs and successfully flight tested aboard an RV in 1972. Figure 3 shows the two axis attitude refence system developed in 1972.

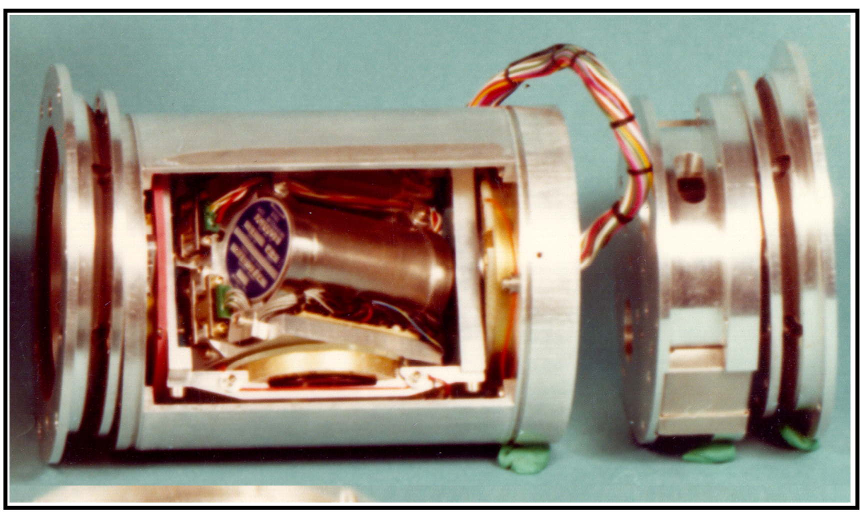

Figure 3: Two-axis attitude reference (1972)

Although gyro and electronics technologies have progressed tremendously in the last thirty years, these initial systems contained most of the basic elements of modern pointing systems developed recently by the Electronic Systems Center.

<u>Directional Altimeter System (1985-1986)</u>

The directional altimeter system was originally developed for testing terrain-aided guidance concepts for maneuvering reentry vehicles. Technologies developed for this system were later used for the development of the ITAG (intertial terrain-aided guidance) system (pages 16-17). In 1986 the Directional Altimeter System was used in the production of Sandia's first SAR images. Figure 4 shows the Directional Altimeter System.

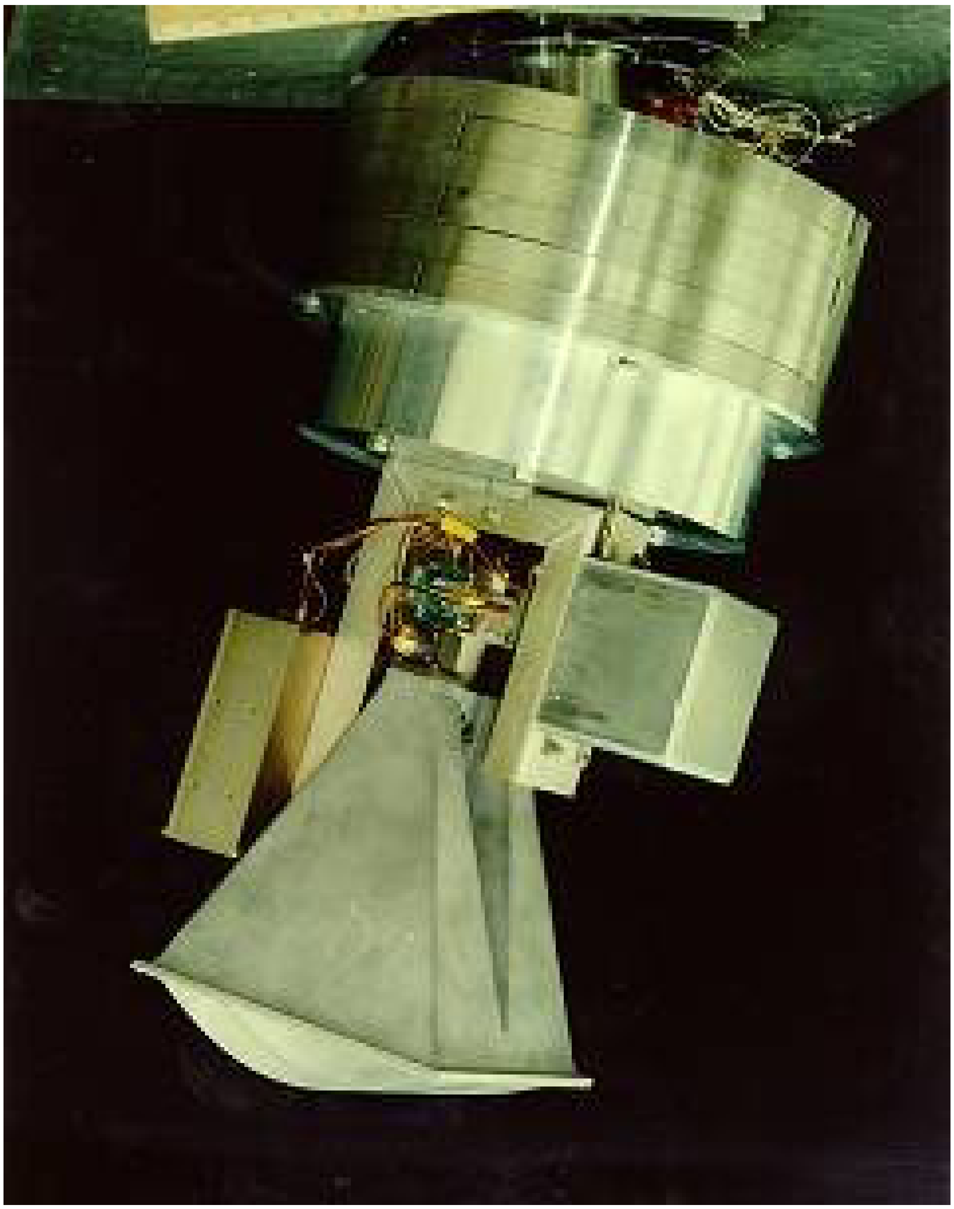

Figure 4: Directional Altimeter System

Advanced Instrumentation System (AIS, 1986-1989, Ref. 1)

The Advanced Instrumentation System was a homing guidance system for a sounding rocket. The objective was to point an RF antenna on a rocket in the direction of a beacon carried by a second rocket. Figure 5 shows the AIS pointing system in an antenna test range.

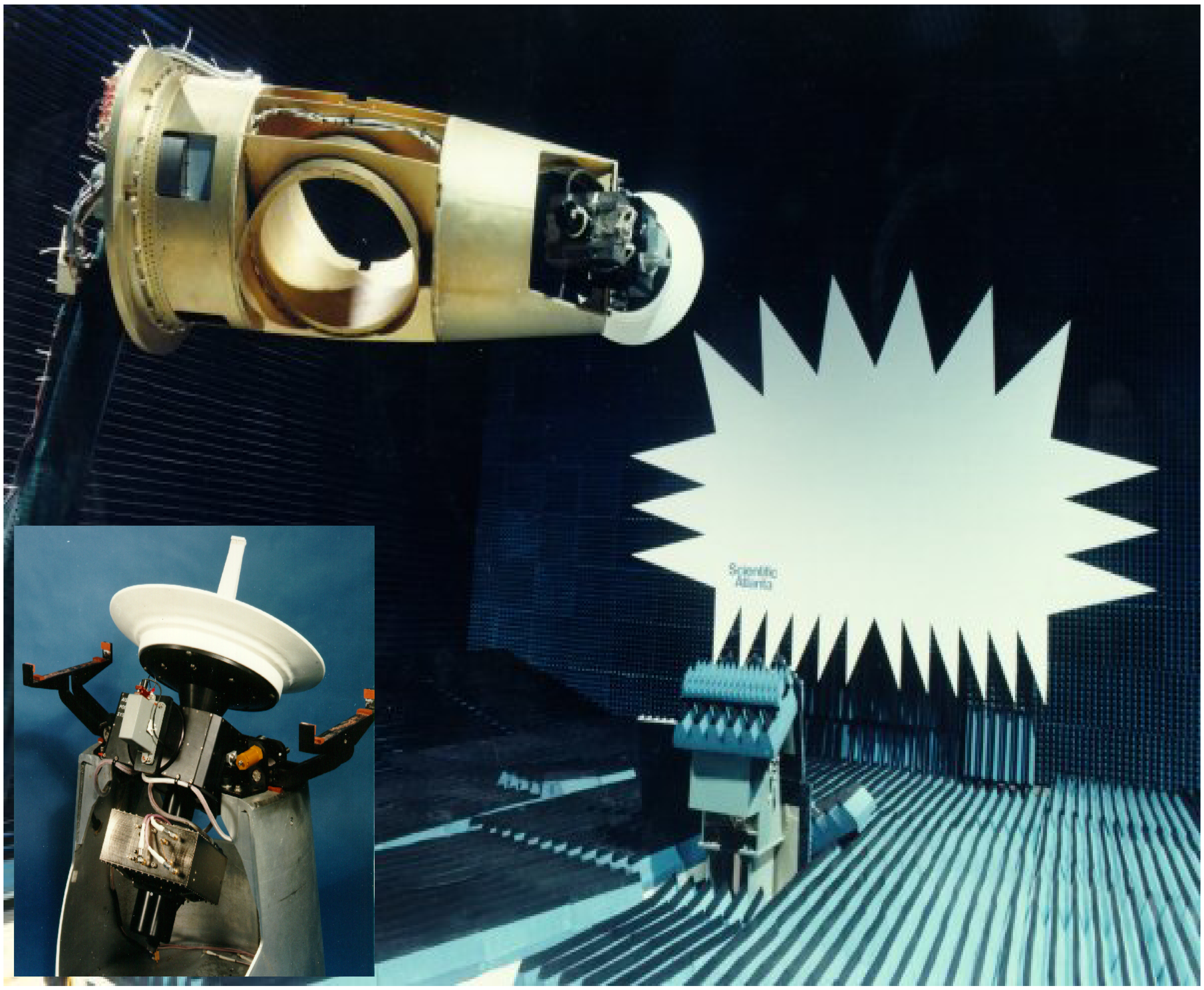

Figure 5: Antenna range testing of the AIS pointing system

An interesting aspect of this system was that two types of angle sensors (RF and gyro) were required to affect the pointing solution. The angle measurements produced by the RF antenna were too noisy to be used alone and produced unacceptable jitter in the antenna orientation. Therefore, gyros were used to provide high fidelity signals needed by the control system to cancel the effects of bearing friction. A heavily filtered version of the RF signal was combined with the gyro signals to produce a control signal which would point the antenna at the beacon. In essence, the antenna signal was used by the control system to bias the gyro signal in the direction resulting in a null in the antenna output, thus pointing the antenna at the beacon on the second rocket.

Proper selections of gain and filtering associated with the signals from the two angle sensors are classic control system optimization problems. Fortunately, by the late 1980's, capable computer-aided control system design tools had become commercially available and facilitated the control system design. The Advanced Instrumentation System project was the first instance of the use of a full suite of these tools in the development of a pointing system by the Electronic Systems Center. The system performed flawlessly during a flight test in January, 1989. The flight test is shown in Figure 6.

Figure 6: Time lapse photo of launches of AIS pointing system and beacon rockets, Kauai Test Range, 1989.

Strip/TFS (1989-1999, Ref. 2)

For almost a decade, the Strip/TFS system was the SAR R&D workhorse for the Electronic Systems Center. The Strip/TFS system is shown in Figure 7.

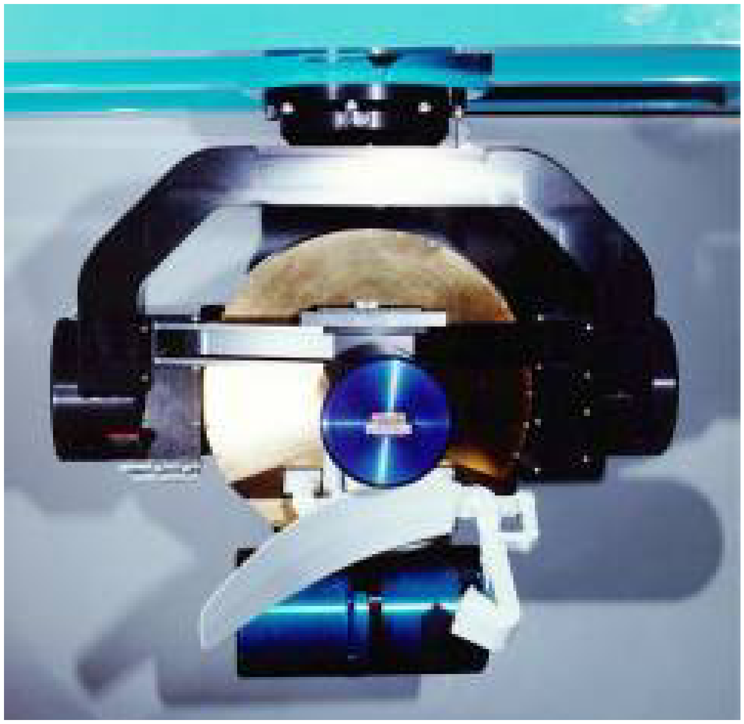

Figure 7: Strip/TFS gimbal assembly

This system could be considered to be the ancestor of our modern SAR systems. It was the first SAR pointing system at Sandia to collocate a full inertial measurement unit (IMU) and antenna on the gimbal assembly. Prior to early 1990, there were no navigation-class IMUs small and light enough to fit on a gimbal assembly with an antenna. Motion measurement and pointing functions were performed by using an IMU located near, but not on, the gimbal assembly. Determination of the antenna position and orientation required a translation of IMU data based on measurements of gimbal angles. This process introduced errors due to imperfections in and misalignments of the gimbal angle transducers. The pointing control problem was aggravated by the compliance of the complex and distributed structure connecting the IMU and antenna. With joint Sandia Electronics Systems Center and Honeywell development of the RLGA (Ring Laser Gyro Assembly), a relatively small navigation-grade IMU (150 cubic inches and 10 lbs) was produced. Problems associated with use of a remotely located IMU were largely eliminated by rigidly attaching the IMU directly to the antenna support structure.

The Strip/TFS antenna pointing system produced excellent performance, which was evident from the superior quality of the generated images. The demonstration of a world-class SAR capability with this system led sponsors to select Sandia for important new SAR development programs. Because of the success of this system, all subsequent SAR antenna pointing systems developed by the Electronic Systems Center utilize collocation of antenna and IMU.

ITAG (Inertial Terrain-Aided Guidance, 1996-1999, Ref. 3)

The ITAG system, to date, contains the only pointing system developed by the Electronic Systems Center for weapon guidance. ITAG was developed in the form of a kit to upgrade the guidance precision of a conventional glide bomb to a terminal accuracy (maximum error) of ten feet. Figure 8 shows the ITAG system integrated into a GBU-15 bomb. Figure 9 is a cutaway of the ITAG system. Figure 10 shows the actual ITAG pointing system.

Figure 8: ITAG/GBU-15 bomb on an F-15 aircraft

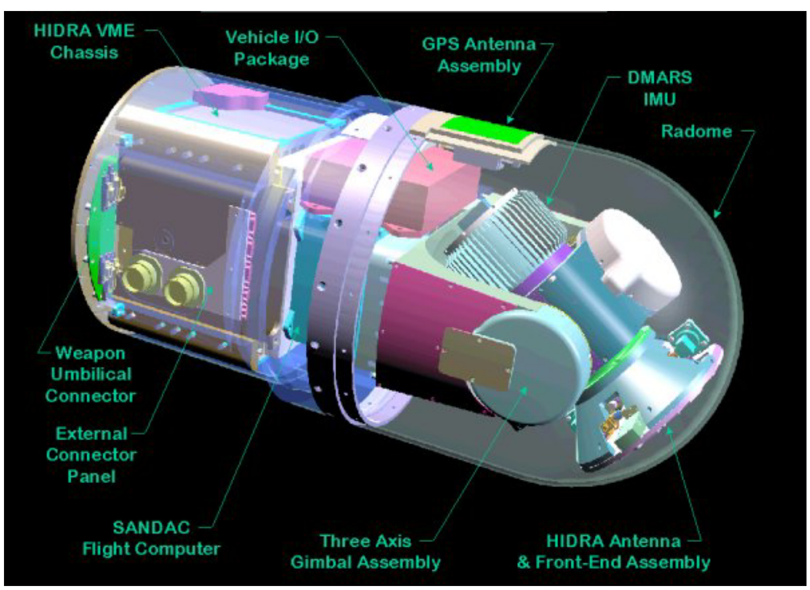

Figure 9: ITAG cutaway drawing

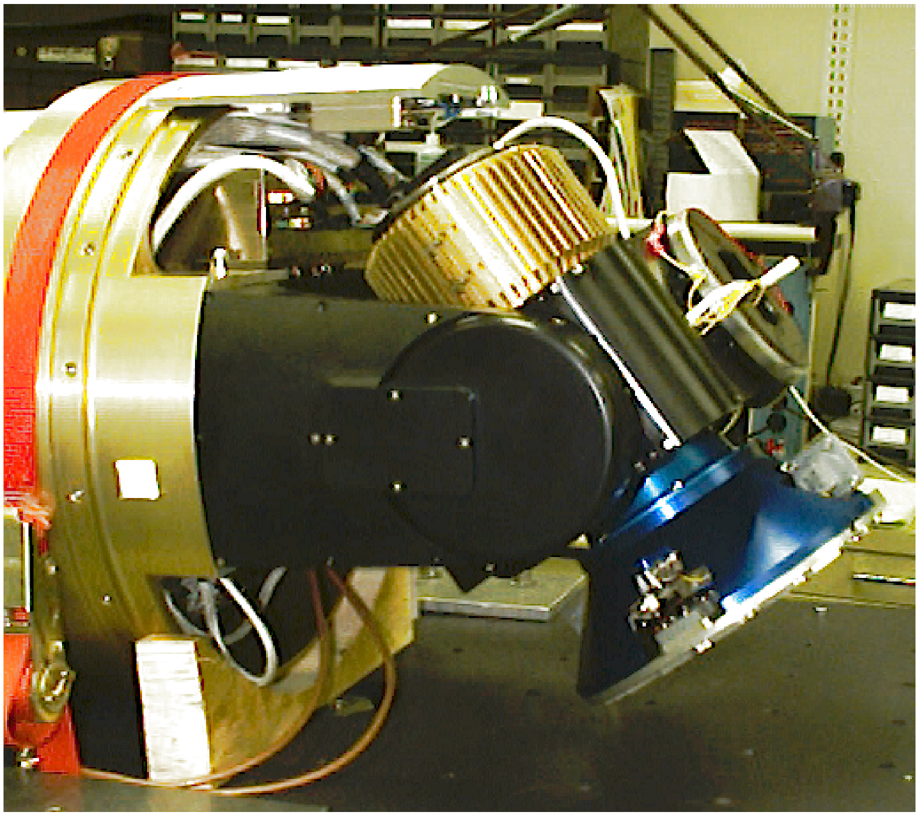

Figure 10: ITAG pointing system

The ITAG system utilized a radar altimeter for terrain elevation profile measurement and a stored elevation database for terrain elevation profile prediction. The accuracy of a trajectory produced by a tactical-grade INS was aided (improved) by correlating the measured terrain profile with the predicted profile. The resulting guidance corrections were provided to the weapon autopilot to produce the desired accuracy.

As in the Strip/TFS SAR system, the item to be pointed in the ITAG system was the radar antenna. Also similar was the use of a gimbal-mounted IMU for host vehicle navigation, antenna motion measurement, and antenna pointing and stabilization. The requirement for relatively small size and low cost led to the use of the DMARS (Digital Miniature Attitude Reference System), a tactical-grade IMU jointly developed by the Electronic Systems Center and Inertial Science, Inc.

Because of the severe operational environments associated with ITAG, advances in pointing system environmental test capability were developed during this program. ITAG was successfully flown at the White Sands Missile Range in June, 1998.

Lynx™ SAR (1997-1999, Ref. 4)

By 1997, advances in the GPS-aiding of inertial navigation systems enabled the use of small, commercially available, tactical-grade IMUs for some SAR pointing system applications. At only 1.5 lbs and 32 cubic inches, Northrop Grumman's LN200 IMU was a good selection for the Lynx™ SAR, a small system developed for General Atomics, Inc. and its family of UAVs (Unmanned Aerial Vehicles). The Lynx™ SAR antenna pointing system weighs about 65 pounds, less than 2/3 as much as the Strip/TFS SAR. The Lynx™ SAR antenna and pointing system is shown in Figure 11.

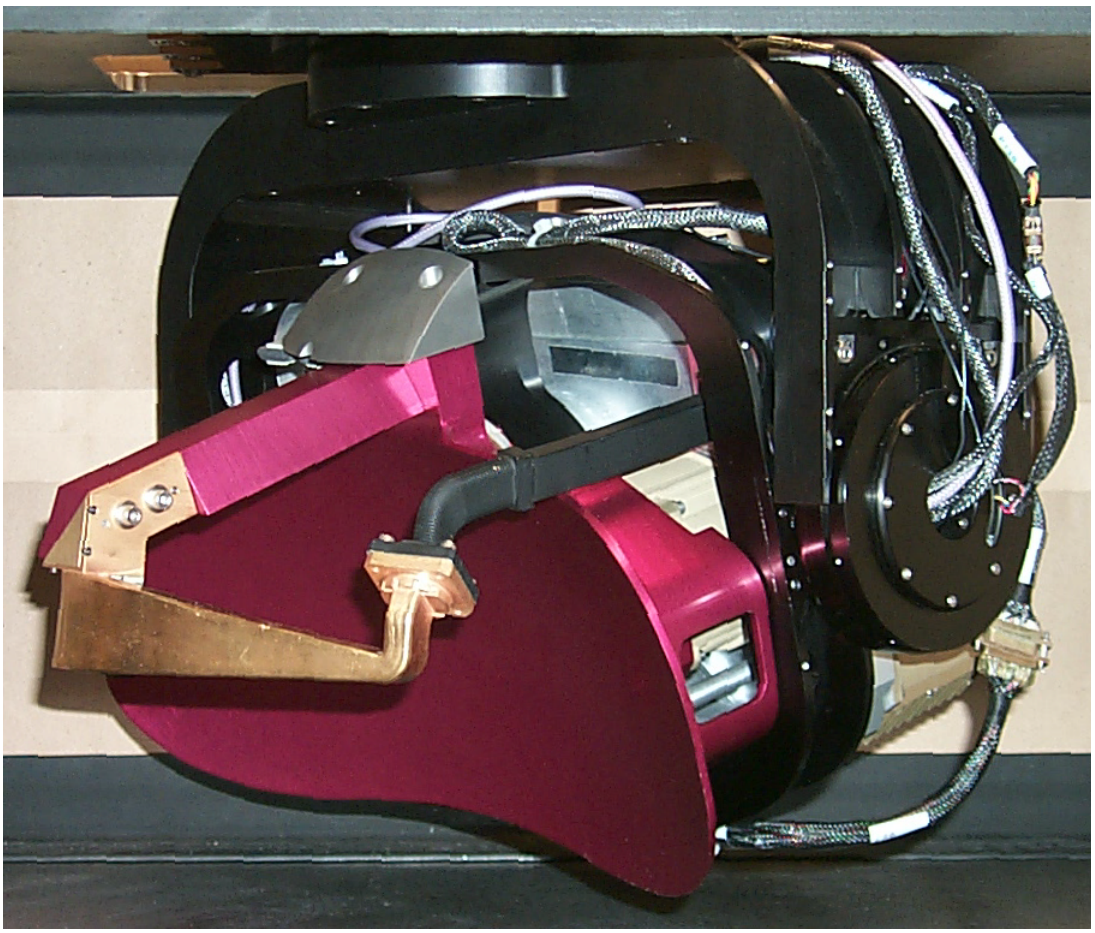

Figure 11: Lynx™ SAR antenna pointing system

In the course of development of the Lynx™ SAR, new capabilities were developed to predict the performance of IMUs in specific pointing system applications. Part of the process involves using accelerometers to develop a profile of specific host vehicle dynamics, which is then used as an input to an error model of the subject IMU. To meet motion measurement requirements, the IMU must demonstrate the ability to accurately measure any host vehicle motion above 1 Hz in frequency. (Lynx™ is a trademark of General Atomics, Inc.)

SARFS (SAR Fielded System, 2000-)

Following the successful development of the Lynx™ SAR, a similar system, SARFS was developed for a Navy aircraft. It is larger than the Lynx system, and provides a longer range capability. Approximately a dozen Lynx™ and SARFS antenna pointing systems have been produced. Several are in use on military missions. Figure 12 shows the SARFS antenna pointing system.

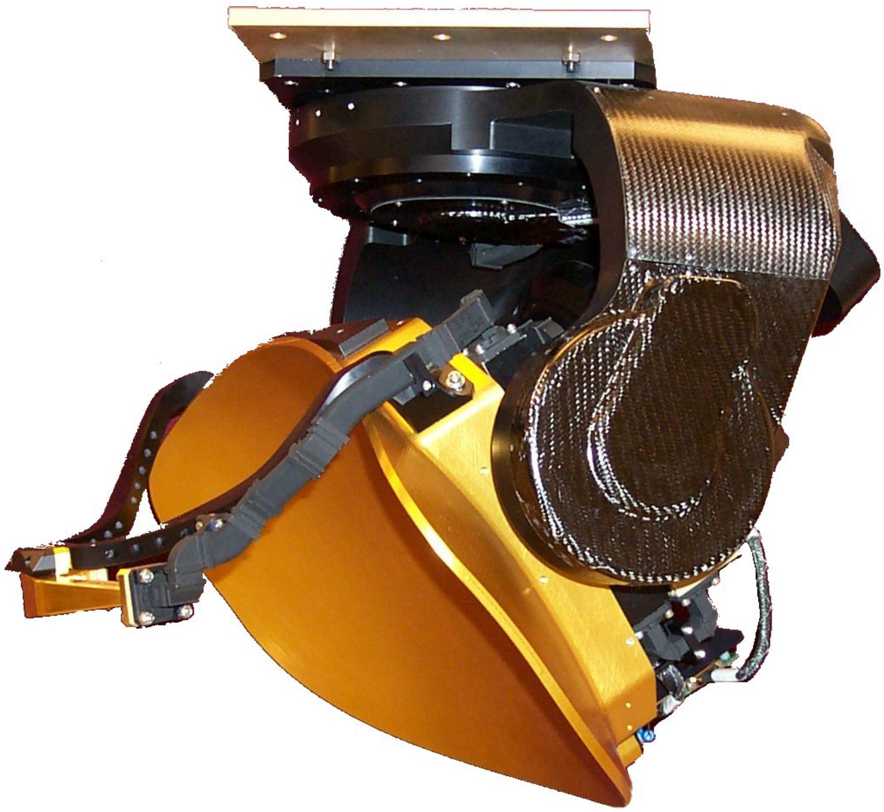

Figure 12: SARFS antenna pointing system

RTV (Rapid Terrain Visualization, 1998- present, Ref. 5)

RTV refers to a dual-antenna, interferometric SAR system with the capability to produce "3-D" images. It was developed between 1998 and 2002 in a program managed by the Joint Precision Strike Demonstration Project Office at Fort Belvoir, Virginia. The host vehicle is a Dash 7 aircraft. Figure 12 shows the RTV system.

The pointing error limit for RTV is a factor of ten more stringent than that of the Lynx and SARFS systems (0.005 degree vs. 0.05 degree). This requirement necessitates the use of a navigation-grade IMU on the antenna. Because of weight and size constraints, the High Accuracy Inertial Measurement System (HAIMS) was used for this application. HAIMS was developed jointly by Sandia and Honeywell. It is based on a military navigator which is in high volume production.

Figure 13: RTV antenna pointing system

The capability to verify pointing performance on the ground before commitment to installation in the host aircraft was developed in conjunction with this project. The verification process begins with the installation of the pointing system in a van, with the antenna pointing out a side door. A video camera with a telescope is attached to the antenna, pointing in the same direction.
At the start of the test, the antenna and video camera are pointed at a high-contrast spot on a distant building. As the van is driven along a roadway, a video record is obtained. The motion of the spot in the field of view provides a measure of pointing error. The pointing error of the RTV antenna pointing system was also measured while airborne, and found to meet the 0.005 degree requirement.

III. DESIGN

Common Design Features

The pointing systems, which have been developed by the Electronic Systems Center, have a number of common attributes. They utilize at least two gimbals to provide the two angular degrees of freedom required by any pointing system (See Figure 14 below). The center-of-gravity of the payload (the item to be pointed) is positioned as nearly as possible at the intersection of the mutually perpendicular gimbal axes. This reduces static disturbing torques due to gravity and dynamic disturbing torques associated with host vehicle accelerations.

Pointing system subcomponents are usually commercially available items. Two pairs of preloaded, angular contact, and thin cross-section ball bearings support each gimbal. For a specific application, preloads are selected based on a tradeoff between bearing friction and structural stiffness, both of which increase with preload. Wiring within the system is routed through the center of the bearing shafts. Slip rings are generally not used, because the angular freedom in most applications is limited.

Electromagnetic subcomponents include direct drive (gearless), DC gimbal motors. Because motor life is seldom an issue, these motors generally use brushes. PWM (pulse-width-modulation) motor drive electronics are employed. Gimbal angle transducers are usually of the non-contacting, AC-coupled variety, either resolvers or inductosyns.

Figure 14 is a drawing of a hypothetical system, showing the gimbal subcomponents.

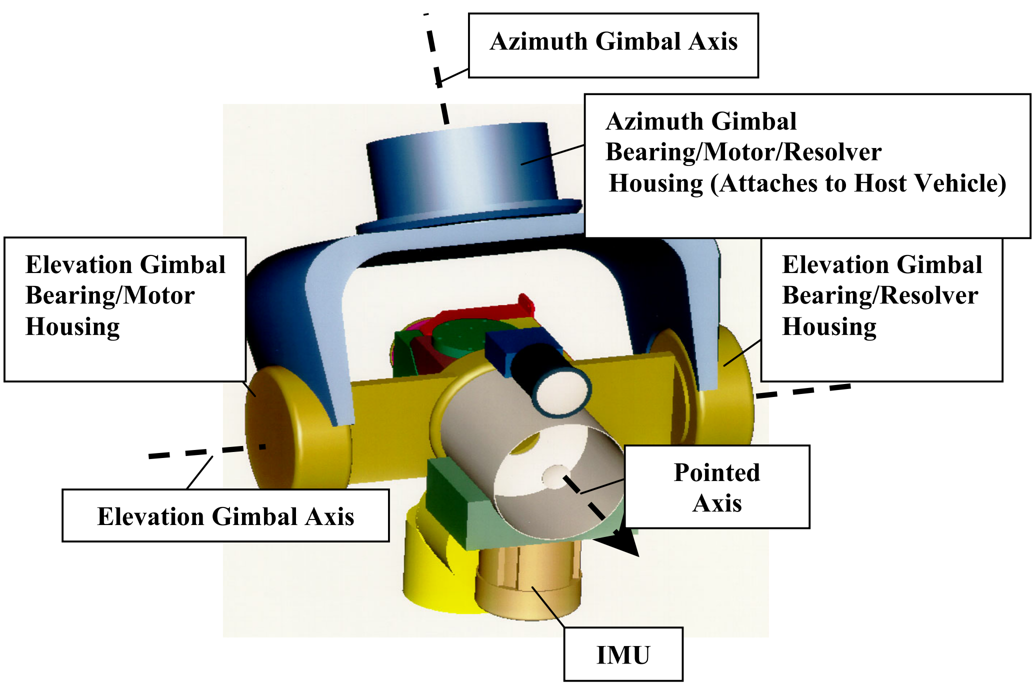

Figure 14: Typical pointing system

Inertial Measurement Units (IMUs)

The IMU is arguably the most critical element of a pointing system. IMU quality tends to increase with size and cost, so proper IMU selection is the key to an optimized design. IMUs include inertial angle sensors (generally gyroscopes) and usually, but not always, accelerometers.

The IMU may perform as many as three functions:

- Inertial angle measurement: This measurement is essential to the decoupling of the angular motion of the pointed object from the angular motion of the host vehicle. By nulling the output of the inertial angle sensors (usually gyroscopes), the pointing control system causes the payload to remain virtually motionless (in an angular sense) in inertial space. Effectively introducing a bias into the inertial angle error signal enables the payload to be pointed in any direction. The quality of the inertial angle measurement, as indicated by parameters such as angle noise, angle drift rate, and measurement update rate, directly affect the pointing error. Virtually every type of inertial angle sensor has been used at one time or another in the course of pointing system development at Sandia. These include single-axis rate gyroscopes, single-axis rate-integrating gyroscopes, two-axis (dynamically tuned) gyros, ring laser gyros, fiber optic gyros, magnetohydrodynamic angular rate sensors, and fluid-filled inertial angle sensors. It is likely that IMUs in future systems will include hemispherical resonator gyros and micro-gyros (gyros fabricated using integrated circuit manufacturing technology).

- Inertial navigation: With linear motion information from accelerometers and angular information from angle or angle rate sensors, changes in the position of the pointing system may be determined by the process known as inertial navigation. GPS information may be used to improve the accuracy of navigation. In applications where pointing at a specific spot on the earth is required, the quality of navigation factors directly into pointing accuracy. Obviously, the quality of the IMU influences navigation quality. Modern Sandia pointing systems use tactical-grade IMUs to point with errors of hundredths of a degree and navigation-grade IMUs to point with errors of milli-degrees. Under development are space-based systems that will use strategic grade IMUs to point within micro-degrees.

- Motion measurement (a.k.a. momeas): In cases where the item to be pointed is the antenna of a SAR, the motion of the antenna must be measured with high fidelity so that the radar data may be compensated for this motion. Although technically a sub-category of inertial navigation, motion measurement for SAR motion compensation (a.k.a. mocomp) is usually treated separately. As mentioned previously, in the frequency range between 1 Hz and 100 Hz, motion must be measured with an error of less than 25 microns. Fortunately, this frequency range is just within the capability of modern tactical and navigation grade IMUs operating aboard a typical host vehicle, generally an aircraft.

IV. ANALYSIS

Computer-aided analysis is an area of ever increasing importance to the pointing system development process. Through analysis and simulation, the need for production and testing of costly prototypes is reduced. Major design issues can be investigated and designs optimized before hardware is available. Most analysis has been focused on structural design and control system design.

Structural analysis is performed to assure the structural integrity of a design. Less obvious, but no less important in pointing system design, is the need to assure that structural compliance is as low as practical. Compliance leads to structural resonances that can greatly complicate designing a high-performance pointing system. Modern analysis tools enable prediction of resonant frequencies and evaluation of design changes to increase stiffness. Also, the transfer functions between gimbal motor torque and angular motion of the inertial sensors can be predicted. This information, which includes the effects of compliance, variable inertia, and temperature changes, is all used in the design of the pointing control system. Figure 15 is a color-coded, computer generated drawing which shows stress profiles in a pointing system gimbal. Figure 16 illustrates a structural vibration mode of a gimbal yoke.

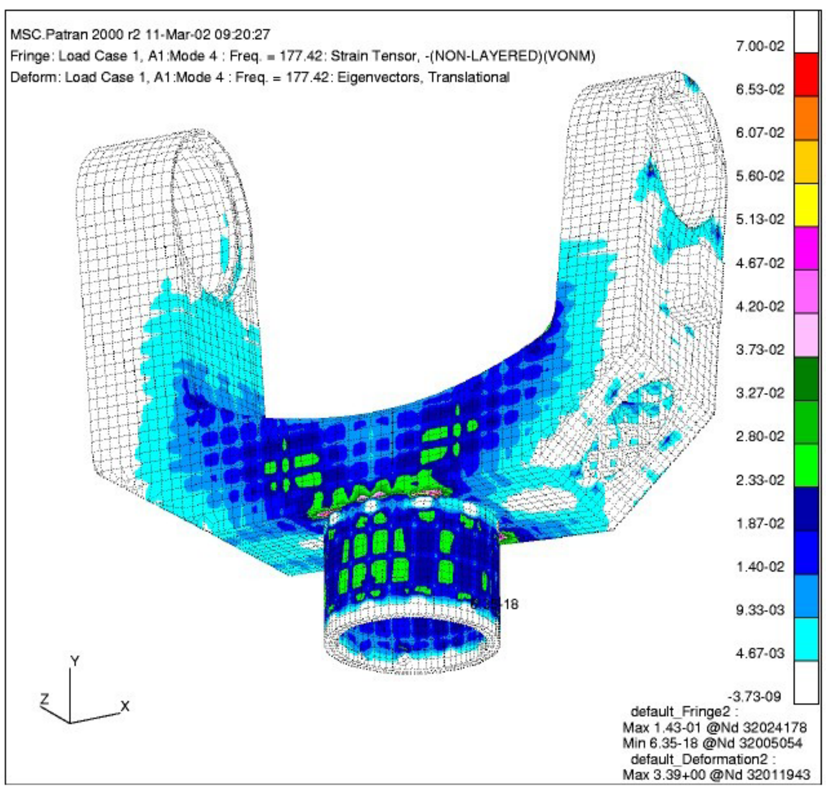

Figure 15: Stress contours in a gimbal structure

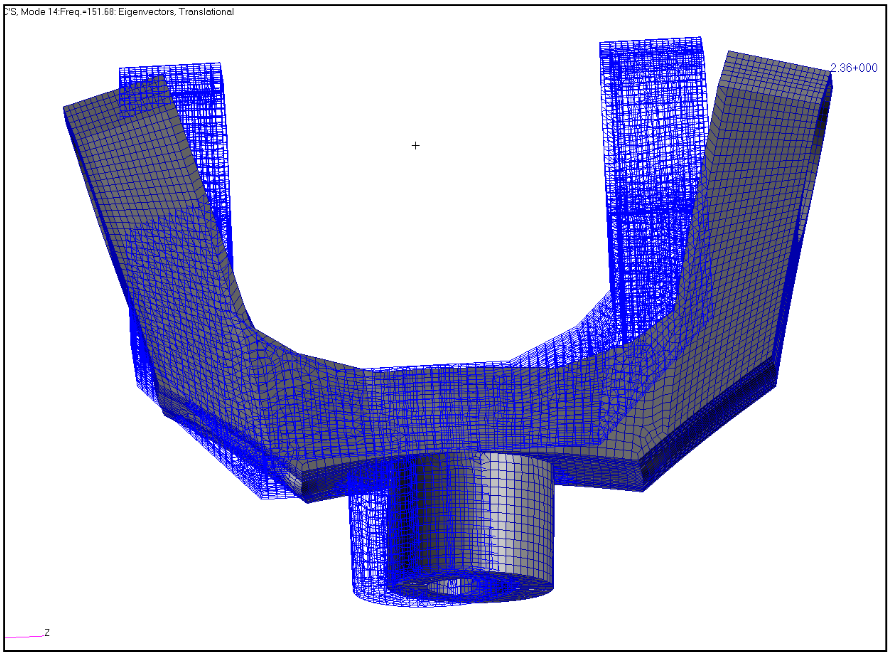

Figure 16: Vibration mode animation

As previously mentioned, pointing control system design is an area of extensive analysis effort. Well in advance of system fabrication, detailed simulations are performed to predict the influence of a myriad of system imperfections such as structural resonance, variable inertia, and interaxis coupling. The simulations are essential to the selection of subcomponents such as resolvers and motors. Acceptable bounds for key IMU parameters such as gyro noise, frequency response, data resolution, and update rate are determined with the aid of simulation. At the present time, the control system analysis, simulation, and design software tools in use by the Electronic Systems Center are predominantly products of MathWorks, Inc. including Matlab™, Simulink™, and the various Toolboxes. Reference 6 documents the control system development process for a specific application.

V. TESTING

Sandia possesses extensive environmental test capabilities. Most of these have, at one time or another, been used to support pointing system development efforts. Testing environments include vibration, shock, acceleration, temperature, humidity, and vacuum. In addition to these general-purpose facilities, specialized pointing system test equipment has been developed or purchased that include "Scorsby" tables for generating angular base motion, vans for ground testing, and a Twin Otter (DHC-6) aircraft for flight testing. Figures 17 to 20 illustrate some of the capabilities that have been used in development testing of Sandia's pointing systems.

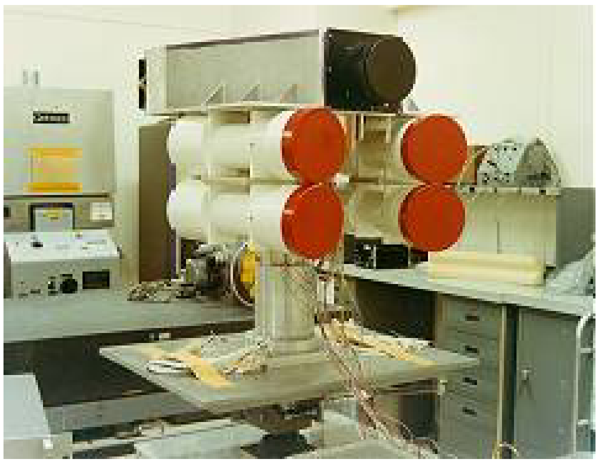

Figure 17: Optical monitoring system on a Scorsby table

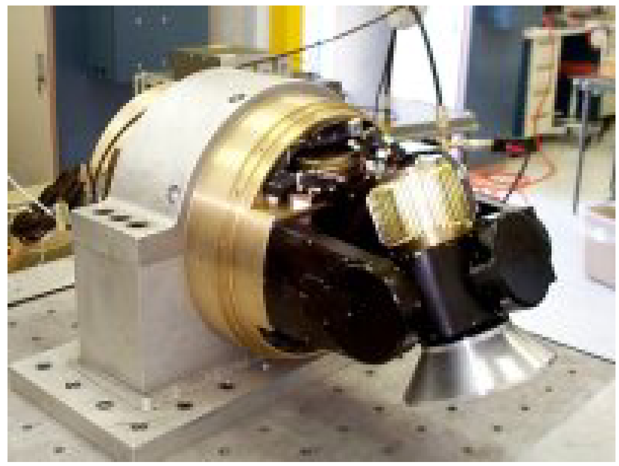

Figure 18: ITAG system on a vibration machine

Figure 19: DHC-6 test aircraft

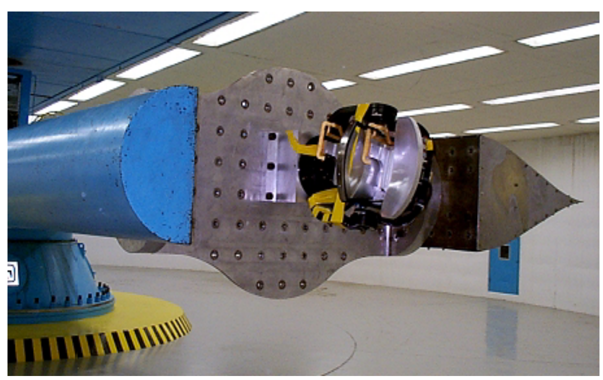

Figure 20: SAR system on a 29-foot underground centrifuge

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VI. PRESENT DEVELOPMENT EFFORTS

Space Telescope , 2000-)

A solid model of the Space Telescope is shown in Figure 21. The pointing error requirement is about one hundredth that of the most demanding SAR application; fortunately, the dynamics of the host vehicle are less than most SAR applications. Nevertheless, meeting the pointing accuracy requirement will require the use of a number of new design features not used on SAR systems. These include:

- Zero-cogging gimbal motors to provide extremely smooth control torque profiles
- Very low drift, low noise gyroscopes for high accuracy pointing control
- Low noise, high bandwidth magnetohydrodynamic inertial angular rate sensors to enable enhanced cancellation of gimbal bearing friction effects (Ref. 6)
- High accuracy gimbal angle transducers (Inductosyns)
- Advanced structural materials to reduce system weight while increasing stiffness
- Strut isolation system to mitigate vibration and distortion from the host vehicle
- FPGAs (Field Programmable Gate Arrays) for high-speed filtering of angle sensor signals
- Structural temperature control system to reduce tolerance variation
- Detailed structural modeling for design optimization
- Bearing friction modeling. Development of a bearing friction test capability.
- Extremely precise gimbal bearing (highest precision category) with space-qualified lubrication

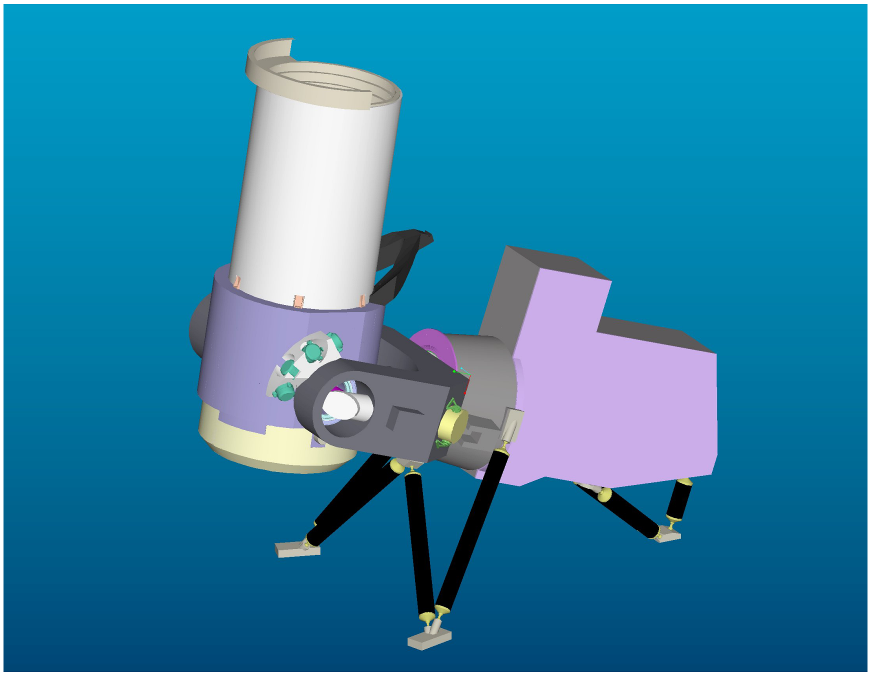

Figure 21: Space Telescope

Joint Tactical Mapper (JTM) (2002-)

This project includes the development of an RTV-like (interferometric) SAR for use aboard a UAV such as the Global Hawk or the Predator-B. The JTM antenna pointing system, shown in Figure 22, will be somewhat larger than that of RTV, but there will be many common design elements including possibly the IMU (HAIMS), control electronics, and gimbal subassemblies (motors, bearings, etc.).

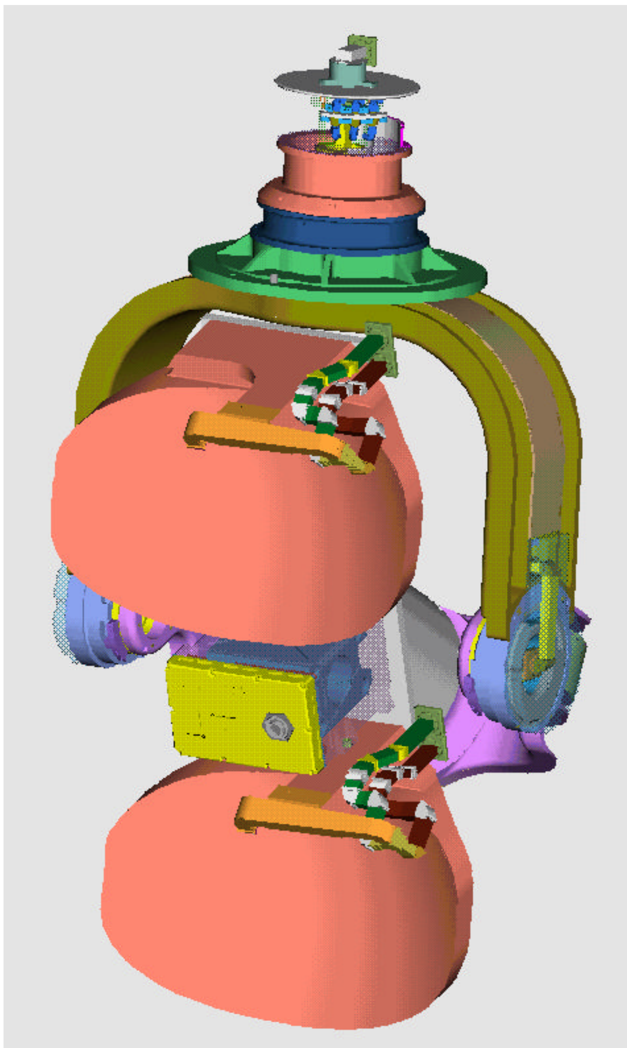

Figure 22: Joint Tactical Mapper antenna pointing system

Ares (2002-)

Ares is an optical surveillance system for stationary ground-based use, either at a fixed site, such as a building, or aboard a land vehicle. Figure 23 shows the Ares system.

Figure 23: Ares optical surveillance system

Considerably simpler than most other pointing systems mentioned in this report, Ares will use only gimbal angle transducers (resolvers) and inertial angular rate sensors to provide the measurements needed to control pointing. To enable development in four months at a cost of only about $200K, Ares makes maximum use of existing designs.

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VII. CONCEPTS FOR FUTURE SYSTEMS

The conceptual design of future pointing systems is underway at Sandia. In the near future, considerable effort is planned to reduce the size, weight, and expense of SAR antenna pointing systems. This would enable the use of SARs in smaller host vehicles such as small UAVs and precision-guided munitions. Most of the necessary improvements will require revolutionary rather than evolutionary design changes. Major areas of design emphasis are discussed individually below.

- Mechanical Design:

The modern Sandia SAR antenna pointing systems share many common design features, as discussed in the Design section of this report. One might conclude that the design for smaller systems could be obtained by simply using smaller versions of the subcomponents. Up to a point this is true. Below is an example of a conceptual design for a small, lightweight gimbal assembly. It is about a foot in diameter, and occupies about one-quarter of the volume of the Lynx SAR. Although it uses conventional subcomponents, it is nearing the size limit below which the use of conventional design approaches is not feasible. For example, the direct drive, DC motors of the type used in present systems become unacceptably inefficient in the small sizes needed for a very small SAR (i.e., Micro-SAR). Similarly, gimbal angle transducers (resolvers) of suitable size lack the necessary accuracy. In summary, present designs are not scalable down to much smaller sizes. Therefore, a completely new design concept is needed, and studies directed at defining such a concept are now underway. Figure 24 is a conceptual model for a very small SAR antenna pointing system.

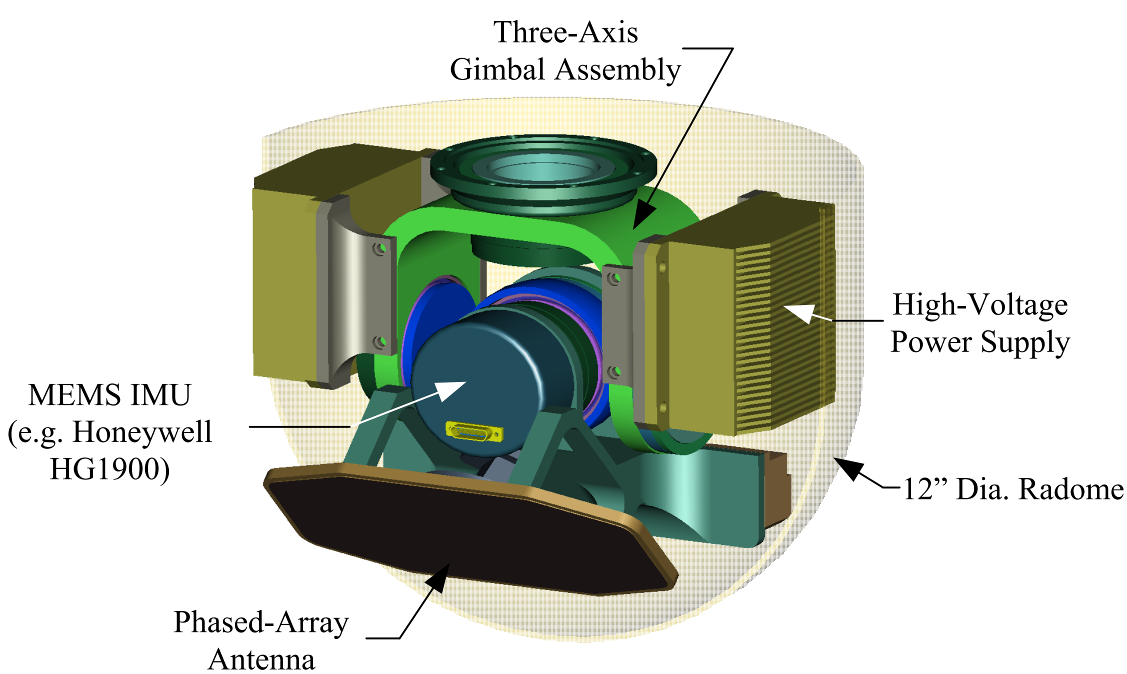

Fig. 24: Concept for a small, lightweight gimbal assembly

-IMU Design:

A substantial reduction in the size of SAR antenna pointing systems will necessitate the use of MEMS IMUs as shown in Figure 24. However, current MEMS IMUs do not have the accuracy to serve as a direct replacement for HAIMS and the LN200 that are used in existing Sandia SAR pointing systems. Figure 24 below illustrates this situation. The present SAR motion compensation requirement is that measurement error be less than 25 microns for vehicle motion at frequencies of greater than 1 Hz. Below 1 Hz, it is assumed that a process known as Autofocus will remove the effects of inertial measurement error. For vehicles of interest, such as the Predator UAV, motion ranges from 25 millimeters at 1 Hz, to 25 microns at 100Hz. Measurement errors in this frequency range arise from a number of sources. At the lower frequencies, errors in the GPS-aided inertial navigation process are most important. At all other frequencies, IMU accelerometer performance is a limiting factor. For example, at large amplitudes, accelerometer scale factor is dominant. At low amplitudes, accelerometer noise becomes most important. At high frequencies, accelerometer bandwidth limits performance. With some simplification, a rectangular area in the amplitude-frequency plane can represent the measurement capability of an IMU. In Figure 25, the area measured (with an error of less than 25 microns) by an LN200 IMU is represented by the blue rectangle. It can be seen to cover the range of motion of the vehicle that is above 25 microns and above 1 Hz (the red area), as required. However, the MEMS IMU (the gray rectangle) does not. Several approaches to addressing this issue are discussed below.

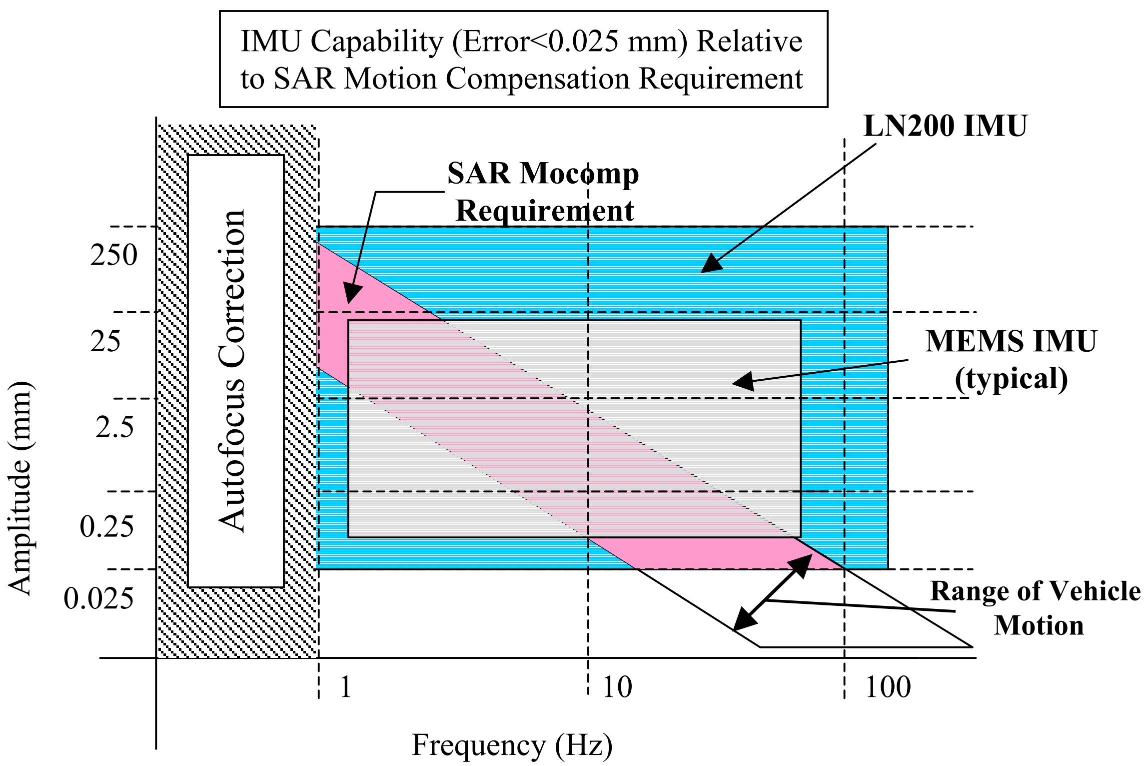

Figure 25: IMU measurement capability relative to SAR mocomp requirement

- Increase the capability of MEMS IMUs:
Obviously, this improvement alone could resolve the issue. There has been substantial progress in the quality of MEMS IMUs in the last few years. Much of the development effort has been directed at specialty applications such as the cannon-launched projectiles. Recently Honeywell, Inc., a leading supplier of IMUs, has announced the HG1900, a general-purpose IMU to be available in early 2003. It will be somewhat smaller than the LN200 (320 cc vs. 500 cc) and use much less power (3 watts vs. 10 watts). Later versions of the HG1900 will have a volume of only 128 cc. However, the HG1900 will be less capable than the LN200, especially in the area of gyro drift rate stability (30 degrees/hr vs. 1 degree/hr). Therefore, it seems unlikely that the HG1900 will meet our SAR mocomp requirements as currently specified.

- Refine SAR mocomp requirements:
It is certain that our mocomp requirements are conservative. The requirement for measurement error of less than 25 microns is based on a worst-case scenario of a pure sinusoidal error. Errors of considerably larger amplitude are surely acceptable in many circumstances. For example, the plot of Figure 26 is a Doppler radar response in which the requirement is that sidelobes must be below 40 DB. As illustrated in the plot, a sinusoidal position error of 25 microns results in peak sidelobes of almost 40 DB, whereas random error of 200 microns is required to obtain this level. Therefore, it seems reasonable to loosen the allowable error requirement to at least 200 microns, at least if the errors are random, as most of them are. Our experience with MEMS IMUs indicates that some can meet this requirement.

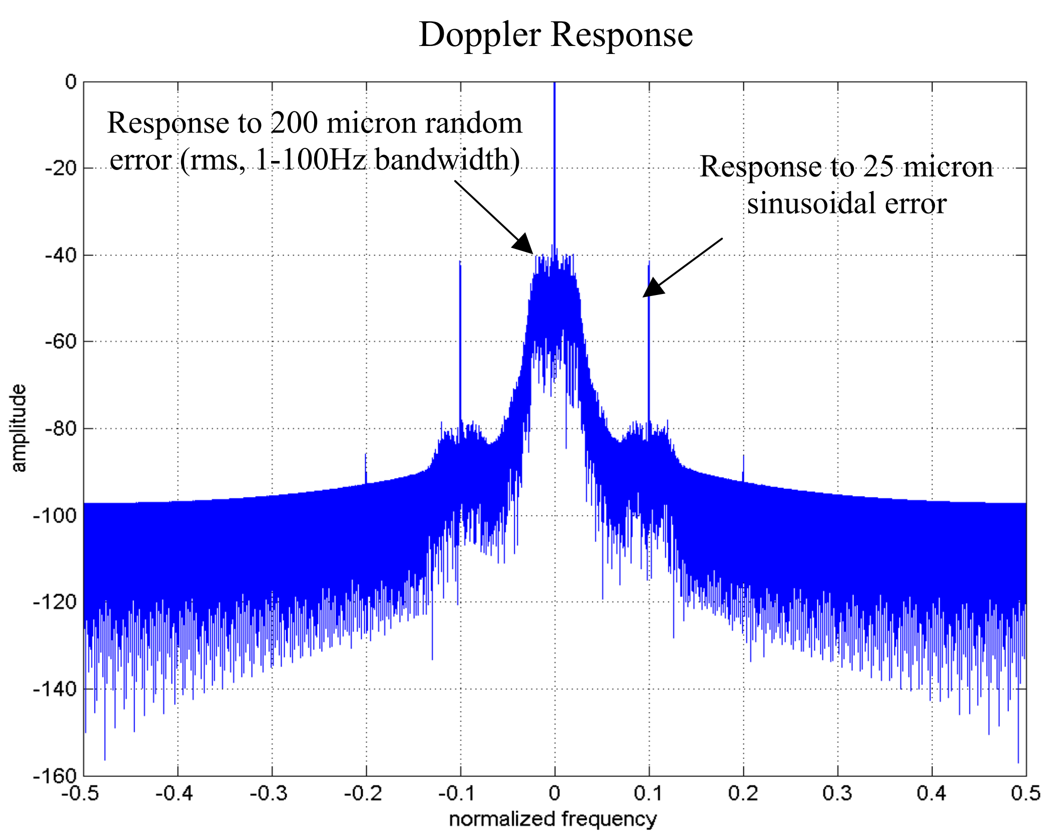

Figure 26: Radar Doppler response to motion measurement errors

- Increase the frequency range of Autofocus

Our present RF Autofocus bandwidth of 1 Hz (ballpark), by which motion measurement errors below 1 Hz are effectively eliminated, is determined by our image formation approach. By going to a different method of image formation, the frequency range of Autofocus could be increased to 10 Hz or more. Changing the image formation technique would require numerous important changes in the complete SAR system. Various tradeoffs would have to be studied before this step were undertaken. However, it's certain that increasing the frequency range of Autofocus would be of tremendous benefit to motion measurement, because the amplitude of vehicle motion is roughly inversely proportional to frequency squared. Therefore, most of the motion to be measured, and associated error, is concentrated at the lower frequencies, where Autofocus is effective. Figure 26 below illustrates that increasing the frequency range of Autofocus to 10 Hz coupled with increasing allowable (random) error to 200 microns would enable our hypothetical MEMS IMU to meet mocomp requirements.

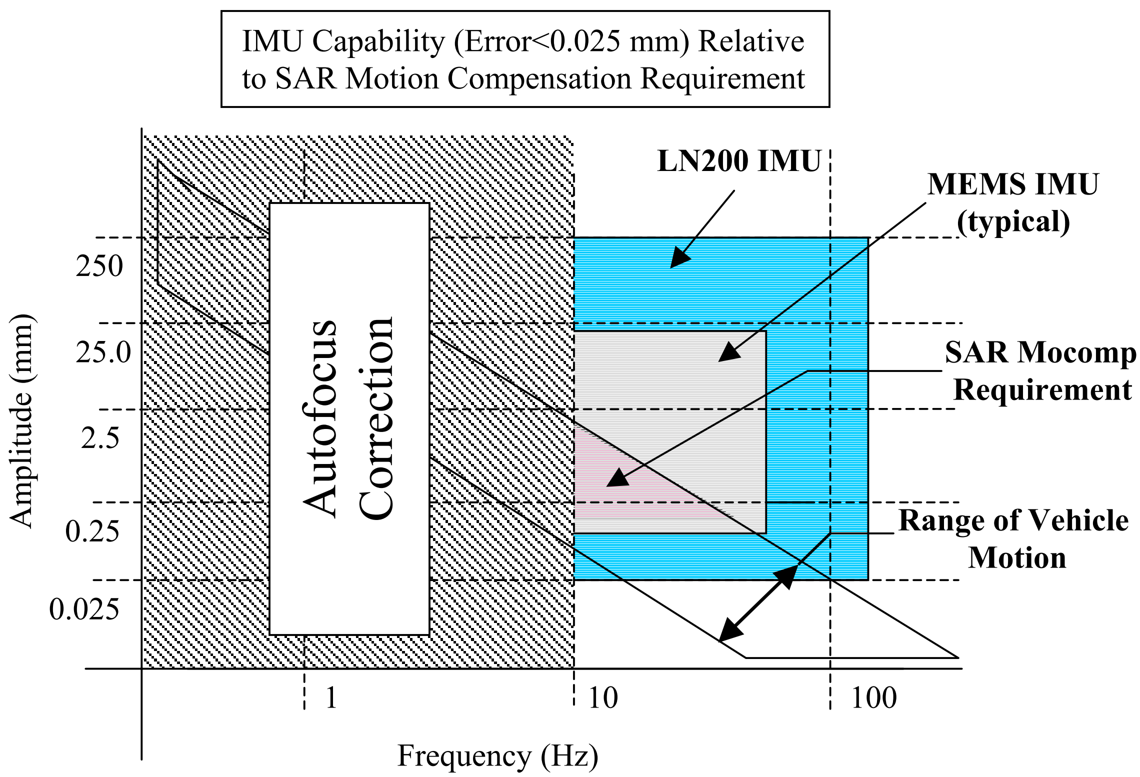

Figure 27: IMU measurement capability relative to SAR mocomp requirement (Autofocus bandwidth extended from 1 Hz to 10 Hz, random noise limit increased from 25 microns to 250 microns)

- Utilize vibration isolation

The gimbal assembly could be supported by a vibration isolation system. This would reduce the motion at frequencies above the Autofocus bandwidth. The bandwidth required of accelerometers, along with accelerometer noise, could be correspondingly reduced. To investigate the possible benefit of isolation, data from a Predator UAV flight was used as input to a simulated (and idealized) isolation system. The results indicate that use of a 10 Hz isolation system could virtually eliminate motion above 30 Hz. Of course, isolation systems bring complications, such as increased angular motion and the requirement for sway space.

While Autofocus improvement, mocomp specification refinement, and vibration isolation have been mentioned in the context of reducing IMU mocomp demands, it is possible that for some applications these modifications could be used to eliminate the need for mocomp entirely. Of course, IMUs would still be needed for antenna pointing and host vehicle navigation.

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