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Title: FORTÉ HARDWARE-IN-LOOP SIMULATION

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FORTÉ Hardware-in-Loop Simulation

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Abstract. Fast On-Orbit Recording of Transient Events (FORTÉ) is a small, low Earth orbit satellite scheduled for launch in August 1997. FORTÉ is a momentum-biased, gravity-gradient stabilized spacecraft. This paper describes the use of a hardware-in-loop simulator, developed by Ithaco Inc. and Los Alamos National Laboratory, in performing FORTÉ mission simulations. Scenarios studied include separation, acquisition on orbit, control system parameter sensitivity studies, sensor noise simulations, antenna deployment and momentum desaturation. Use of the simulator to refine control algorithms and sequences is also described.

Introduction

Fast On-Orbit Recording of Transient Events (FORTÉ) is a small low Earth orbit satellite scheduled for launch in August 1997. The satellite, shown in Figure 1, will be inserted into a 800 km circular orbit with an inclination of 68°. FORTÉ is a momentum-biased, gravity-gradient stabilized spacecraft. Active stabilization is achieved with a low-power, low-mass attitude control and determination system (ACDS). The ACDS hardware, control algorithms, and simulator were produced by Ithaco Inc..

FORTÉ Satellite

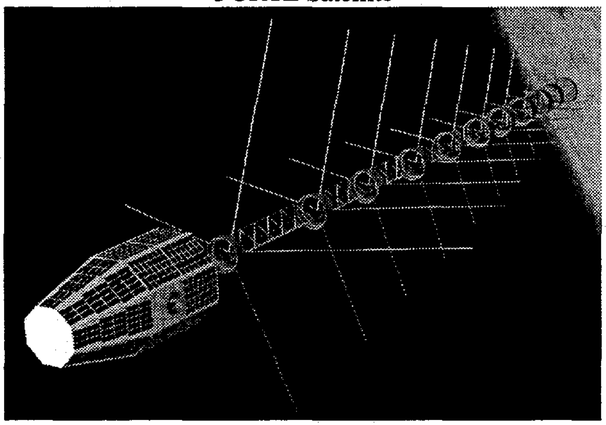

Figure 1

The primary sensor and actuator of the FORTÉ flight ACDS is an Ithaco SCANWHEEL®[1], generically referred to as the scanwheel. The sensor portion of the scanwheel detects the CO_2 layer of the Earth's atmosphere and is used for roll and pitch attitude information. The actuator portion of the scanwheel is a momentum wheel that is mounted on the pitch axis.

Three 2-axis magnetometers are mounted parallel to the spacecraft axes such that any two magnetometers can provide complete three-axis geomagnetic field measurements. A set of dual wound Ithaco Torqrods™, generically referred to as torqrods, are mounted parallel to the spacecraft x, y, and z axes. Magnetometer and scanwheel data are used to calculate a set of correction dipoles. The correction dipoles control the magnetic field generated by the torqrods. Interaction between the generated magnetic field and the local magnetic field produce a control torque on the spacecraft.

The PC-based simulation accurately simulates the dynamic performance of the satellite in a space environment. The primary purpose of the simulation is a test platform for the attitude control algorithms. Disturbance torques modeled include gravity gradient, aerodynamic drag, magnetic residual dipole and solar radiation pressure. Spacecraft parameters modeled include moments of inertia, centers of gravity and pressure, and surface area. On-board actuators and sensors are also modeled. A simple circular orbit is used along with a spherical harmonic magnetic field model.

As delivered, the PC simulation was designed to support both open and closed loop modes. In open-loop mode, all control laws are implemented inside of the simulation. This configuration works well for running many what-if simulations. However there remains a need to exercise the flight algorithms implemented in the spacecraft processor. This configuration, referred to as closed-loop, links the simulator with the flight ACDS actuators, data acquisition card (DAC) and the controls software residing in the spacecraft computer, allowing the entire system to be tested as a unit.

The Los Alamos FORTÉ team modified the original simulation in order to move the entire simulation onto an IBM PC. This modification necessitated modifying the original hardware modeling. Other aspects of the simulation have also evolved in the testing process. More accurate orbit propagation and magnetic field modeling are now used. A primary antenna deployment model has also been added.

Control Modes

B-Dot Mode

B-dot mode is capable of autonomously orienting the satellite with the primary antenna stowed given an arbitrary set of initial conditions. B-dot mode will be used to acquire a specific (minimal roll and yaw, pitching 360° per orbit) attitude following separation from the launch vehicle. In this mode magnetometers and torqrods are used together to minimize body rates. The scanwheel is used to produce momentum bias which provides a preferred inertial orientation, the pitch axis aligned with orbit normal, for the spacecraft. In acquired B-dot with the primary antenna not deployed the spacecraft pitches over once per orbit in the orbit frame of reference. Roll and yaw errors are less than 5°.

Normal Mode

Normal mode is the nominal ACDS control mode. The goal of normal mode is to maintain a nadir-pointing attitude with the pitch axis aligned with orbit normal. In addition to providing momentum bias the wheel is used to control pitch. The y-axis torqrod is used to control roll. Yaw is not sensed or controlled directly, but is quarter-orbit coupled to roll through the momentum bias. The x and z-axis torqrods are used to remove excess momentum from the wheel as it accumulates due to external disturbances, thus maintaining the wheel speed near its set speed. The scanwheel sensor supplies roll and pitch data as long as the Earth is in the field of view (EFOV).

TOMS-EP and Wakeshield have observed moderate duration (~2 minutes) data upsets distorting pitch and roll on the order of 10-20 degrees. The FORTÉ optical system has not been upgraded to correct this problem so similar upsets are expected. A set of thresholds was added to the FORTÉ ACDS spacecraft code in an effort to minimize ACDS response to suspect roll and pitch information when in normal mode. If the attitude of the spacecraft exceeds the thresholds, which should not happen under nominal conditions, then the torqrods are disabled. A proportional wheel speed controller is used to maintain wheel speed in order to minimize short term pitch errors. The spacecraft continues disabling the torqrods until either the attitude errors decrease and thresholds are again achieved, at which point normal mode control resumes, or until a control mode change is commanded from the ground. Thresholds are nominally set to ± 10° roll and pitch.

Manual Mode

Manual mode is a test mode that can be used in special situations. Actuator commands are uplinked from the ground station. Scanwheel speed is via a proportional controller. Commands can either be executed immediately following the uplink or a time delay can be used. Manual mode will be used to execute ACDS hardware tests. Manual mode may be used at anytime to "safe" the spacecraft.

Simulation Features

Hardware Interface

The satellite ACDS hardware configuration is shown in Figure 2. Magnetometer and scanwheel sensor information is read by the data acquisition card (DAC). Using inputs from the DAC, the spacecraft computer applies the control algorithms to generate the appropriate actuator control commands. Actuator control commands consist of a wheel speed control voltage and 2 bits per torqrod on each axis. The control values are written to the DAC where they are sent to the flight hardware.

Hardware Configuration

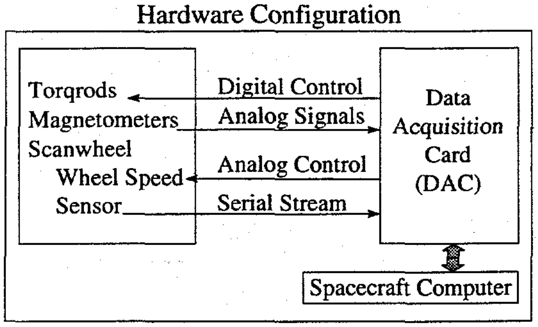

Figure 2

Testing the flight ACDS systems and control algorithms is very limited without the simulation. The scanwheel was supplied with a test hood which simulates the infrared signature of the Earth at a fixed attitude. In another test, the torque rods are driven for extended periods of time while the magnetometers are read. While such tests indicate hardware aliveness, they fail to test the ACDS control algorithms. To accurately test the algorithms the scanwheel and magnetometer data need to correspond to a valid spacecraft attitude and orbital location. Simulated sensor data must also change corresponding to the spacecraft's dynamic reaction to the torqrods and momentum wheel. The hardware-in-loop-simulation was designed to fulfill these needs.

For testing purposes the hardware-in-loop simulation replaces the flight hardware box on the left in Figure 2 and allows testing of the ACDS routines by simulating the space environment. Sensor information is simulated and sent to the spacecraft computer via the DAC. The DAC then sends actuator commands from the spacecraft computer to the simulation where the spacecraft response is simulated.

Figure 3 is a diagram of the closed loop simulation setup. The simulation is run on a 120 MHz Pentium PC containing three hardware interface boards. A National Instruments PC-DIO-96 is used for the torqrod and 88-bit scanwheel serial stream. A Cyber Research DAS 1601 board is used to perform an analog-to-digital conversion on the wheel speed control voltage signal. The digital-to-analog conversion for the magnetometer signals is done with a Analogic DAC812 hardware interface board.

Closed-Loop Simulation Setup

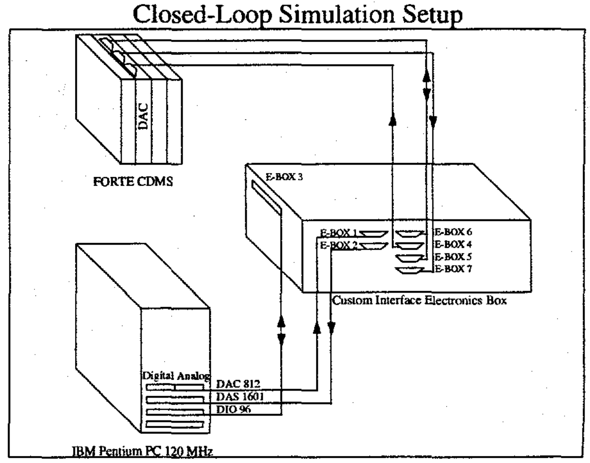

Figure 3

All signals that run between the DAC and the PC are buffered and conditioned in a single custom interface electronics box. The interface box consists of a power converter and two wire-wrap boards, one digital and one analog. The analog wheel speed control voltage is sent through a simple unity gain buffer on the analog board before going on to the PC. The analog board is also used to add 2.5 volts to each of the magnetometer signals before entering the DAC. The torqrod control signals are sent through non-inverting digital buffers on the digital board. The 88-bit scanwheel sensor information is sent to the digital board as 11 multiplexed bytes which are then shift serially and sent to the DAC in a serial stream exactly replicating the data stream from the flight scanwheel.

The following sections provide an overview of the simulation and its capabilities. See reference [2] for additional details on the original simulation.

Simulation Inputs

Many simulation parameters can be varied without code recompilation through the use of input files. The following parameters are input into the simulation through the namelist input file:

- simulation integration rate
- simulation end time
- initial attitude
- initial rates
- satellite mass properties
- actuator initial states
- actuator saturation values
- open-loop control loop gains
- open-loop spacecraft computer states
- disturbance torque parameters
- sensor noise
- sensor quantization
- output file name

A close_hw_loop switch, antenna_deployed switch and epoch_offset value have been added. Variables to be saved to the output file are also selected from the namelist file.

The orbit propagation routine is initialized through the use of an input file containing a NORAD two-line element set. The element set describes the satellite position and heading at the epoch. The element set data is read into the simulation at startup time.

Sensor Models

Scanwheel Sensor

Roll and pitch attitude information is obtained via the Earth horizon sensor portion of the scanwheel. A complex model for the sensor portion of the scanwheel was designed by Ithaco. The model is capable of discerning two anomalous conditions where the scan cone completely misses the Earth or the scan cone never leaves the Earth (occurs when the cone is pointed too far down into the Earth). Gaussian noise (mean and standard deviation defined in the namelist file) is also added to the simulated sensor information.

The output of the flight scanwheel sensor is an 88-bit serial stream containing information regarding where the sensor detected the earth. When the simulation is run in closed loop mode the sensor leading edge (LE), trailing edge (TE) and number of scans values are generated by the simulation. The values are written by the PC to the custom hardware interface box where an 88-bit serial stream is generated. Handshaking between the DAC and serial stream output from the custom hardware is an exact replica of the flight scanwheel.

A second source of scanwheel sensor noise, denoted upset noise, has been built into the simulation by Los Alamos. The source of the upsets is a third input file. The upset noise is added to the raw LE and TE. All upset times are resolved during processing.

Magnetometers

In closed-loop mode the magnetometer data is processed so as to exactly replicate the characteristics of the flight hardware. Noise levels, offsets and gains are set individually for each primary and redundant magnetometer so as to match test data. The magnetometer signals are then quantized, digital to analog converted, and passed to the custom hardware interface box.

Disturbance Models

The atmospheric density, magnetic residual dipole, gravity gradient and solar radiation pressure models are unchanged from the original Ithaco simulation code.

An additional model was developed at Los Alamos National Laboratory to simulate FORTÉ primary antenna deployment. The FORTÉ primary antenna is made up of 11 rings and 10 sets of four antenna elements that are mounted on the antenna mast. As the antenna is deploying each ring locks into place followed by the release of its antenna elements. These actions produce disturbance torques on the yaw axis. Torque disturbances can be described by the following three equations.[3]

$$\tau_1 = A_1 \cdot e^{-at} \qquad (eqn.1)$$

$$\tau_2 = A_2 \cdot e^{-c\omega_{21}t} \cdot \sin(\omega_{21}t) \qquad (eqn.2)$$

$$\tau_3 = A_3 \cdot e^{-c\omega_{31}t} \cdot \sin(\omega_{31}t) \qquad (eqn.3)$$

The first torque disturbance, called "kick-off", is due to the initial movement of the antenna assembly at the start of deployment. "Kick-off" is described by τ_1. Approximately 44 seconds after "kick-off" the first ring locks into place. τ_2 describes the torque introduced due to each ring lock-in. One to two seconds following the ring lock-in the associated set of antenna elements is released, and unwind from the mast. The resultant torque disturbance is described by τ_3. Nine more sets of ring lock and element deploy torques are generated over the remaining 400 seconds of deployment. The same equations with different magnitudes, A, and frequencies, ω, are used to model these disturbances.

Actuator Models

Torqrods

In closed-loop mode the torqrod control signals are generated in the DAC, buffered in the custom hardware interface box and read by the simulation via the PC-DIO-96 card. Each torqrod is represented by a direction bit and on/off bit. The digital signals are integrated by the PC at a rate equal to the simulation integration rate, specified by fsim in the namelist file, nominally 1000 Hz. The effect of each torqrod is calculated then applied to the spacecraft dynamics.

Momentum Wheel

The actuator portion of the scanwheel is modeled as a momentum wheel. In closed loop mode, as with the flight scanwheel, the momentum wheel speed is controlled by an analog voltage signal generated in the DAC. The analog signal is buffered in the custom interface hardware and input into the simulation via the DAS 1601 card.

Environmental Models

An Earth's magnetic field model is used to simulate magnetometer readings and compute disturbance torques in the simulation. The 1995 International Geomagnetic Reference Field (IGRF) model has replaced the spherical harmonic model used in the original simulation from Ithaco. The IGRF model represents the main (core) field without external sources. The IGRF model coefficients are based on all available data sources including geomagnetic measurements from observatories, ships, aircraft and satellites.

An accurate orbit propagation routine has replaced the simple circular orbit used in the original simulation. A NORAD two-line element set is used for the satellite ephemeris in the simulation. An offset time from epoch can also be entered into the simulation from the namelist file. Simulation initial year, month, day and time are all derived from the ephemeris epoch and offset time. The element set data is input into a NORAD standard SGP4 orbit propagation routine. The routine calculates satellite orbital position in earth-centered-inertial coordinates as a function of time.

Simulation Outputs

A graphical display is key to visualizing the attitude of the spacecraft and monitoring sensor and actuator information in real time. Figure 4 is a sample screen display. A three-dimensional animation of the spacecraft orientation is displayed on the screen in real time during simulation runs. The corresponding three-dimensional wire drawing of the spacecraft is contained in a configuration file used by the simulation. In the simulation the spacecraft wire drawing is rotated by a orbit-body direction cosine matrix before being drawn on the screen at a one second update rate. The spacecraft is drawn with the antenna either stowed or deployed.

Real Time Display

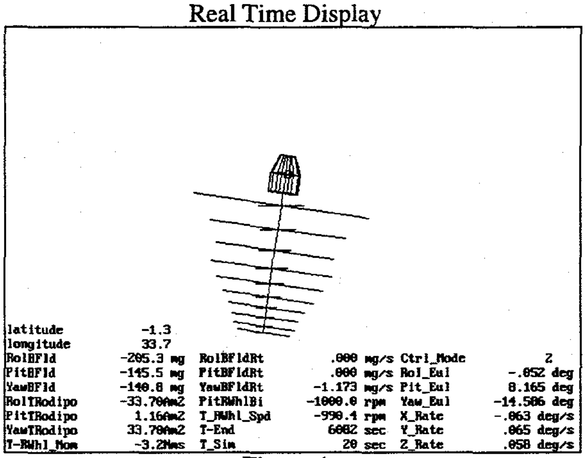

Figure 4

Several variables are also displayed in real time on the screen. These include:

- body-frame magnetic field components and rates
- torqrod dipole moments
- scanwheel momentum
- scanwheel speed
- scanwheel set speed (only valid for open-loop)
- current simulation run time
- simulation end time
- control mode (only valid for open-loop)
- Euler angles and rates

Values are updated at a 1 Hz rate.

Variables, specified via the namelist file, also can be written to an output file at a 1 Hz rate. Choices include:

- Greenwich right ascension
- Greenwich mean time
- year/month/day
- Julian day
- time since simulation start
- satellite position and velocity
- magnetic field in various reference frames
- torqrod on times and correction dipoles
- scanwheel scans, speed and momentum
- scanwheel sensor leading edge, trailing edge (noisy or raw)

- Earth in scanwheel sensor field of view
- scanwheel sensor output serial stream
- Euler angles

Use of Simulation

Development Tool

The simulation was a powerful tool during the attitude control code development process. The flight ACDS control algorithms were tested extensively while running the simulation in closed loop mode. By simply changing namelist parameter values the algorithms were readily tested under a wide variety of configurations.

Control system parameters were refined with the use of the simulation. For example, the pitch bias term in the wheel speed controller is determined by running the simulation in closed-loop mode over multiple orbits starting with a nadir pointing attitude. The resulting steady state pitch value is then used as the pitch bias term.

Control system parameter sensitivity studies are completed with the use of the simulation. By changing one parameter at a time the effects of the parameter being studied can be seen. This technique was used to refine control system gains.

Sensor noise simulations are a critical component of attitude control system design and refinement. Noise tests were first run on the flight magnetometers and scanwheel horizon sensor. Gaussian noise with a mean and standard deviation computed from the results of the hardware noise tests are added to each of the sensors in the simulation. Sensor noise sensitivity simulations are run by increasing the standard deviation of the sensor noise in increments and running the simulation. Noise parameters are easily changed in the namelist file.

Mission Simulations

The simulation allows thorough testing of all attitude control configurations under a wide variety of space environment scenarios. Scenarios studied include separation, acquisition on orbit, antenna deployment and momentum desaturation.

Separation / Acquisition on Orbit

The FORTÉ scanwheel will be powered up once separation from the Pegasus-XL Launch Vehicle is detected. The wheel will spin up to its natural speed and the satellite will go into a B-dot control mode. Several simulations were run to determine what wheel speed would result in the fastest B-dot acquisition following separation.

Initial estimates showed the spacecraft attitude at separation to be 0° roll, pitch and yaw. Worst case tip-off rates were ± 3°. Separation runs in B-dot mode were completed for wheel speeds of 450 and 1000 rpm. Initial roll, pitch, and yaw angles of ± 3° and 0° and zero Euler rates were used for a total of 27 simulations at each wheel speed. The results showed that the simulations run with a wheel speed of 450 rpm acquire the fastest. In addition, with 3-orbits worth of Euler angle data for each simulation it is clear that 22 of the 27 runs at 450 rpm acquire. The remaining 5 simulations were run again, this time for 10 orbits. The results proved that these 5 separation runs also acquire

Deployment

Primary antenna deployment poses the most risk to the FORTÉ satellite. Virtually all features of the simulation were used in a comprehensive study of deployment. Deployment was simulated is several different control modes. Normal mode proved to be the most stable and was used in all of the following simulations. Over 300 normal mode deployment simulations were run under different conditions. Control configurations, initial spacecraft attitude and orbital position in the orbit were varied. The following baseline run was used as a reference. Conditions for all of the following runs equal those of the baseline unless otherwise stated. The antenna is deployed at exactly 10 seconds into the run. A pitch bias of 6.16°, roll bias of 0° and a wheel speed of 2050 rpm are used. Normal mode attitude threshold limits are set to 17.4° and -39.4° roll, ±50° pitch. Wheel speed saturation[4] was set to 2500 rpm.

In the first set of 25 deployment runs wheel set speeds of 1900, 1950, 2000, 2050 and 2100 rpm are used. Initial wheel speeds equal to the set speeds and ±50 and ±100 rpm are used. Selecting the wheel speed involves trading off the additional yaw stiffness provided by a higher speed with the lack of dynamic range to control negative pitch error. In 11 of the runs the attitude threshold limits are not exceeded and the deployment is controlled effectively. In 7 runs the threshold limits are exceeded but the deployment is still controlled effectively. In the remaining 7 runs the spacecraft is brought under control following pitching over once. The results showed that the optimal wheel set speed is 2050 rpm. The corresponding run is used as the baseline configuration.

The next set of simulation runs vary from the first set by introducing an initial roll bias of -10.0°. A roll bias is used in an effort to center the roll error within the roll threshold limits. The antenna is deployed 2421 seconds into the run after the roll bias has had a chance to take effect. Results showed using a roll bias has adverse effects. By centering the error within the threshold limits, the magnitude of the error is increased. This increased roll error couples into yaw and pitch to produce larger errors. An additional low frequency oscillation in roll, and consequently yaw is also introduced.

The next series of runs focused on the introduction of a pitch bias. A bias of 20° is used in an effort to compensate for the negative pitch error induced at the start of deployment. An initial pitch of 14° is used for all simulations. Compared to the baseline set, more runs stay within the threshold limits. However, there is also an increased number of simulations that pitch over before being brought under control. Since pitching over is less desirable than exceeding the threshold limits, a pitch bias was not considered a precursor to deployment.

Deployment induces a negative pitch error. It is possible that if deployment is initiated at a time of a positive pitch rate that pitch error during deployment will be minimized. Testing shows creating a positive pitch rate prior to deployment does not help the situation. This is primarily due to the mode switching gymnastics required to generate a positive pitch rate and the systems response to the rate.

Location along the orbit during the deployment has a significant effect on the simulation results. A set of 61 runs was made where deployment was initialized 100 seconds later in each subsequent run, corresponding to 61 equidistant places in orbit. All of the runs are controllable with the spacecraft never pitching over. Latitude of deployment is the most critical factor. Deployment at two portions of the orbit produce runs that exceed the threshold limits. The runs where deployment is initiated between 54° and 27° latitude descending and between -64° and -19° latitude ascending exceed the limits. The threshold limits are not exceeded in the remaining 45 runs. Figure 5 is a plot of maximum and minimum roll and pitch errors as a function of deployment time. The roll threshold limits are also included. Maximum pitch is not a function of deployment time because the pitch response to deployment is all negative. Therefore the maximum pitch occurs under nominal conditions and is independent of deployment time. Figure 6 is the corresponding plot of latitude and longitude, as a function of deployment start time. Deployment must begin at a point in orbit such that when the control algorithms request the most amount of control, the system will physically be able to satisfy the torque request. For the FORTÉ ACDS, the zone of maximum control corresponds to locations near the magnetic poles where the interaction of the torqrods with the Earth's magnetic field will generate maximum control torque.

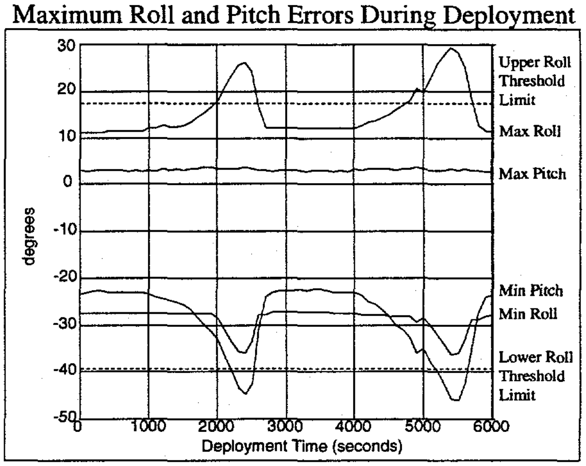

Figure 5

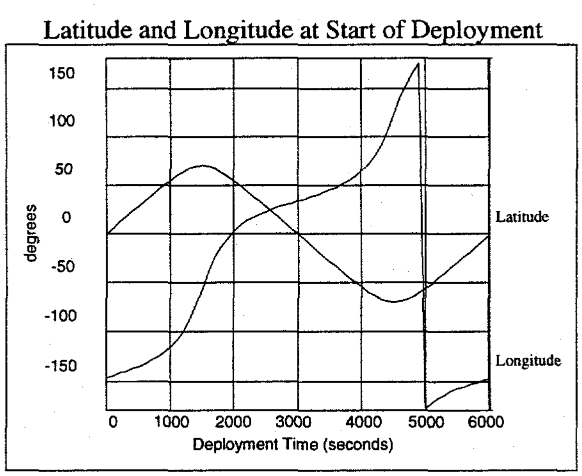

Figure 6

Attitude angles and rates oscillate in normal mode under nominal conditions. A set of runs was done to determine what effect these oscillations, used as initial conditions, will have on deployment. A ten orbit undeployed run in normal mode under nominal conditions was executed to determine the maximum and minimum attitude angles and rates. A set of deployment simulations was then run using the data. Three initial conditions for each axis were used, maximum, zero, and minimum angles. Every combination of initial attitude angles for each axis prior to deployment was used, for a total of 27 runs. The same was done for rates. All simulations remained within threshold limits. The system performance proved to be adequately insensitive to initial attitude angles and rates.

Based on results from many simulations, the following deployment scenario has developed.

- Normal mode
- Wheel set speed = 2050 rpm
- Threshold limits 17.4° and -39.4° roll, ±50° pitch

A set of two passes during ascending orbits will be chosen as a time to deploy. Deployment will be initiated at the start of the first pass. This will allow time for initial spacecraft reaction to deployment to be monitored. By the second pass the spacecraft should be nominally stable. Plots of Euler angles and wheel speed during simulated deployment are included in Figure 7.

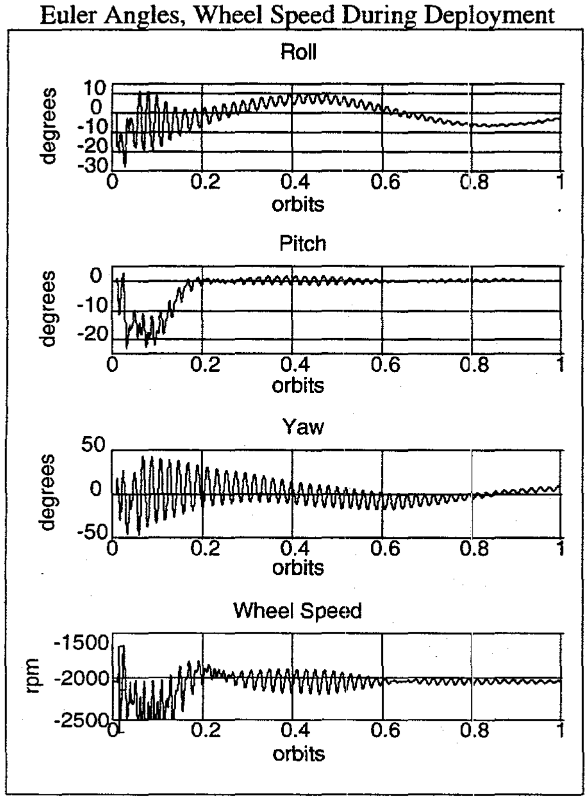

Figure 7

Desaturation

Following deployment the wheel speed will be reduced to 1000 rpm in order to conserve power. In normal mode, desaturation is used to move the wheel speed towards its set speed. Desaturation is invoked by using the x and z-axis torqrods to produce a pitch error. The control system will respond to the error which will move the wheel speed. Using desaturation, the wheel speed will be brought down to its nominal rate of 1000 rpm while inducing minimal pitch error. Simulations show that desaturation will take approximately one half of an orbit.

Operator Training

The simulation enables spacecraft operators to become familiar with the satellite dynamics in space, sensor tolerances and limitations, and actuator capabilities. Several FORTÉ mission simulations were run while running the ACDS simulation in closed loop mode. With the simulation running in real time in the background, the first few weeks of the FORTÉ mission were simulated, starting with separation from the launch vehicle. At each contact operators downloaded housekeeping data which included ACDS hardware states and attitude information for the preceding orbits. Also available to the operators are real time roll and pitch attitude displays. Mission segments including separation, acquisition on orbit, increasing wheel speed, transition to normal mode, deployment and desaturation were enacted in real time through commanding from the ground station.

Conclusion

The hardware-in-loop simulation has proven to be a valuable tool for the FORTÉ ACDS team. The simulator was used to develop and refine attitude control algorithms. Without the simulation a good deployment strategy could not have been developed.

Acknowledgment

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Author Biographies

Kimberly K. Ruud is a technical staff member at Los Alamos National Laboratory. She received a Bachelor of Science in Electrical Engineering from South Dakota State University in 1994. In 1996 she received a Masters of Science in Electrical Engineering - Signal Processing and Communications from the University of New Mexico. Her interests include spacecraft attitude determination and control, digital signal processing and digital control system design.

Hugh S. Murray is a Technical Staff Member at the Los Alamos National Laboratory. While he performed his undergraduate work at Carnigie Melon University, he holds a PHD in Nuclear Engineering from the University of Arizona. Currently, he is a Team Leader responsible for the technical management of the research and development for space programs and projects associated with advanced multispectral sensors and small satellite systems navigation applications. His work at the Laboratory has emphasized advanced sensors and control systems research and development. In addition to authoring numerous publications associated with his work he has been the Project Leader for developing multi-spectral detection and imaging systems and small satellite autonomous attitude control and determination systems. He was the program manager for the successful development of micro-miniature embedded threat warning detection systems for small satellite applications that included sensors in the near infrared, broad-band RF and x-ray regime.

Troy K. Moore joined Los Alamos National Laboratory as a technical staff member in 1984. He has been involved in the development of ground support systems, data acquisition systems and space-based instrumentation for the past 9 years. Troy earned a Masters of Science in Electrical Engineering from Kansas State University in 1981.

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[1] SCANWHEEL is a registered trademark of Ithaco Inc.

[2] S.M.Fox, P.K.Pal, H.Murray, "Attitude Control and Determination Subsystem Simulator for the Fast On-Orbit Recording of Transient Events Satellite", 18th Annual AAS Guidance and Control Conference Paper AAS 95-042, February, 1995.

[3] Tom Butler and Scott Doebling, "Estimate of Torques Disturbing Satellite During Antenna Deployment." Los Alamos National Laboratory internal memo.

[4] FORTE scanwheel functional testing in vacuum at Sandia National Laboratory, 6/97.