THE ATTITUDE AND ORBIT CONTROL SYSTEM DESIGN FOR TRIANA

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Abstract

This paper presents an overview of the Attitude and Orbit Control System (AOCS) design for the TRIANA mission. The TRIANA spacecraft is being developed as part of NASA's Small Explorer (SMEX) program and is currently scheduled for launch aboard the U.S. space shuttle in October 2000. The first part of this paper highlights the SMEX program directives and describes the science objectives and imposed mission requirements, while the remainder is devoted to the AOCS design. The AOCS description will address the mission trajectory design for the L1 Lissajous orbit, orbit determination and injection/maintenance maneuvers, attitude determination and control, and momentum management. Simulated performance results will accompany key AOCS operational modes such as Sun Acquisition, Science, and Delta H. Also included in the AOCS discussion are the significant trades made in arriving at the baseline AOCS design.

Key words: Attitude Control System, Trajectory Design

Introduction

The TRIANA spacecraft is being developed as part of NASA's Small Explorer (SMEX) program and is currently scheduled for launch aboard the U.S. space shuttle in October 2000. The purpose of the SMEX project is to design, develop, test, and launch high-quality, low-cost, scientific spacecraft within a three-year period. However for TRIANA, the mission timeline has been decreased by one year requiring innovative measures to procure and/or produce the necessary hardware to satisfy the two-year development cycle. The cost has also been capped at $75 million for the entire mission, which includes development, integration and test, five years of mission operations, and, contingency. Satisfying the stringent cost and schedule guidelines, and at the same time, insuring system reliability requires the use of techniques which have proven successful on previous SMEX missions. One such technique is the synthesis of operational testing with spacecraft level closed-loop attitude control system testing throughout the integration phase.[1] Another technique is to thoroughly test and evaluate the attitude control system in both open-loop and closed-loop fashions prior to launch in order to identify and correct potential problems on the ground.[2] In addition, TRIANA is the first mission to employ the SMEX•Lite satellite technology developed by the Goddard Space Flight Center.[3] The SMEX•Lite technology enables rapid development of a spacecraft by only requiring modifications, as necessary, of a core system of existing hardware and software designs which in turn increases system reliability and at the same time helps to reduce both cost and schedule.

By far, the most challenging aspect of this mission is developing and delivering an Attitude and Orbit Control System (AOCS) that adheres to both the strict cost and schedule guidelines being imposed by the SMEX project, and at the same time, meets the specified mission objectives and performance requirements. The proposed AOCS design requires modification of a significant portion of the AOCS specific flight software algorithms and interface hardware with respect to the SMEX•Lite baseline, but can be easily achieved within the allotted time frame given the inherent flexibility of the SMEX•Lite design. Also the addition of a propulsion module is new to the SMEX series of missions and requires special attention especially with regard to shuttle safety.

The purpose of this paper is to present an overview of the AOCS design for the TRIANA mission. The following sections highlight the TRIANA mission objectives, performance requirements, and AOCS design. The AOCS description addresses the mission trajectory design for the L1 Lissajous orbit, orbit determination and injection/maintenance maneuvers, attitude determination and control, and momentum management. Simulated results are presented to emphasize performance of key AOCS operational modes such as Sun Acquisition, Science, and Delta H. Also included in the AOCS discussion are the significant trades made in arriving at the baseline TRIANA AOCS design.

Mission Objectives and Requirements

The science requires that the spacecraft provide continuous imaging of the full Earth disk with a spatial resolution of 5 km. Viewing the full sunlit Earth can be accomplished by positioning the spacecraft at the Earth-sun L1 point. However since this point is naturally unstable, placing the spacecraft in a Lissajous orbit about the Earth-sun L1 point will produce nearly full disk coverage, allow a maintainable orbit, and prevent communication loss due to solar interference. Therefore, the TRIANA satellite will be launched into a Class I 10° Lissajous orbit about the Earth-sun L1 point. The derived science pointing and jitter performance needed to collect stable Earth images are presented in Table 1. A close inspection of Table 1 shows that the spacecraft must maintain an absolute pointing accuracy of 0.03°, 1°, and 0.03° about the X, Y, and Z axes respectively. The AOCS is allotted 80% of the total pointing budget and is assigned the full jitter requirement of 0.225 arc-sec for the X and Z axes, and 52.0 arc-sec for the Y axis. Jitter is specified for all periods less than or equal the integration time of 30 ms.

Table 1: Science Pointing and Jitter Requirements

Requirement	X	Y	Z
Pointing Accuracy (3σ)	0.03°	1.0°	0.03°
Jitter > 33 Hz (3σ)	0.225 arc-sec	52.0 arc-sec	0.225 arc-sec
Attitude Knowledge (3σ)	0.015°	0.5°	0.015°

In addition to the stated science requirements, the mission requires that the AOCS achieve a 2 year mission lifetime (5 years for consumables), provide the L1 injection capability and orbit maintenance over the mission duration, and maintain a sun exclusion zone of greater than 2° for communication. Furthermore the AOCS must provide a three-axis stabilized platform with sufficient pointing accuracy to place and maintain the Earth within the instrument field of view of 0.58°, and provide momentum unloading throughout the mission lifetime. During the initial sun acquisition sequence, the AOCS must point the +Y axis to within 10$^{\mathrm{o}}$ of the sun given an arbitrary attitude with high tip-off rates about the body axes (introduced by the booster stage) and without discharging the battery below 80%.

The fully deployed, on-orbit TRIANA satellite configuration is illustrated in Fig. 1, where the instrument boresight is aligned with the -Y body axis and the X and Z body axes comprise the focal plane of the science telescope. Also note that the antenna is 1.3 m in diameter and each array is 1.4 m by 0.75 m.

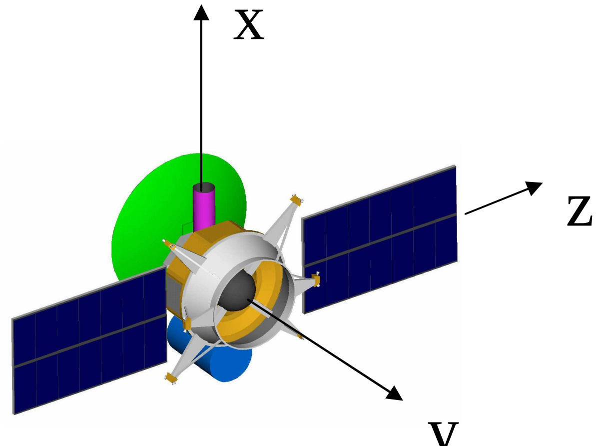
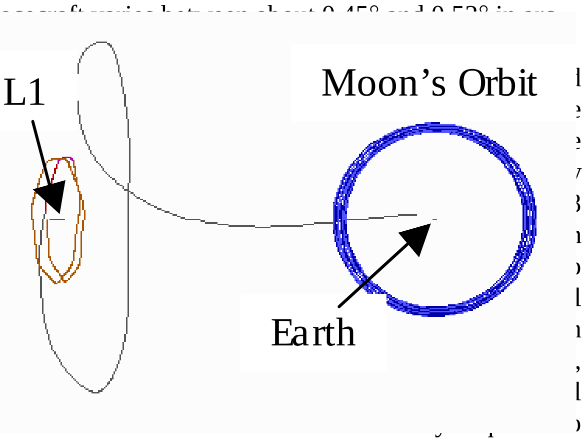


Fig. 1: Fully Deployed, On-Orbit Configuration

L1 Lissajous Orbit Design and Maintenance

Due to the extremely short development cycle, a simple trajectory design approach is being implemented for the TRIANA mission. The planned trajectory incorporates a direct insertion into the Earth-sun L1 libration point as shown in Fig. 2. Upon arrival at the L1 position, an insertion burn will place the spacecraft into the Class I 10° opening Lissajous pattern about the stationary L1 point as illustrated in Fig. 3. The directional arrows present in Fig. 3 indicate the changing shape of the Lissajous pattern over the anticipated five year mission period. The 10° limitation represents the maximum angular separation of the spacecraft-Earth line from the Earth-sun line. In addition, a solar exclusion zone of 2° is being established as the orbit minimum to eliminate possible communication interference, and thus the Lissajous pattern will vary from 2° to 10° over the 5 year mission as shown in Fig. 3. From L1, the spacecraft will view at least 94% of the sunlit Earth at all times. Also note that from the L1 distance of 1.5 million kilometers, the Earth diameter as viewed by the spacecraft varies between about 0.45° and 0.53° in arc



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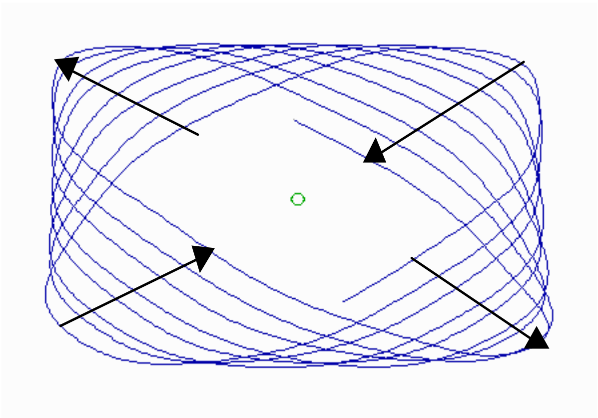


Fig. 2: Direct Insertion Trajectory
Figure 3: Lissajous Pattern

reach the L1 point. The solid rocket will burn for approximately 80 seconds, after which the spacecraft will begin its transit to the L1 point. Eight minutes following the STAR 48 burnout, TRIANA will exit the Earth's umbra and begin a sun acquisition sequence.

Since TRIANA will be launched from the shuttle, the mission design is considerably more complex and involves additional launch and injection variables as compared to using an expendable launch vehicle. For example, the following four variables have been identified as significant drivers in the mission design, (1) the STAR 48 total delta-V capability, (2) the TRIANA/STAR 48 attitude orientation at ignition, (3) timing of the shuttle release, and (4) a missed release opportunity (missing a release on the designated orbit and having to release at a later time). Errors present in any one of the above four variables will have a significant impact on the size of the corresponding trajectory correction maneuver.

The TRIANA transfer trajectory to L1 is located approximately 20° north of the ecliptic and requires a planned Mid-Course Correction (MCC) maneuver one day after the STAR 48 burn. The MCC will be primarily in the velocity direction and will correct for any injection errors attributed to uncertainties in the design variables listed above. A second MCC burn is planned near the first crossing of the Earth-sun plane perpendicular to the ecliptic approximately four months following launch. In April 2001, just under six months after launch, a major maneuver will be required to insert the spacecraft into the 10° Lissajous orbit about the L1 libration point. The Lissajous Orbit Insertion (LOI) burn will last up to three hours and will decrease the spacecraft velocity by approximately 175 m/s. Due to the actual thruster configuration (i.e. canting and center of mass offsets), the actual delta-V expended will be on the order of 199 m/s.

Stationkeeping is required to maintain the spacecraft in the desired Lissajous orbit about L1. Maneuver execution efficiency is the leading source of error in the mission orbit, where the delta-V accuracy obtained from TRIANA's thrusters is expected to be within 5% of a planned delta-V. This 5% error is particularly large for the LOI burn, and therefore two LOI correction burns are planned at 25 and 50 days following the initial insertion. After the day 50 LOI correction maneuver, nominal stationkeeping will begin and continue for the mission duration. Every three months, small stationkeeping maneuvers, on the order of 50 cm/s, will be required to correct for the 5% execution errors. In addition, the maintenance maneuvers will correct for residual delta-V created from periodic momentum unloading, and for the 1 cm/s velocity knowledge error generated from the ground based orbit determination solution. Without stationkeeping, a spacecraft velocity error of 1 cm/s will cause the spacecraft to escape from the L1 orbit within four to five months. All necessary maintenance maneuvers are performed in the spacecraft-Earth direction and use the spacecraft ±Y axis thrusters. Since the Lissajous orbit minimum is 2° by design, no maneuvers perpendicular to the Earth-sun line are required to maintain the solar exclusion zone.

The designated propulsion system uses a traditional monopropellant hydrazine design. The fuel tank is a 28" spare tank acquired from the CASSINI program with a total fuel capacity of 133 kg. At an expected wet mass of 403 kg (133 kg fuel plus 270 kg dry spacecraft mass), the corresponding total delta-V capability is 864 m/s. The short development timeline for this mission led to the decision to use the available 28" tank, which in turn enables the spacecraft to fly fuel-rich. At the current time, the plan is to fill the tank with only 72.5 kg of hydrazine (wet mass of 342.5 kg) providing a delta-V capability of 513 m/s. The baseline delta-V budget for TRIANA is shown in Table 2, where the total amount required is 396 m/s, leaving a margin of 117 m/s or 22.8%. From Table 2, the 137 m/s MCC burn accounts for a 9 m/s error in the STAR 48 delta-V performance, a 4° error in attitude pointing (booster plus shuttle), 60 seconds of error in the STAR 48 ignition time, and a one orbit delay in release time.

Table 2: Delta V Budget

Maneuver	m/s

MCC-1 (Initial correction)	137
MCC-2 (Orbit shaping maneuver)	21
LOI (Lissajous Orbit Insertion)	199
LOIc (LOI correction burns)	15
Stationkeeping	23
Momentum Management	1
TOTAL	396

In order to satisfy the mission objectives, TRIANA operations require continuous ground station coverage. This coverage can only be achieved by a system of at least three ground stations spaced equally apart in longitude. TRIANA will be supported via a yet-to-be-determined commercial ground network that will provide telemetry and tracking services. The tracking service is required to provide both tone ranging and coherent Doppler tracking capabilities. Since the tone ranging service may interfere with telemetry, the ranging time must be minimized. Also since the tracking service is generally an expensive addition to any ground station, the number of required tracking stations must be minimized. Telemetry only stations can support the mission when tracking is not required. Therefore, a tentative tracking schedule, that would minimize tracking hardware and tone ranging times, has been developed from a covariance analysis. The schedule requires two tracking ground stations with each providing continuous coherent Doppler during their approximate eight hours of visibility per day. Each would also provide five minutes of tone ranging at the beginning and end of each daily eight hour pass. The total tracking would consist of 16 hours of Doppler and 20 minutes of ranging per day. The Doppler data is assumed accurate to a minimum of 8 mm/s and the tone ranging to at least 100 m. A three week batch orbit determination solution combined with the proposed tracking data will produce an orbit trajectory accurate to 6 km and 0.2 cm/s.

To capture and hold the Earth within the instrument's 0.58° field of view, the onboard ephemeris must be accurate to within 0.038°. At the L1 distance, an angle of 0.038° translates to a position error of 1000 km. Using a simple onboard propagator, the ephemeris accuracy will degrade to 1000 km within four days. Alternatively, utilizing an accurate ground propagation system, the ephemeris accuracy will degrade to 1000 km in about nine weeks. Thus, three weeks of tracking data every nine weeks coupled with biweekly ephemeris updates will satisfy the onboard ephemeris accuracy requirement.

Trajectory Design Trades

A trade study was performed to evaluate alternative launch options to the selected direct L1 transfer approach, where the results are presented in Table 3. The direct transfer was chosen because of the fuel-rich spacecraft and the need to simplify operations. Alternatively, the lunar swingby approaches undoubtedly save fuel but increase the complexity of the mission design and early orbit operations. The constrained direct insertion enables the mission to meet the 10° orbit requirement within 3 months following launch but requires an additional 40 m/s of fuel. If the spacecraft remains fuel rich as the design matures, the constrained direct insertion method can be revisited.

AOCS Configuration

The TRIANA AOCS is configured to operate as a three-axis stabilized platform to comply with the stated mission requirements. The AOCS employs digital controllers hosted in the Spacecraft Computer System (SCS) for normal mode operations, while Safehold operation is accomplished using a digital controller executed from the SCS boot mode architecture.

Flight Hardware

The primary AOCS sensor compliment consists of a Digital Sun Sensor (DSS), a set of six Coarse Sun Sensors (CSS), a three-axis gyro package, and a star tracker, while the actuator suite includes four reaction wheels and twelve thrusters. Both the gyro package and star tracker information is sent directly to the SCS over a MIL-STD-1553 data bus. The sun sensors interface to a Utility Hub (UHUB) which contains the electronics

Table 3: Trajectory Design Trades

Direct Insertion	Constrained Direct Insertion	Direct Lunar Swingby	Phasing Loops/Lunar Swingby
3 MCC maneuvers	3 MCC maneuvers	Not possible for some dates	6 MCC maneuvers
LOI of 175 m/s	LOI of 215 m/s	No LOI	No LOI
High MCC delta V costs	High MCC delta V costs	High MCC delta V costs	Low MCC delta V costs
Launch window of 27 days	Launch window of 27 days	Launch window of 2 days	Launch window of 14 days
Exceeds 10° constraint for 2 months	Meets 10° constraint	Meets 10° constraint	Meets 10° constraint
Total delta V ~ 345 m/s	Total delta V ~ 385 m/s	Total delta V ~ 170 m/s	Total delta V ~ 130 m/s
One critical maneuver – LOI	One critical maneuver – LOI	One critical maneuver – MCC1	Two critical maneuvers
Simple operations	Simple operations	Simple operations	Complicated operations

necessary to process the sensor information and pass it along to the SCS over the MIL-STD-1553 data bus. The UHUB is also responsible for sending commands and monitoring telemetry related to the operation of the thruster valves. Reaction wheel commands processed by the digital control algorithms in the SCS are transmitted to each wheel over the MIL-STD-1553 interface. In addition to the AOCS hardware, Earth image information collected from the instrument will be used to eliminate the onboard ephemeris error and satisfy the overall pointing requirements.[4] A top level TRIANA AOCS data flow block diagram is presented in Fig. 4.

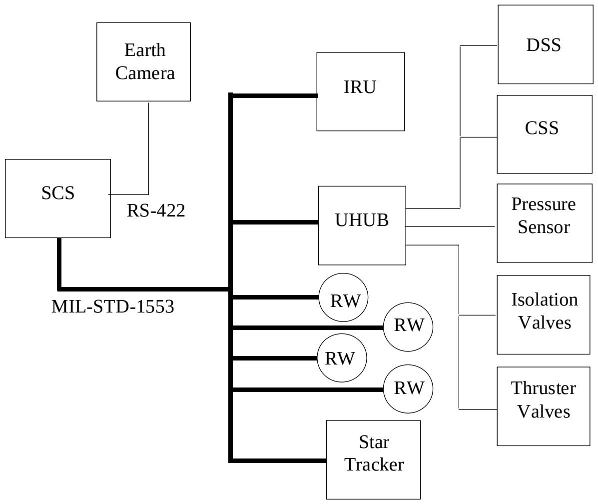
The sun sensors, reaction wheels, and UHUB form the basic SMEX•Lite attitude control hardware compliment. Use of this existing technology reduces cost and schedule, and at the same time increases reliability. The star tracker and gyro package, considered add on components, are necessary to meet the specified science requirements. Implementation of the MIL-STD-1553 interface for these two components eliminates the need for custom interfaces, thus saving schedule time while increasing system reliability. However a mild increase in cost and power consumption is associated with MIL-STD-1553 interface selection. Likewise, the propulsion system is a new addition to the SMEX•Lite architecture and requires power and data interface modifications to the UHUB in order to accommodate the thruster valve driver electronics.

Sensor/Actuator Orientation

The CSS configuration provides 4π steradian coverage in all modes of on-orbit operation insuring a sun vector measurement from any arbitrary spacecraft orientation. The DSS field of view is limited to ±64°about the +Y axis and is autonomously substituted for the CSS derived sun vector whenever available. The gyro package contains three orthogonal one-axis gyros which are used to measure spacecraft body rates. Knowledge of the body rates is required for instrument capture and on-board attitude determination. The four reaction wheels are oriented in a pyramid configuration such that spacecraft maneuvering and control capability is retained in the event that any one wheel fails. Each wheel can provide a maximum torque authority of 0.2 N-m and a momentum capacity of 8.6 N-m-s. The twelve thrusters are configured on four identical three thruster modules to provide on-axis torque couples and/or thrust in any direction. Using twelve thrusters inherently provides the capacity to accommodate valve failures and still retain the necessary orbit maintenance and momentum unloading capabilities. The selected thrusters are sized at 4.45 N and are positioned at a distance of about 0.75 m radially outward from the spacecraft Y axis. The minimum pulse resolution for the thruster drive electronics is 50 milliseconds, one half of the 10 Hz attitude control cycle.

Fig. 4: Data Flow Block Diagram

Attitude Control Design Trades



The first design trade was to use the SMEX•Lite architecture as a starting point. Given the existence of a protoflight unit, the cost and schedule requirements could be satisfied. Additional design trades performed included examining the cost differential associated with reducing the number of reaction wheels from four to three as well as reducing the total number of thrusters. The decision to keep the fourth wheel was based on the redundancy provided and the ability to increase the time between momentum unloading maneuvers. The increase in operational value was determined to outweigh the actual component cost. Likewise employing twelve thrusters results in an increase in the actual hardware cost but at the same time, this configuration eliminates the need for orientation maneuvers prior to and after maintenance operations. The identical thruster pods also simplify the integration procedure and reduce the delivery time needed for the entire propulsion module. The desire to have functional redundancy of the sun vector measurement as well as to minimize changes to the SMEX•Lite baseline led to the decision to retain the DSS.

Operational Modes

The TRIANA AOCS is designed to operate in one of five primary mission modes as shown in Table 4. During the first two modes, angular rates are reduced about each axis as the solar arrays are pointed towards the sun. The third mode provides a three-axis stabilized platform for science data taking operations, while the fourth and fifth modes are used for orbit maintenance and momentum management.

Safehold

Safehold is entered whenever there is a processor cold start or a gyro failure. During this mode, the +Y axis is oriented along the sun line while transverse rates are nulled by controlling the reaction wheels using position and rate information derived from the sun sensors. Rate about the sun line is estimated using wheel tachometer telemetry and is also controlled by the wheels. Note that thruster firings are precluded in this mode. The sole purpose of this mode is to establish and maintain an attitude that is both power and thermally safe for a period of time, the length of which is determined by the amount of momentum in the system when the Safehold mode is entered.

Sun Acquisition

The Sun Acquisition mode is executed upon separation from the booster stage and/or whenever an anomaly occurs (other than a gyro failure or processor cold reset). During this mode the four reaction wheels are used to null body rates and align the +Y axis to the sun line using a combination of sun vector measurements and gyro data. Like Safehold, this mode is used to establish and maintain an attitude that is both power and thermally safe. This mode is also used as a means for activating the attitude determination functions prior to transitioning to the Science mode. In addition, the ability to ground command to the Delta H mode is available and may be necessary during the initial sun acquisition sequence as large tip-off rates will saturate the wheel capabilities. Upon completion of any Delta H commanded from Sun Acquisition, the AOCS will autonomously return to the Sun Acquisition mode.

Science

During the Science mode, the four reaction wheels are actively controlled to align the science telescope with the center of the Earth disk. The coarse target quaternion is derived from the onboard ephemeris data and is used to capture the Earth within the instrument field of view. Once the Earth is acquired, a new target quaternion is generated from a combination of the Earth image information, the current estimated attitude, and the onboard ephemeris data. Between image updates, approximately every 10 minutes, the target attitude is propagated using the available onboard ephemeris information. This approach introduces only relative ephemeris errors instead of absolute errors. During this mode, control errors are formulated from the target quaternion and the estimated attitude generated via a Kalman filter. The filter uses sun sensor and star tracker measurements to update a gyro propagated attitude solution. Both the Delta V and Delta H modes are accessible from Science via ground command with an autonomous return.

Delta V

Delta V is used for orbit maintenance and will be executed approximately every three months. During this mode the reaction wheel torque commands are zeroed while the thrusters are operated to apply the desired thrust as well as on/off pulse to control the vehicle attitude. For this mode, position and rate information is derived soley from the gyros. Upon completion of the Delta V mode, the AOCS software automatically enters the Delta H mode to remove residual momentum prior to returning to the Science mode.

Delta H

Delta H is used for momentum management throughout

Table 4: AOCS Operational Modes

Mode Name	Sensors	Actuators	Control	Description
Safehold	DSS, CSS, Tachometers	Reaction Wheels	Rate Damping and Sun Pointing	Used for safing
Sun Acquisition	DSS, CSS, IRU, Tachometers	Reaction Wheels	Rate Damping and Sun Pointing	Used for L&EO and safing
Science	CSS, DSS, IRU, Star Tracker, Tachometers, Earth Image	Reaction Wheels	Three-Axis Stabilized, Kalman Filter derived attitude	Used for Earth pointing
Delta V	IRU, Tachometers	Thrusters	Three-Axis Stabilized	Used for orbit maintenance
Delta H	IRU, Tachometers	Thrusters	Three-Axis Stabilized	Used for momentum unloading

the course of the mission. It is desirable to couple the orbit maintenance maneuvers with momentum unloading on the three month maintenance schedule, however, it is not required as the twelve thruster configuration provides the freedom to execute Delta H with pure torque couples and thus produce minimal thrust disturbances. During Delta H, the reaction wheels are driven to zero speed while the thrusters are fired to remove system momentum and control attitude. Like Delta V, position and rate information is provided by the gyros. Upon completion of a Delta H mode, the AOCS software automatically returns to the previous mode.

Simulated Results

Performance of the TRIANA AOCS is presented for the initial sun acquisition sequence and also for the nominal science data taking operations.

The first simulation characterizes the vehicle performance during the initial sun acquisition after separation from the STAR 48 booster. For this simulation, the spacecraft is given initial body rates of 93°/s, 347°/s, and 0°/s about the X, Y, and Z axes respectively, where these large rates represent the residual angular motion introduced by the booster stage. It is obvious that the reaction wheels do not have the momentum capacity to absorb the large induced rates and therefore the thrusters are required to remove the system momentum prior to sun acquisition. In order to acquire and hold the sun normal to the solar arrays, the AOCS employs the Sun Acquisition mode in combination with the Delta H mode. The performance during this sequence is illustrated in Fig. 5, where the angle between the +Y axis and the sun line is presented. From this figure, the sun oscillates between 60° and 120° from the +Y axis until about 65 seconds when the actual sun acquisition occurs. The Delta H mode is entered from the Sun Acquisition mode, via command, 10 seconds after the start of the simulation and autonomously exits after 55 seconds when the system momentum has been reduced to less than 1 N-m-s. Twenty seconds following exit from Delta H (i.e. return to the Sun Acquisition mode) the 10° sun pointing requirement is satisfied. In fact the +Y axis closes into a steady state offset of about 1° from the sun line as shown in Fig. 5.

The second simulation depicts the nominal pointing performance during Science mode operations. The result is presented as the angle between the instrument boresight and the Earth center and is shown in Fig. 6. An inspection of this figure shows that the boresight pointing error is generally between 0.020° and 0.026°. The RSS of the X and Z axis pointing errors (see Table 1) yields a combined axis requirement of 0.042°. Thus the current pointing performance is better than the specified requirement by a factor of two. Note that this simulation represents the pointing performance when the Earth images have been introduced into the target attitude and does not reflect the relative ephemeris errors which would cause the boresight pointing error to drift. Also it is assumed that the misalignment between the star tracker and the instrument has been calibrated out. For the situation of the initial instrument acquisition, an absolute ephemeris error of 0.038° in both the X and Z axes will create a boresight pointing error on the order of 0.1°, well within the 0.58° field of view. Similarly, the Y axis pointing error (not shown) is well within the 1° requirement and is on the same order of magnitude as the X and Z axis errors.

Conclusion

This paper has presented the SMEX program directives, highlighted the TRIANA mission objectives, and described in detail the TRIANA AOCS design. As part of the AOCS design definition, the hardware components were described as well as the operational modes employed to satisfy the mission requirements. Throughout the text, attention was paid to highlighting specific trades that resulted in an overall program cost and/or schedule reduction. Finally, the TRIANA satellite AOCS performance was simulated to assess the vehicle behavior during the primary operational modes. The simulated results show that the spacecraft satisfies all imposed requirements.

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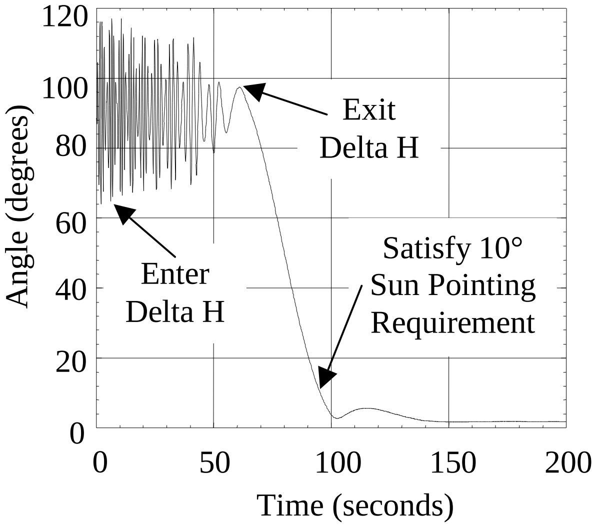

Fig. 5: Initial Sun Acquisition Performance

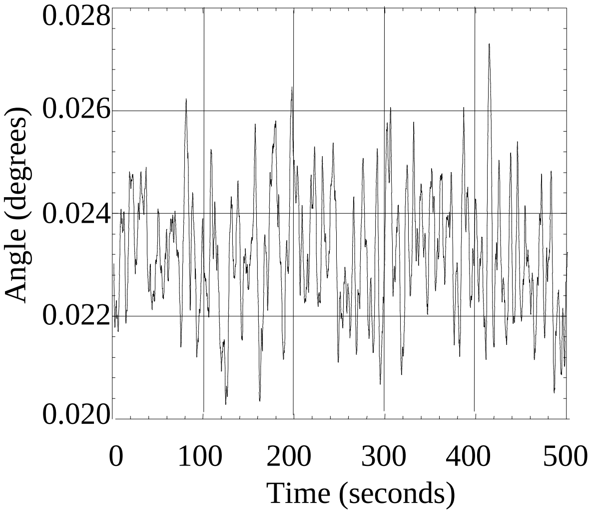

Fig. 6: Nominal Science Mode Performance