THE ATTITUDE CONTROL SYSTEM DESIGN FOR THE TRANSITION REGION AND CORONAL EXPLORER MISSION

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Abstract

This paper presents an overview of the Attitude Control System (ACS) design for the Transition Region And Coronal Explorer (TRACE) satellite mission. The TRACE spacecraft is the fourth in NASA's SMall EXplorer (SMEX) series of missions and is scheduled for launch in September 1997. The first part of this paper highlights the SMEX program directives and describes the science objectives and imposed requirements, while the remainder is devoted to the ACS design. The current ACS configuration is a three-axis stabilized, zero-momentum system which re-uses much of the third SMEX satellite design in an effort to decrease overall subsystem costs and increase system reliability. In addition to the primary sensors, TRACE will carry a Global Positioning System (GPS) sensor as part of NASA's technology development and demonstration. The GPS sensor will provide time, position, velocity and attitude information to the ACS and will become a prime sensor after initial verification and validation. The GPS information will not only be used to supplement the ACS attitude determination effort, but will also be utilized to predict ground station contacts onboard the spacecraft. The station contact information will then be sent to the ground and used for spacecraft operations and ground pass scheduling.

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Nomenclature

$\mathbf{B}$	Measured magnetic field vector
$\mathbf{H}$	Total system momentum vector
$\mathbf{h}$	Measured wheel momentum vector
$\mathbf{h}_{cmd}$	Wheel momentum command vector
$\mathbf{I}$	Spacecraft inertia tensor
K_a	Slew deceleration control gain
K_b	Rate damping control gain
K_h	Fine pointing position control gain
K_i	Fine pointing integral control gain
K_p	Precession control gain
K_s	Wheel rate control gain
K_{tf}	Fine motor torque control gain
K_{ts}	Slew motor torque control gain
K_u	Momentum unload control gain
$\mathbf{m}_{cmd}$	Torque rod command vector
$\mathbf{S}$	Measured sun vector
$\mathbf{T}_{cmd}$	Wheel torque command vector
t	Time
x	Subscript denoting the pitch axis
y	Subscript denoting the roll axis
z	Subscript denoting the yaw axis
θ	Rotation angle about eigenaxis
v	Unit vector parallel to eigenaxis
ω	Inertial angular velocity vector
ω_c	Commanded roll wheel speed
ω_w	Measured roll wheel speed

Introduction

The Transition Region And Coronal Explorer (TRACE) is the fourth in a series of NASA's SMall EXplorer (SMEX) spacecraft scheduled for launch in September 1997. The prime directive of the SMEX program is to develop and launch high-quality, low-cost, scientific spacecraft within a three-year period. In order to meet the imposed SMEX program requirement, new and innovative techniques are being developed and employed to increase spacecraft system reliability and at the same time reduce overall program cost and schedule.[1] Substantial re-use of previous SMEX technology is also adapted and applied to follow-on missions to further decrease cost and increase reliability.

The purpose of this paper it to present a brief overview of the TRACE science mission followed by a detailed discussion of the Attitude Control System (ACS) configuration. Throughout this paper, emphasis will be placed on the design trades driven by program cost and schedule. The TRACE ACS design approach is compliant with the SMEX philosophy, and will use the Sub-millimeter Wave Astronomy Satellite (SWAS is the third SMEX mission) ACS as a baseline. In addition to the primary sensor suite, TRACE will carry a Global Positioning System (GPS) sensor as part of NASA's technology development and demonstration. The GPS sensor will provide time, position, velocity and attitude information to the ACS and will become a prime sensor after initial verification and validation.

TRACE Mission

The primary science objective of the TRACE mission is to explore the relationship between the fine scale magnetic fields in the solar surface and features in the photosphere, chromosphere, transition region and corona. Quantitative images of these regions will be collected using an 8.5 arcminute by 8.5 arcminute field of view science telescope and will be used to study the structure and evolution of the sun's magnetic field with a spatial and temporal resolution of one arcsecond and one second respectively.

The science requires that the spacecraft accurately point to solar target regions specified by coordinates on the sun or sun's limb while compensating for the solar rotation of the target region. Therefore, the TRACE satellite will occupy a 600 km, 6 AM sun synchronous, circular orbit and provide continuous solar observations for a period of approximately 8 months. In order to satisfy the remaining science requirements, the TRACE ACS must maintain a pitch and yaw pointing accuracy of 20 arcseconds and be able to quickly maneuver to other target regions according to a stored timeline onboard the spacecraft. Since roll errors influence target pointing away from the sun center, a stable roll reference must be kept onboard the vehicle where (1) the knowledge requirement is 2.55° (3σ) and (2) the roll drift rate must be limited to 1°/hour to avoid pixel blurring. In addition, high frequency pitch and yaw jitter which creates unwanted image motion is attenuated by a secondary mirror (within the main telescope) using an open loop control system driven by information generated from a Guide Telescope (GT). The GT is part of the TRACE instrument package and also provides the pointing error signals to the ACS during science data taking operations.

The fully deployed, on-orbit TRACE satellite configuration is illustrated in Fig. 1, where the instrument boresight is aligned with the +Y body axis (roll) and the X and Z body axes, designated as pitch and yaw respectively, comprise the focal plane of the main telescope. Also note from Fig. 1 that the GT is attached and aligned to the main science telescope.

TRACE ACS Hardware Configuration

The TRACE ACS is configured as a three-

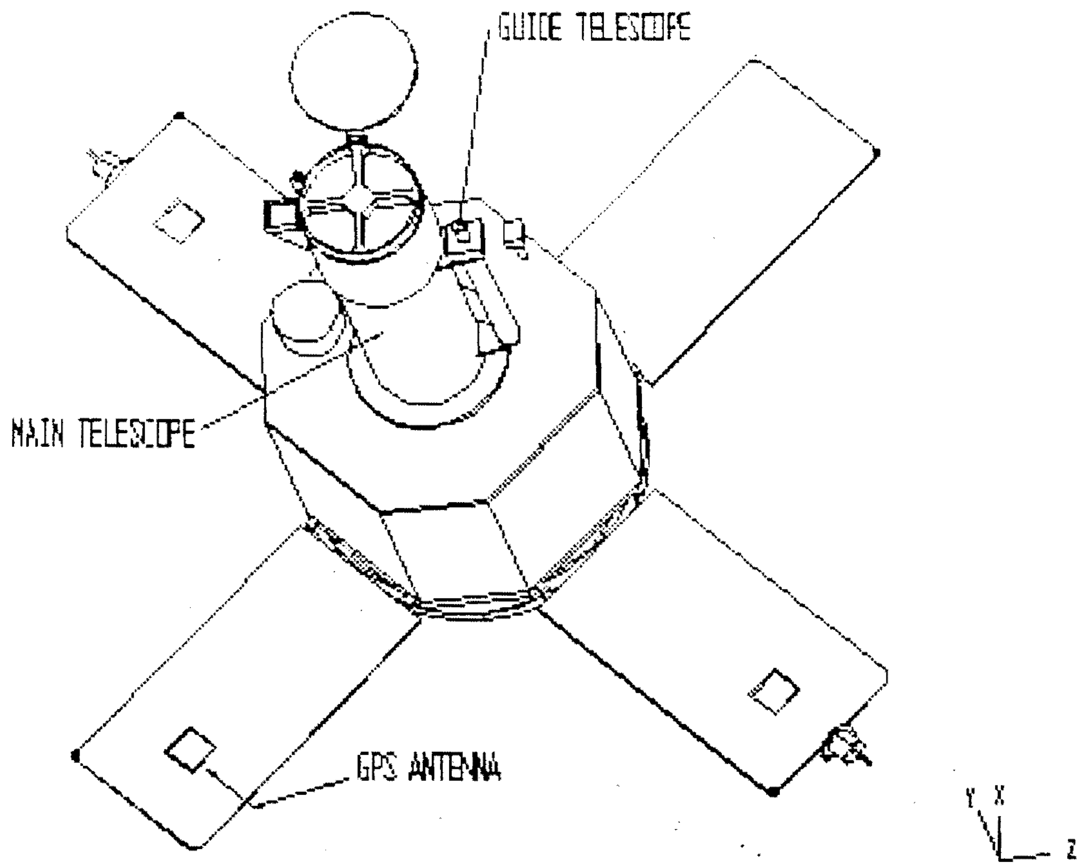

Fig. 1. Fully Deployed, On-Orbit TRACE Satellite Configuration

axis stabilized, zero-momentum system. The ACS utilizes a digital controller hosted in the Spacecraft Computer System (SCS) microprocessor for normal science mode operations as well as an independent analog controller hosted in the Attitude Control Electronics (ACE) for initial sun acquisition and safehold control. The primary difference between the TRACE ACS implementation and the SWAS baseline is that during science data taking operations, the fine pointing control loops are directly closed about the instrument provided GT signals (the same sensor generates the main telescope secondary mirror control signals). The remainder of the ACS hardware (sensors, actuators, and electronics), excluding the GPS, is identical to the SWAS compliment in an effort to reduce cost and schedule as well as increase reliability. The individual ACS hardware elements are highlighted in the following paragraphs, while the TRACE data flow is illustrated in Fig. 2.

<u>Attitude Control Electronics</u>

The ACE contains the initial acquisition and safehold control systems, and provides the MIL-STD-1553 interface between the ACS sensors and actuators (excluding the GT and the GPS sensor) and the SCS. The active acquisition/safehold electronics are designed for maximum reliability with conservative component deratings, and Single Event Upset (SEU)/Single Event Latchup (SEL) resistant devices which are capable of tolerating three times the mission total dose radiation requirement of 10 krad.

Coarse Sun Sensor

The ACS uses a set of analog Coarse Sun Sensors (CSS's) to measure the sun vector from any arbitrary spacecraft orientation. A minimum of six CSS's are required and are located on the spacecraft solar arrays as well as the fore and aft sections to provide 4π steradian coverage in all modes of on-orbit operation.

Digital Sun Sensor

The ACS uses a Digital Sun Sensor (DSS) to precisely measure the sun vector in order to insure that power constraints are not violated, and to provide an accurate and stable inertial reference during sun pointing modes of operation.

Fluxgate Magnetometer

The ACS uses a Three-Axis fluxgate Magnetometer (TAM) which is capable of measuring the geomagnetic field vector in all on-orbit modes of operation.

Global Positioning System

The GPS sensor provides time, position, velocity and attitude information to the SCS over a MIL-STD-1553 data bus. Three microstrip patch antennas are used to receive the GPS signals and are mounted on the solar arrays in a plane normal to the telescope longitudinal axis. This antenna configuration is selected as the most suitable for minimizing multipath interference.

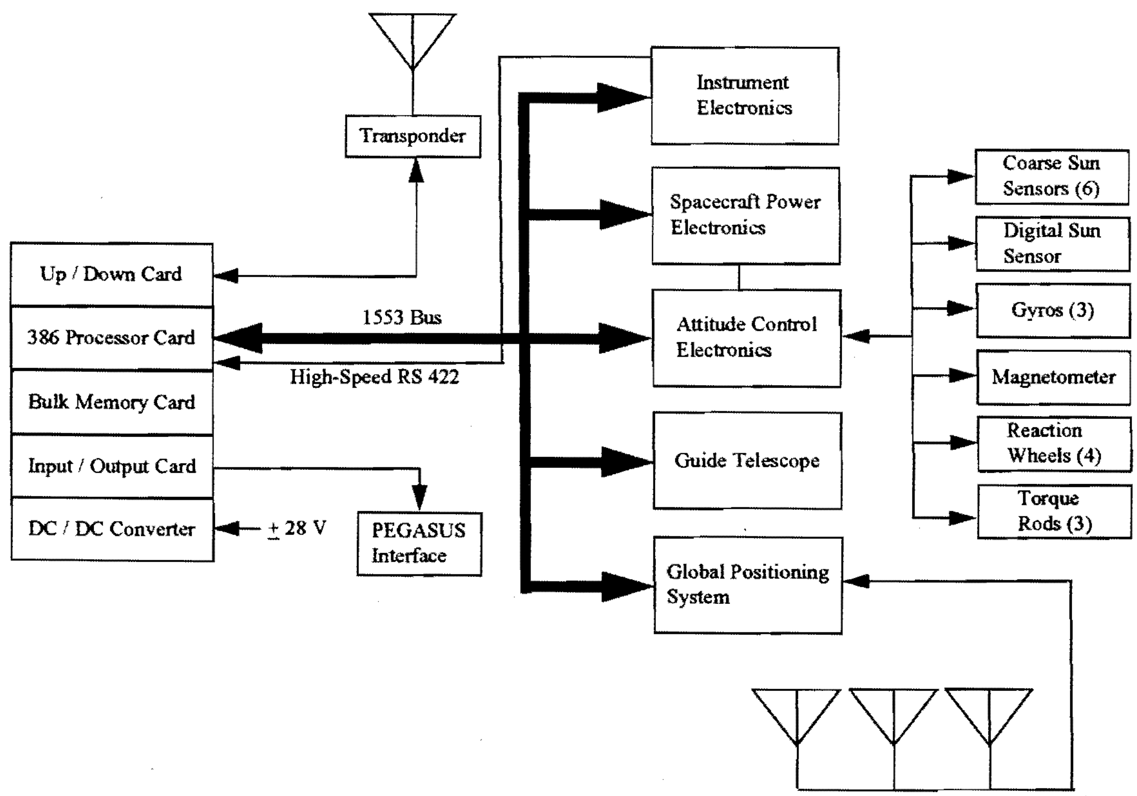

Fig. 2. TRACE Data Flow Diagram

Guide Telescope

The ACS accepts steering error signals from the GT which is part of the TRACE instrument package. The GT focuses the sun's image on a four quadrant photo diode detector which then generates a signal proportional to the angular error between the TRACE instrument boresight and the sun line. The instrument can be pointed to arbitrary offsets up to 1° from the sun center by using a pair of rotating wedge prisms within the GT to steer the image on the focal plane and then commanding the ACS to null the error signals. Tracking, fine pointing and slews are all accomplished by steering the prisms and nulling the GT errors signals. The GT null error signals are available as soon as a single photo diode is illuminated and the ACS receives a valid data flag. When all four photo diodes are illuminated the sun image is within the linear range of the telescope field of view (±110 arcsecond). The instrument computer filters the null error signals and then transmits the data to the ACS controller over the MIL-STD-1553 interface.

Gyro Package

The ACS uses a set of three two-axis gyros (oriented in a redundant configuration) to measure spacecraft body rates. Knowledge of the body rates is required for GT capture, roll rate damping sufficient to meet the drift rate requirements and avoid instrument pixel blurring, and on-board attitude determination. The gyros are required to have a drift rate not exceeding 1°/hour after on-orbit calibration. Calibration information will be derived on the ground using science instrument solar images as a truth model and uploaded to the spacecraft as necessary.

Magnetic Torquer Coils

The ACS uses three electromagnetic torquer coils for initial acquisition/safehold rate damping and precession control as well as momentum management during science operations. The magnetic torquers are sized to provide a minimum of 150% of the maximum anticipated momentum unloading required to support the nominal mission operations and also to provide initial despin and sun pointing precession within the battery capacity constraints.

Reaction Wheels

The ACS relies on Reaction Wheels (RWs) for primary attitude control during normal operations and to provide a momentum bias during initial acquisition/safehold procedures. The ACS uses four RWs configured in a tetrahedron such that the spacecraft maneuvering and control capability is retained in the event of the loss of any one wheel. Nominal wheel operation avoids extended activities near zero speed to maintain hydrostatic pressure of the bearing lubricant. The wheels are sized to provide a minimum of 115% of the torque and a minimum of 120% of the momentum storage required to support nominal mission operations.

Design Trades

Design trades were performed to examine the cost differential associated with reducing (1) the number of RWs from four to three and (2) the number of gyros from three to one. Although the specific hardware costs are reduced, the cost required to modify and/or develop drawings, test procedures and software exceeds the potential hardware savings.

TRACE ACS Operational Modes

The ACS subsystem is responsible for determining and controlling spacecraft attitude during all modes of operation. Digital control is provided by the SCS, while the ACE is used in a standalone mode of operation during initial acquisition and anomalous situations. The ACS modes of operation are described in the following sections and are summarized in Table 1. A close inspection of Table 1 indicates that all TRACE ACS modes use previous SMEX technology in an effort to reduce the cost associated with the hardware/software development and validation.

Acquisition/Safehold

The ACS is capable of autonomously measuring the sun vector and maneuvering the spacecraft to orient the solar arrays towards the sun after separation from the launch vehicle is detected. Initial acquisition utilizes the ACE in a standalone

Table 1. TRACE ACS Operational Modes

Mode Name	Sensors	Actuators	Control Elements	Description
Acquisition/ Safehold	CSS, DSS, TAM	Torque Rods, 1 RW	Analog Electronics: B-dot, +Y Axis Sun Precession, Momentum Bias	Electronics in ACE box, used for initial sun acquisition and safehold Heritage - SAMPEX, SWAS
Digital Sunpoint	CSS, DSS, TAM	Torque Rods, 1 RW	Digital version of Acquisition/Safehold: B-dot, +Y Axis Sun Precession, Momentum Bias	SCS 386 processor, used for L&EO and safehold backup Heritage - SAMPEX, SWAS
Magnetic Calibration	TAM	Torque Rods		Used to calibrate the magnetometer contamination matrix Heritage - SAMPEX, SWAS
Science Point: Inertial Sunpoint	CSS, DSS, TAM, Gyros, GPS	Torque Rods, 4 RWs	Science Control Laws, Momentum Management, Kalman Filter: Three-axis Control	SCS 386 Processor, used for inertial sun pointing prior to GT hand-off Heritage - SWAS
Science Point: Fine Sunpoint	CSS, DSS, TAM, GT, Gyros, GPS	Torque Rods, 4 RWs	Science Control Laws, Momentum Management, Kalman Filter: Three-axis Control	SCS 386 Processor, used for fine sun pointing and science data taking Heritage - SWAS

mode and only employs a minimal suite of hardware components in order to minimize power usage. This mode is accomplished by first establishing a momentum bias vector normal to the solar arrays (along the +Y axis) using a single RW, and then using a combination of magnetic B-dot damping and precession control to nudge the momentum bias vector to the sun line as sensed by the DSS and CSS's. A functional block diagram of the acquisition/safehold mode is presented in Fig. 3. Once the spacecraft has completed the sun acquisition, the initial acquisition controller is capable of maintaining solar array pointing towards the sun for an indefinite period of time with the +Y axis aligned to within ±20° of the sun line.

Initial acquisition can be initiated from an arbitrary attitude with spacecraft body rates of up to 6°/second. This mode also serves as the satellite safehold and can be used to recover the vehicle in the event of a major anomaly such as failure of the SCS or the gyro package, and satisfies the Goddard Space Flight Center requirement for an independent analog safehold.

Digital Sunpoint

Digital Sunpoint is a transition mode between initial acquisition and the Science Point mode. It is functionally identical to the ACE initial acquisition except for being implemented within the SCS. This mode is always initiated by ground command and can be used as a backup safehold mode to compensate for failures within the ACE and to ease transitions between the ACE and SCS by providing an elementary mode for checkout of SCS functions. Digital Sunpoint uses the DSS, the CSS's, one RW, and the magnetic torquers to keep the +Y axis aligned to within ±20° of the sun line. This orientation also insures that the sun is within the field of view of the DSS to facilitate hand-off to the science mode.

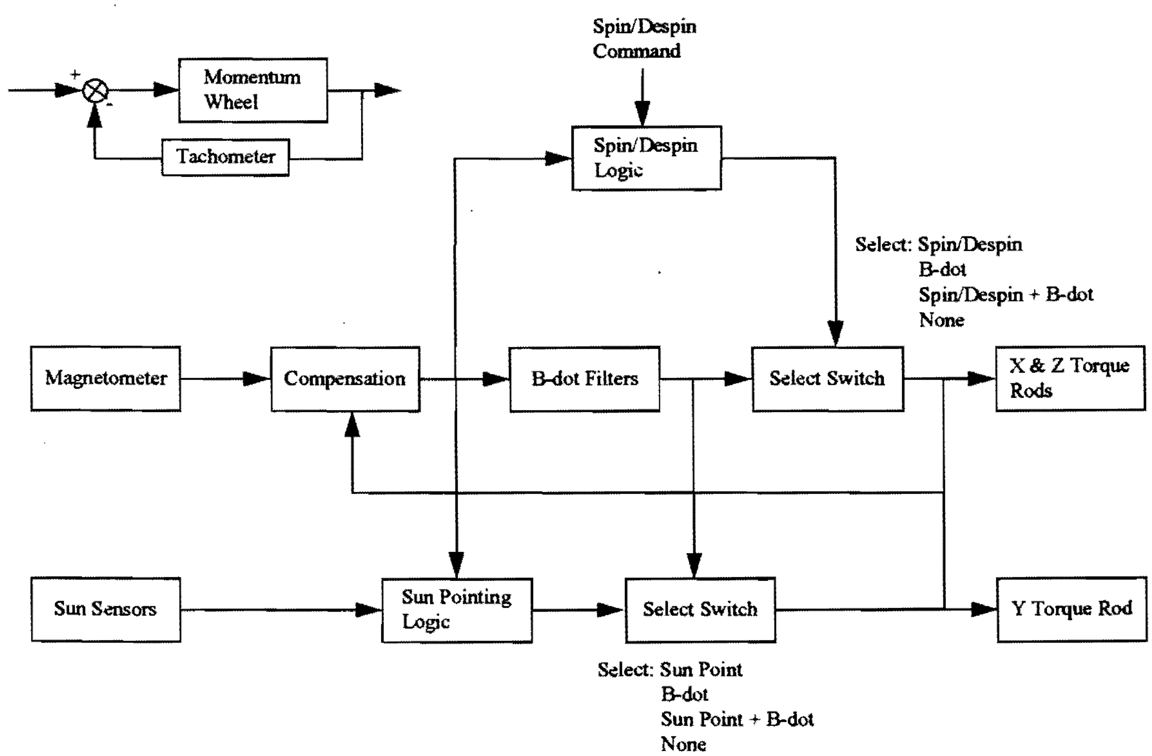

Fig. 3. Acquisition/Safehold Mode Block Diagram

Magnetic Calibration

Magnetic Calibration is intermittently executed to construct the TAM contamination matrix attributed to the magnetic actuators. The individual torque rods are activated in sequence and their effect on the TAM is measured and stored in the SCS.

Science Point

The nominal mission ACS capabilities are implemented with digital control laws hosted in the SCS microprocessor. Science Point mode can be separated into two submodes of operation: Inertial Sunpoint and Fine Sunpoint. The primary difference between the two submodes is that Inertial Sunpoint uses the DSS to sense the sun line while Fine Sunpoint receives controller error signals from the GT. The purpose of Inertial Sunpoint is to serve as (1) a transition from the initial momentum bias state to Fine Sunpoint operation, and (2) as a power safe mode in the event the GT loses lock on the sun. Functional block diagrams of both the Inertial Sunpoint and Fine Sunpoint submodes are presented in Figs. 4 and 5 respectively.

Inertial Sunpoint Inertial Sunpoint maintains the spacecraft in a sun pointing orientation with the +Y axis (the axis normal to the solar panels) on the sun line to within 0.5° and zero roll rate. The GT can then acquire the sun from this attitude by performing a search using the wedge prisms. The initial attitude reference is provided by observations of the sun using the DSS and magnetometer measurements of the local geomagnetic field vector. The gyro package is used to propagate the vehicle attitude and is corrected using inertial updates from the DSS and the TAM via a Kalman filter. The pointing control laws utilize errors derived from the filter attitude solution and a target attitude as well as the gyro supplied rate information to maintain sun pointing prior to the GT hand-off. Attitude control is maintained by torquing the RWs, while excess wheel momentum is unloaded via the torque rods.

Fine Sunpoint Fine Sunpoint employs the same ACS software algorithms

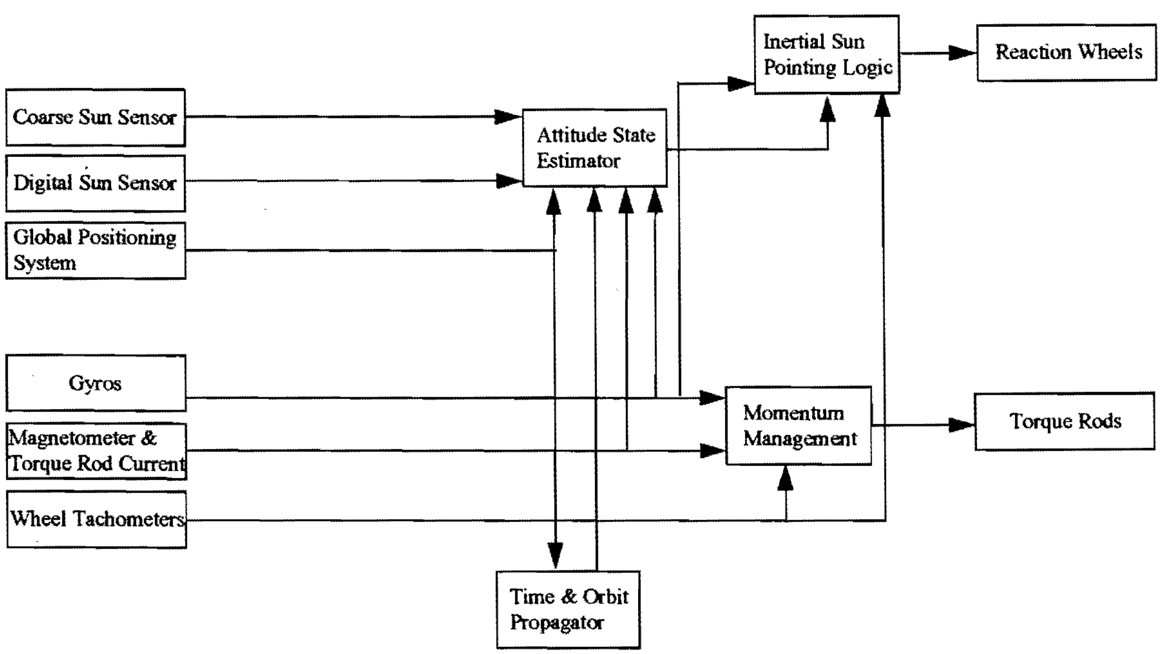

Fig. 4. Inertial Sunpoint Block Diagram

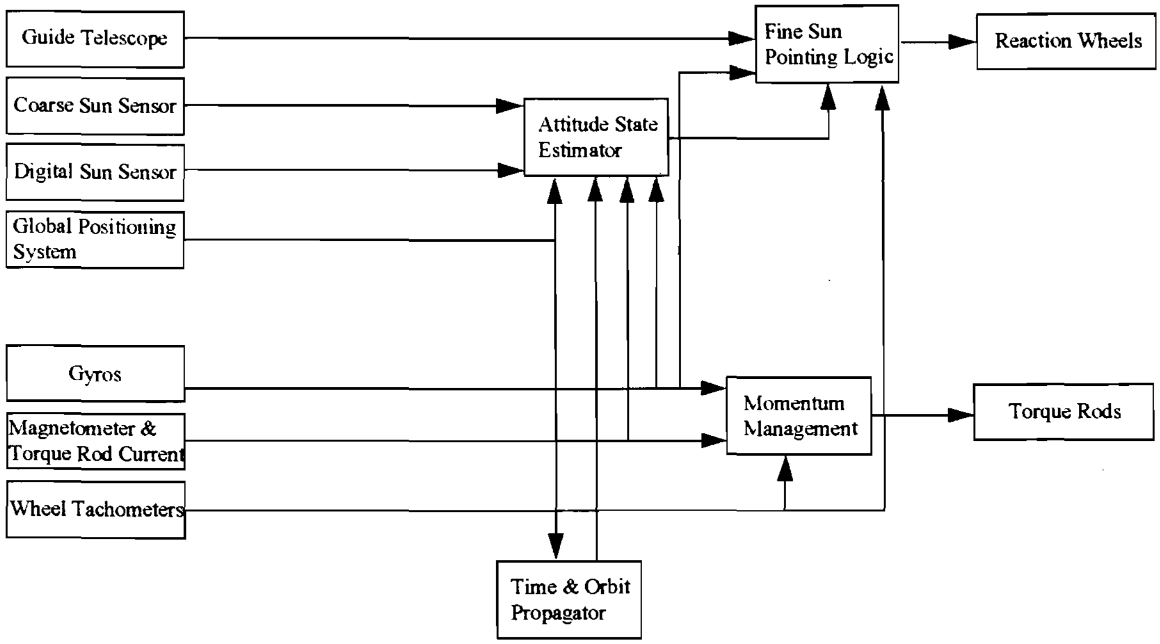

Fig. 5. Fine Sunpoint Block Diagram

as Inertial Sunpoint except for substitution of the GT error signals for the filter derived pitch and yaw error information. The accuracy of the GT allows for a finer pointing of the science instrument to the desired sun features by continuously using the ACS controller to null the fine error signals transmitted by the GT. The gyro package is used to propagate onboard attitude knowledge with inertial updates from the DSS and the TAM incorporated using a Kalman filter. Spacecraft rates, and in particular the roll axis, are damped using information from the gyros to maintain levels below the 1°/hour drift requirement in order to avoid pixel blurring during science data taking operations. Control torques are generated by the RWs and wheel momentum is regulated with the torque rods.

During Fine Sunpoint, the instrument incorporates an Image Stabilization System (ISS) which is used to provide active stabilization of the instrument line of sight by removing jitter beyond the bandwidth of the ACS. The ISS consists of a gimbaled mirror driven in two axes by piezo electric actuators which null the same GT error signal provided to the ACS. The ISS bandwidth extends about 1 decade beyond the ACS (to > 1.5 Hz) and primarily compensates for high frequency, small amplitude structural and mechanical vibrations. Adverse coupling between the ISS and ACS control loops is avoided since the optical paths of the ISS mirror and the GT are separate. Furthermore, the low inertia and small travel of the ISS mirror never develops any appreciable momentum, and therefore inertial coupling is negligible.

TRACE periodically slews to acquire a new target according to a stored timeline, on ground command, or autonomously as the opportunity to observe a transient phenomenon becomes available. The separation between targets may be up to 1° and slews must be completed within 2-3 minutes including settling time. Fine Pointing slews are performed by simply steering the GT wedge prisms to a new position and commanding the ACS to null the error signal. In order to maintain the error signals within the unsaturated region of the GT field of view, the instrument must monitor the commanded step errors and only issue the next step when the null errors are within a 20 arcsecond deadband. Since all slews are small in magnitude, no appreciable momentum is developed, and therefore excitation of the flexible body modes, including the hinged instrument door, is not anticipated to pose a problem.

Global Positioning System

The GPS sensor derived information will be used to perform three functions: (1) provide the onboard spacecraft clock reference, (2) predict ground contact Acquisition Of Signal (AOS) and Loss Of Signal (LOS) times for the Wallops and Poker Flats ground stations, and (3) supplement the ACS software. The predicted AOS and LOS information will be sent to the ground and used for spacecraft operations and ground pass scheduling. For the ACS specific routines, the time, position and velocity data will be used to update the epoch for the onboard time and state vector propagation routines, while the attitude solution will be coupled with the gyro and TAM data to produce a derived roll attitude result. A block diagram of the complete GPS task architecture is presented in Fig. 6.

The primary reason for including the GPS demonstration is to further this technology and generate a product for future space applications. A second goal is to demonstrate features of the technology which will help reduce program costs on future missions. For example, synchronization of the onboard spacecraft clock, and generation of the navigation and ground pass scheduling information will enable the SMEX program to eventually eliminate functions currently performed on the ground, and thus reduce the overall mission cost.

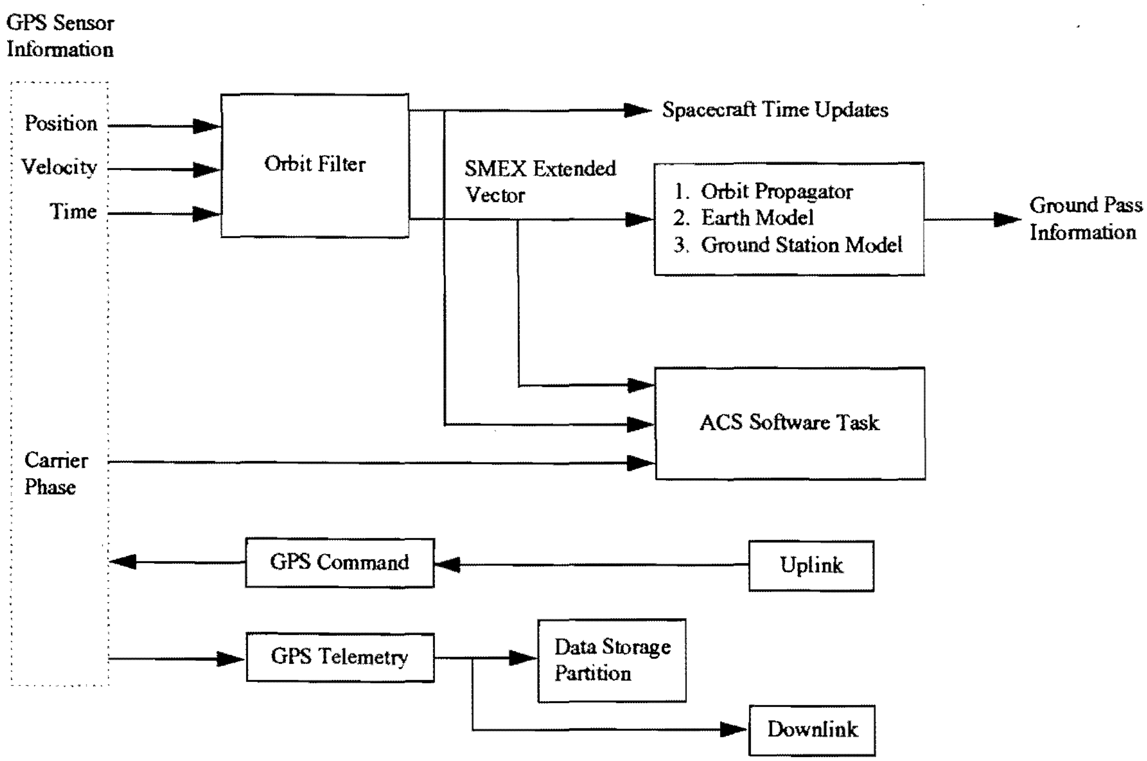

Fig. 6. GPS Task Architecture

Simulation Results

In order to evaluate the TRACE ACS performance during all modes of operation, a three-axis, non-linear, time-domain simulation is developed using the TREETOPS software package.[2] The high fidelity simulation code parallels the anticipated ACS flight software architecture in an effort to reduce the cost involved with porting the software to the flight processor. A functional block diagram of the ACS flight software architecture is illustrated in Fig. 7. In the following paragraphs, the control laws for the individual operational modes are presented followed by an example of the simulated TRACE vehicle performance.

Acquisition/Safehold-Digital Sunpoint

As previously described, the Acquisition/ Safehold and Digital Sunpoint logic maintain a fixed RW speed along the instrument boresight (roll axis) while the three magnetic torquers damp unwanted rates and orient the solar arrays towards the sun. The wheel speed control law and the torque rod command logic are executed at a 10 Hz rate and a 2 Hz rate respectively. The RW speed control law can be expressed as:

$$T_{cmd\,y} = K_s(\omega_w - \omega_c) \qquad (1)$$

while the magnetic torquer commands are generated using the following equation:

$$\begin{aligned} m_x &= -K_b \frac{dB_x}{dt} \\ m_y &= -K_b \frac{dB_y}{dt} + K_p \mathrm{sign}[S_x B_z - S_z B_x] \qquad (2) \\ m_z &= -K_b \frac{dB_z}{dt} \end{aligned}$$

Note that in the actual ACS hardware/ software, Eqs. (1) and (2) are implemented in both an analog form (Acquisition/ Safehold mode) and a digital representation (Digital Sunpoint mode).

Science Point

The Inertial Sunpoint and Fine Sunpoint control laws are identical in form, with the only difference being the error signals used to construct the eigenaxis rotation angle. As previously stated, during the Inertial Sunpoint submode, the pitch and yaw errors are provided via the Kalman filter whereas during the Fine Sunpoint submode, the pitch and yaw errors are generated by the GT. In both submodes, the roll error is derived from the Kalman filter.

The Science Point mode control law is operated at 10 Hz and is divided into two functions: slew and fine pointing. The slew logic is executed whenever the eigenaxis rotation angle is greater than 2.8° and is in the form of a nonlinear momentum control law given as:

$$\begin{aligned} \mathbf{h}_{cmd} &= \mathbf{H} - (\mathbf{I}\cdot\mathbf{v})\sqrt{2K_a\theta} \\ \mathbf{T}_{cmd} &= K_{ts}(\mathbf{h}_{cmd} - \mathbf{h}) - \omega \times \mathbf{H} \end{aligned} \qquad (3)$$

Fine pointing control is equivalent to a linear Proportional Integral Derivative (PID) law and is expressed as:

$$\begin{aligned} \mathbf{h}_{cmd} &= \mathbf{H} - [K_h\theta(\mathbf{I}\cdot\mathbf{v}) + K_i\int\theta(\mathbf{I}\cdot\mathbf{v})dt] \\ \mathbf{T}_{cmd} &= K_{tf}(\mathbf{h}_{cmd} - \mathbf{h}) \end{aligned} \qquad (4)$$

The fine pointing control logic is activated when the rotation angle is less than 2.8°, however, any initial transition from slew to fine pointing control requires an eigenaxis rotation angle of less than 600 arcseconds. Also during slews, the integral term of the PID control law is zeroed to increase performance.

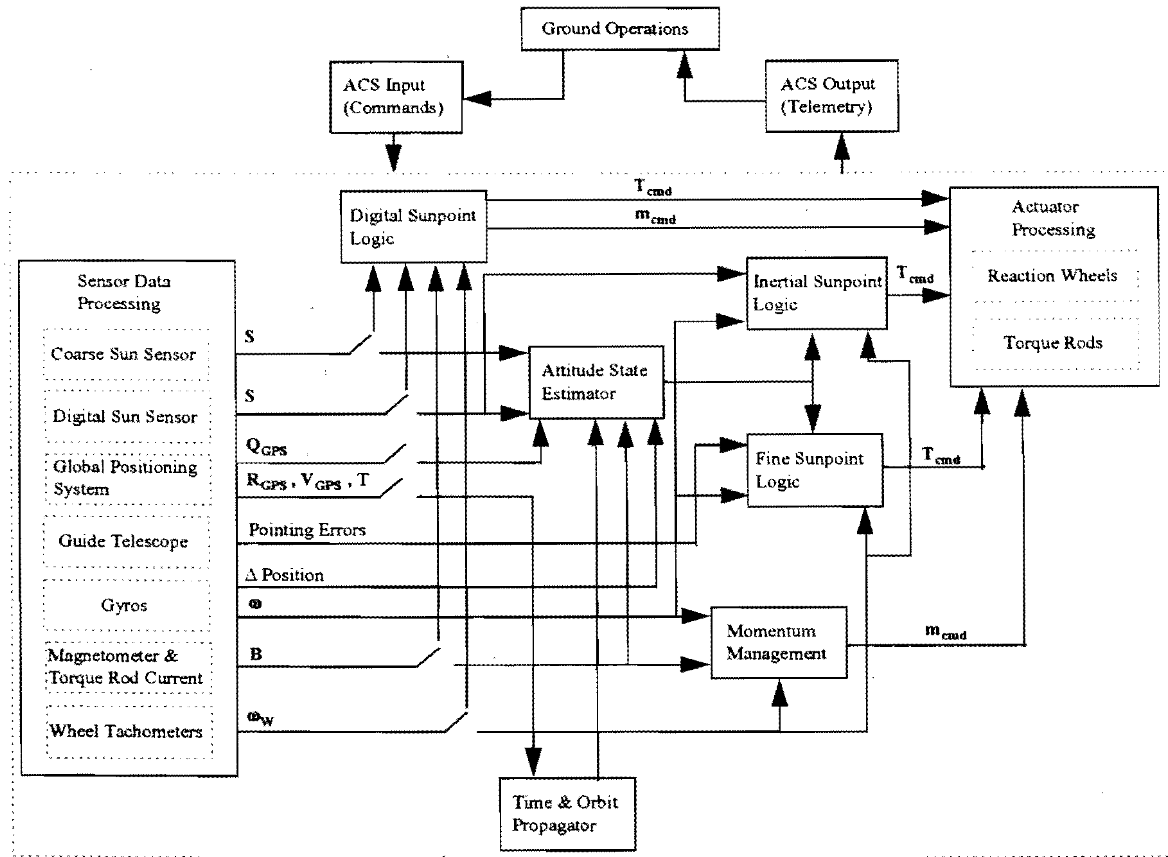

Fig. 7. TRACE Software Architecture

The Science Point mode control laws are also subject to RW power, speed (3.6 N-m-s) and torque (0.154 N-m) limits. As a result of the constraint logic, the RW speeds are maintained at a near constant value (still creating a zero-momentum system) in order to avoid zero-speed crossings and prolong wheel life.

Momentum management is performed during both slew and fine pointing control, where the excess RW momentum is removed at a 1 Hz rate by the 60 Amp-m^2 magnetic torquers according to the following control law:

$$\mathbf{m}_{cmd} = K_u(\mathbf{H} \times \mathbf{B}) \qquad (5)$$

Performance

The high fidelity simulation is used to characterize the vehicle behavior after the TRACE satellite separates from the launch vehicle, enters the initial acquisition sequence, transitions to the zero-momentum, three-axis stabilized Inertial Sunpoint submode, and then switches to the GT for pitch and yaw attitude errors during science data taking operations. The simulation is run for 5 orbits (approximately 30000 seconds) using the mass properties and control gain values given in Table 2. At the start of the simulation, the spacecraft instrument axis is 180° from the sun line with an initial roll rate of 6°/second. These conditions represent an assumed worst case initial acquisition situation.

Table 2. Simulation Parameters

Variable	Value
I	$\begin{bmatrix} 59.22 & -1.14 & -0.80 \\ -1.14 & 40.56 & 0.10 \\ -0.80 & 0.10 & 57.60 \end{bmatrix}$ kg - m^2
K_a	$0.0002 \ \frac{1}{s^2}$
K_b	$2.0 \times 10^{+8} \ \frac{\text{Amp - m}^2\text{ - s}}{\text{Tesla}}$
K_h	$0.589 \ \frac{1}{s}$
K_i	$0.111 \ \frac{1}{s^2}$
K_p	35.0 Amp-m^2
K_s	1.0×10^{-3} N - m - s
K_{tf}	$1.508 \ \frac{1}{s}$
K_{ts}	$1.7 \ \frac{1}{s}$
K_u	$3.0 \times 10^{+6} \ \frac{\text{Amp - m}^2}{\text{N - m - s - Tesla}}$
ω_c	$83.33 \ \frac{\text{rad}}{\text{sec}}$

The angle between the instrument boresight (roll axis) and the sun line is depicted in Fig. 8, where the top curve shows the entire time span and the lower curve is an expanded view beginning just after the start of orbit 3. From the top figure, the instrument boresight is initially 180° from the sun line and converges to around 20° after about an orbit. The vehicle continues to oscillate about this 20° angle until the Science Point control logic is commanded at the conclusion of the second orbit at which time the angle approaches zero. A close inspection of the bottom curve shows that once the Inertial Sunpoint submode begins, the angle is reduced to about 0.45° and then to zero after the Fine Sunpoint submode is commanded at 3.3 orbits. The 0.45° angle bias during Inertial Sunpoint is a result of the DSS resolution and misalignment, whereas during Fine Sunpoint, the GT signals are accurate to a quarter of an arcsecond and the sensor has perfect alignment.

To compliment Fig. 8, the spacecraft body rates are presented in Fig. 9. The X and Z axis inertial rates (top and bottom curves) show initial rate damping and precession of the spacecraft. Once the angle between the instrument axis and the sun line reaches 20°, the X and Z axes rates oscillate with an amplitude on the order of 0.4°/second. The oscillation occurs as the rate damping and precession effects approach equilibrium. The Y axis rate (middle curve) shows the damping of the 6°/second initial rate followed by a twice per orbit (0.12°/second) oscillation after the first orbit. When the Science Point mode is commanded (at the start of orbit 3), all three body rates approach zero to complete the transition to the three-axis stabilized, zero-momentum state.

The torque rod dipole commands and the RW speeds are illustrated in Figs. 10 and 11 respectively. As shown in Fig. 10, all three torque rods show strong activity during the initial acquisition phase and then are reduced to a few amp-m^2 during the momentum management function of the Science Point mode. From Fig. 11, the roll axis wheel (dashed line) runs at a speed of 83.33 radians/second during initial acquisition while the other three wheels remain at rest. Once Science Point is activated at the end of orbit 2, all four wheels converge to a speed of about 21 radians/second and stay at this level for the remainder of the simulation.

Once the Fine Sunpoint submode is activated (at around 3.3 orbits), pitch and yaw control switches from the filter derived errors to the GT measured pitch and yaw attitude errors which are presented in Fig.

12. A close inspection of this figure shows that when this submode is initiated, a single photo diode is illuminated in the pitch axis (solid line) and in the yaw axis (dashed line) as the two signals are saturated at -110 arcseconds and +110 arcseconds respectively. The TRACE ACS quickly nulls the saturated signals and at the same time focuses the sun's image on all four photo diodes, thus creating the linear range errors shown in the remainder of the figure. The pitch and yaw attitude errors remain on the order of 5 arcseconds for the remainder of the simulation, thus satisfying the 20 arcsecond science requirement.

Figure 13 shows the derived roll attitude error from the time when the Science Point mode is first activated. The Kalman filter is initialized with a deterministic solution generated from the DSS and TAM measurements. The initial attitude error is on the order of 6.8° and then quickly converges to less than 1° in about a quarter of an orbit. During the last orbit, the roll attitude error then stabilizes between 0° and -0.5°. The dominant error in the roll attitude solution is the uncertainty in the geomagnetic field measurement, especially over the poles. To model this uncertainty, the onboard magnetic field coefficients are offset from the truth model by five years. An examination of the roll attitude error during the Fine Sunpoint mode (orbits 3.3 to 5) shows that the error is within the science imposed knowledge requirement.

Conclusion

This paper has presented the SMEX program directive, highlighted the TRACE science mission and described, in detail, the TRACE ACS design. As part of the ACS design definition, the hardware components were described as well as the operational modes employed to meet the mission requirements. Also presented was a description of the TRACE GPS Technology demonstration. Throughout the text, attention was paid to highlighting specific factors which will result in an overall program cost reduction. Finally, the TRACE satellite ACS performance was simulated to assess the vehicle behavior during the primary operational modes. The results show that the spacecraft meets the science imposed requirements.

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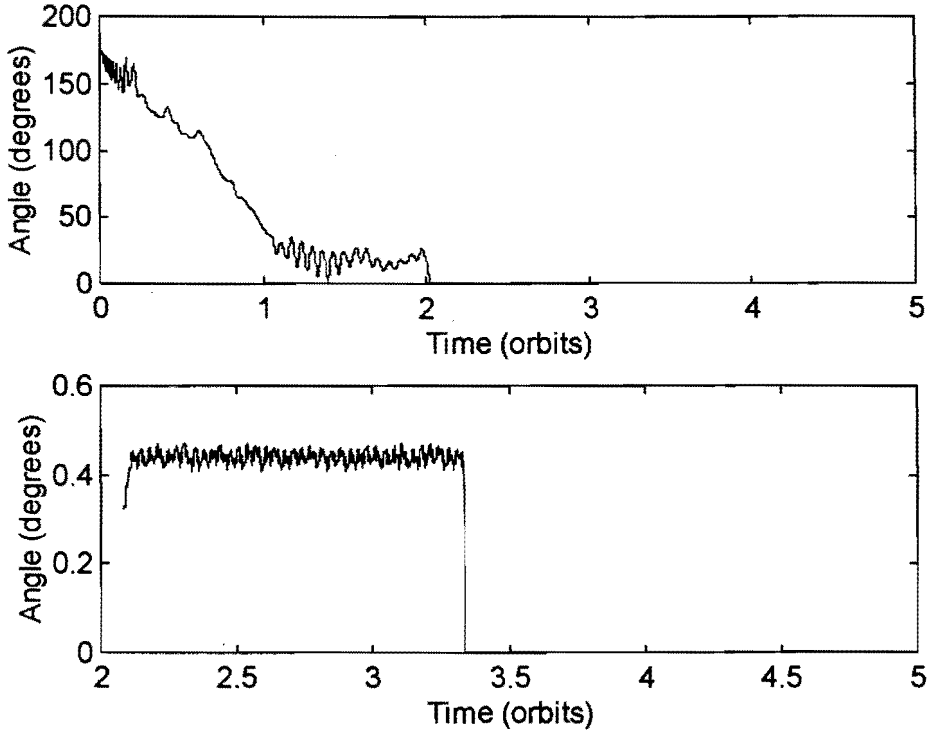

Fig. 8. Angle Between the Instrument Boresight and the Sun Line

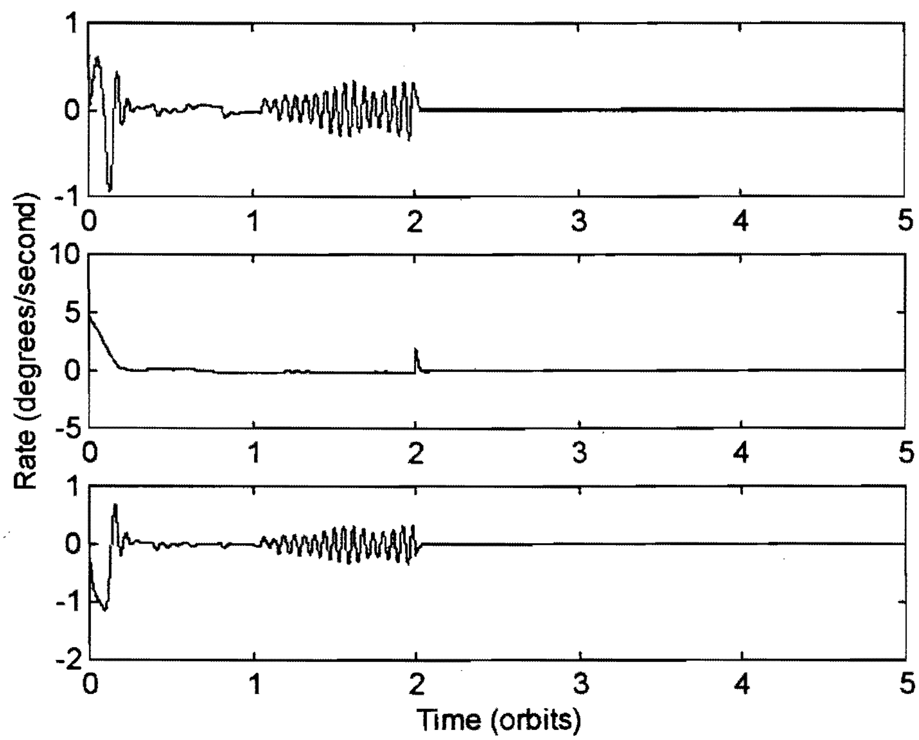

Fig. 9. X, Y and Z Axis Inertial Rates

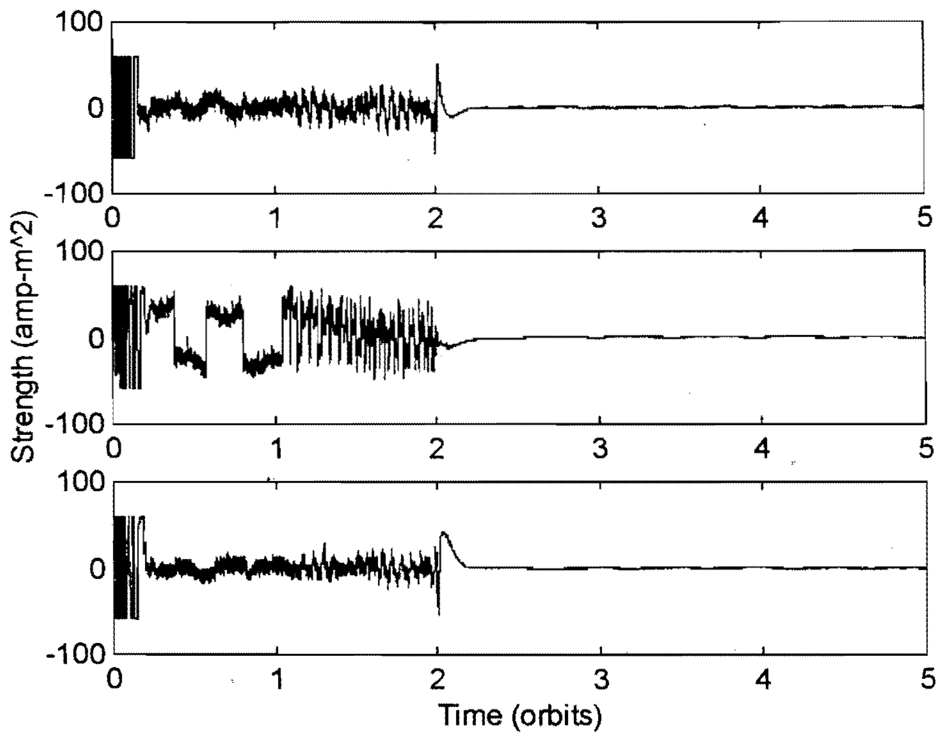

Fig. 10. X, Y and Z Torque Rod Dipole Commands

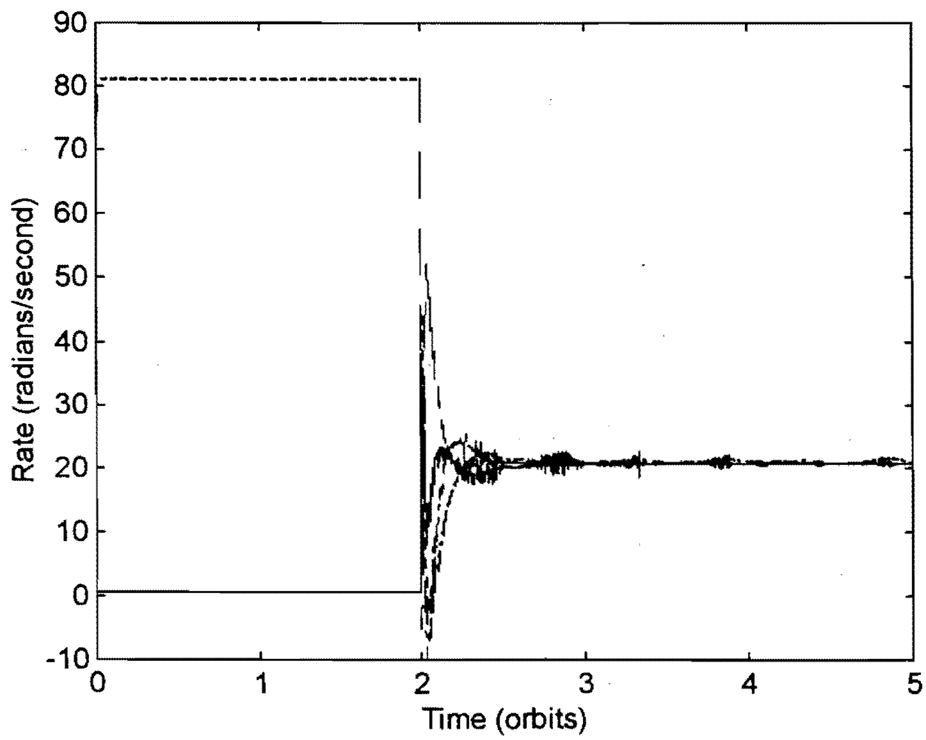

Fig. 11. Reaction Wheel Speeds

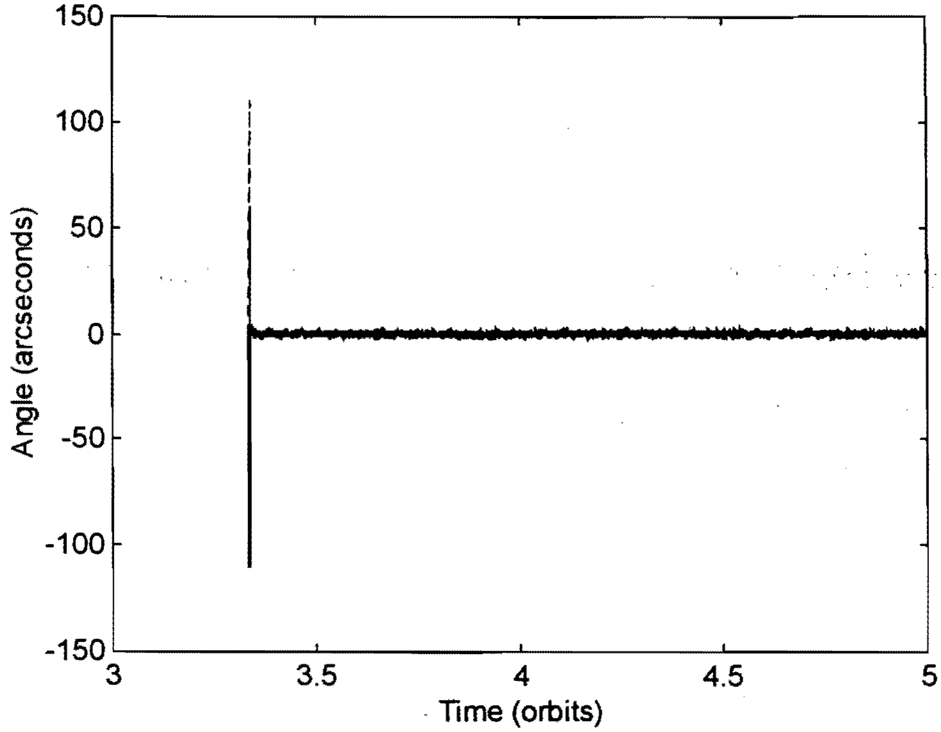

Fig. 12. Pitch and Yaw Guide Telescope Errors

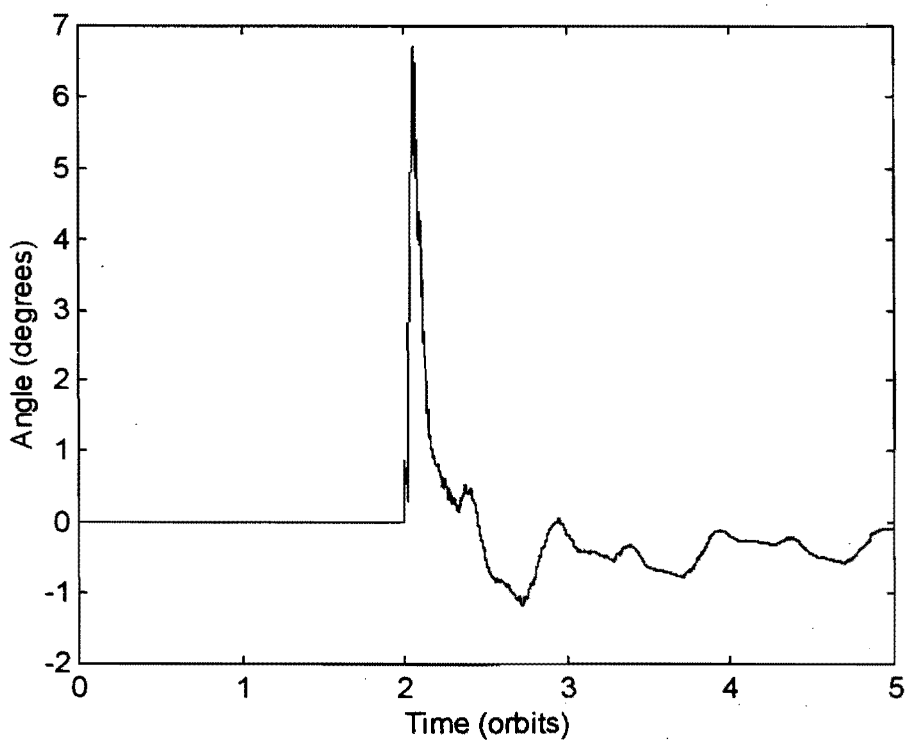

Fig. 13. Roll Attitude Error

Biography

Darrell Zimbelman received his B.S., M.S. and Ph.D. degrees in Aerospace Engineering from the University of Colorado at Boulder in 1986, 1987, and 1990 respectively. Since then he has worked as an Attitude Control System Engineer for the Fairchild Space and Defense Corporation and ITHACO, Inc. He has participated in various flight programs including EUVE, TOPEX/POSEIDON, FAST and SWAS. Currently, he is working at the Goddard Space Flight Center in the Attitude Control and Stabilization Branch of the Special Payloads Division. He is responsible for the attitude control system and the GPS technology demonstration on the TRACE spacecraft.