Precision Control, Knowledge and Orbit Determination on a Small Spacecraft Bus
The OrbView-4 Attitude Control System

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Abstract. High resolution, Earth imaging missions place stringent requirements on the spacecraft Attitude Control System (ACS) in terms of pointing accuracy, attitude knowledge, and orbit knowledge. For OrbView-4, a body scanner, the spacecraft must also be agile to maximize the number of targets that can be imaged each orbit. These requirements dictate a robust, high performance design that allows rapid target acquisition and high line scan rates for mapping while maintaining precise knowledge and control of the camera line of sight vector. The OrbView-4 ACS combines state of the art components with robust algorithm design to meet these objectives. Equipment selection, attitude determination, attitude control, and GPS based onboard orbit determination are discussed as the elements of an ACS design for an advanced Earth imaging spacecraft.

An overview of the OrbView-4 mission is presented along with a discussion of the requirements imposed on the ACS. The system architecture is described in terms of its hardware and software elements. The design of the attitude determination, orbit determination and attitude control algorithms are discussed, and the results of a system performance analysis are summarized.

OrbView-4 Mission Overview

Orbview-4 is a high resolution commercial Earth imaging satellite providing 1 meter panchromatic and 4 meter multispectral imaging capability. The OrbView-4 satellite also has a hyperspectral sensor with 8 meter Ground Sample Distance (GSD) added to and integrated with the camera to provide target spectral information.

The OrbView-4 mission is to generate, process, and distribute panchromatic, 4-band multispectral, and hyperspectral imagery on a commercial basis. The OrbView-4 payload will acquire 1 meter panchromatic imagery between 0.45-0.9 μm, 4 bands of 4 meter GSD multispectral imagery in the 0.45 to 0.9 μm spectral band, and 280 bands of hyperspectral imagery in the 0.45 to 5.0 μm spectral band. Imagery tasking originates with customers who have a need for imagery. In response to customer requests the OrbView Operations Center (OOC), after assessing customer needs and priorities as well as spacecraft constraints such as attitude agility, imaging rate, and downlink capacity, uplinks imaging tasking commands to the spacecraft. Subsequently, the collected wide band imagery data is either downlinked directly to distributor owned data downlink and processing centers, or stored on board in solid state memory and downlinked to one of two OrbView ground terminals for dissemination to the customer. The OOC maintains high latitude and CONUS ground stations as primary downlink sites.

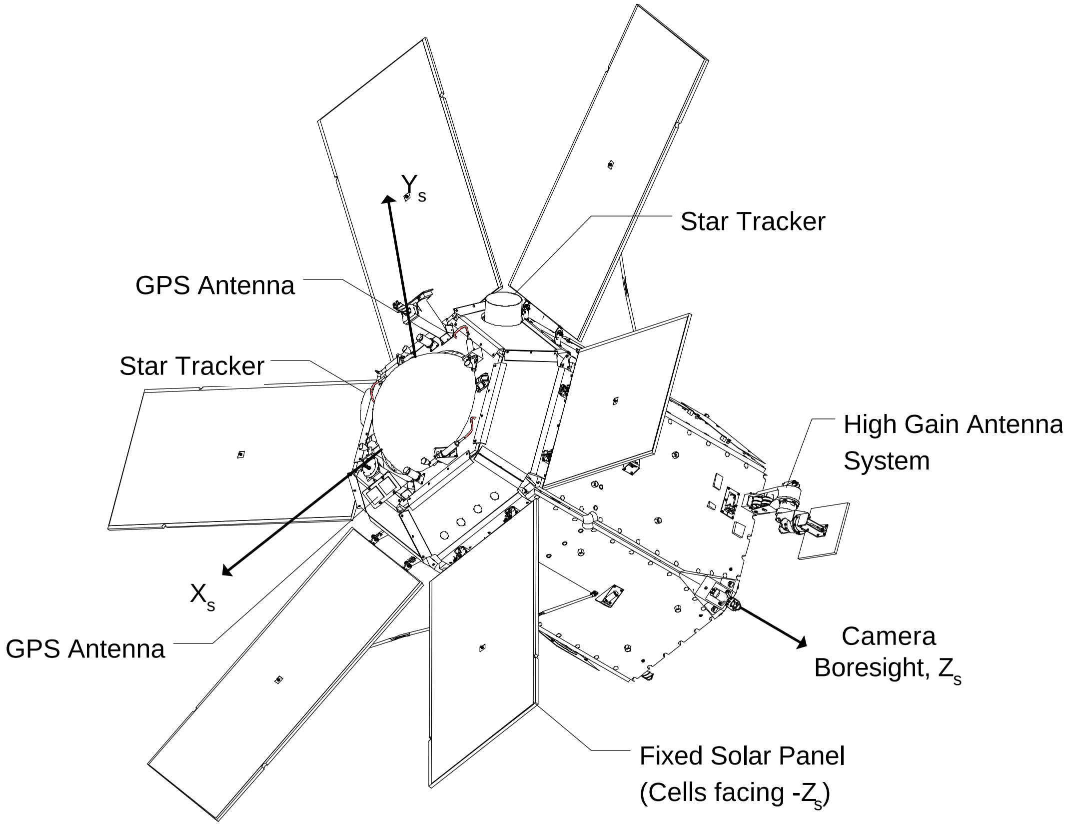

Figure 1. OrbView-4 Imaging Spacecraft

The spacecraft bus is responsible for providing all on-orbit support required for the camera to obtain imagery as commanded by the OOC. This includes data handling, data transmission, tasking implementation, thermal control, attitude control, structural stability, power, clocks, and attitude knowledge required for metric accuracy. The spacecraft gathers health and engineering housekeeping data and downlinks it to the OOC. The spacecraft receives compressed and uncompressed imagery data from the payload, formats and stores it on board as required, and downlinks an image data stream to the Earth ground terminals for transmission to the data processing segment. The data stream also contains data required to support post-pass radiometric calibration, image motion compensation, and geolocation. The spacecraft's mission lifetime is 5 years. The basic spacecraft design approach is single-string, with selective redundancy applied where necessary to achieve reliability needs. An outline of the OrbView-4 spacecraft is shown in Figure 1.

OrbView-4 will be launched by a Taurus™ launch vehicle into a sun-synchronous orbit with a 470 km altitude, and 97.25 degree inclination. The descending nodal crossing time will be nominally controlled to 10:30 AM, local solar time. The size of the altitude error envelope is set to maintain a 3-day maximum revisit time to any point on the globe within a field of regard defined by a 50 degrees maximum elevation angle in any direction from nadir. The nominal orbit period is about 94 minutes with eclipses ranging in duration from 34 to 36 minutes.

The spacecraft is required to support one or more imaging windows each orbit. An imaging window typically includes a mix of slow camera motions to scan a target and collect its image, and fast target-to-target slewing. This mix is highly variable. A single imaging window may consist of a single, long scan with no slews, or of several small-target scans with many slews between. In practice, each imaging window contains a variety of imaging types.

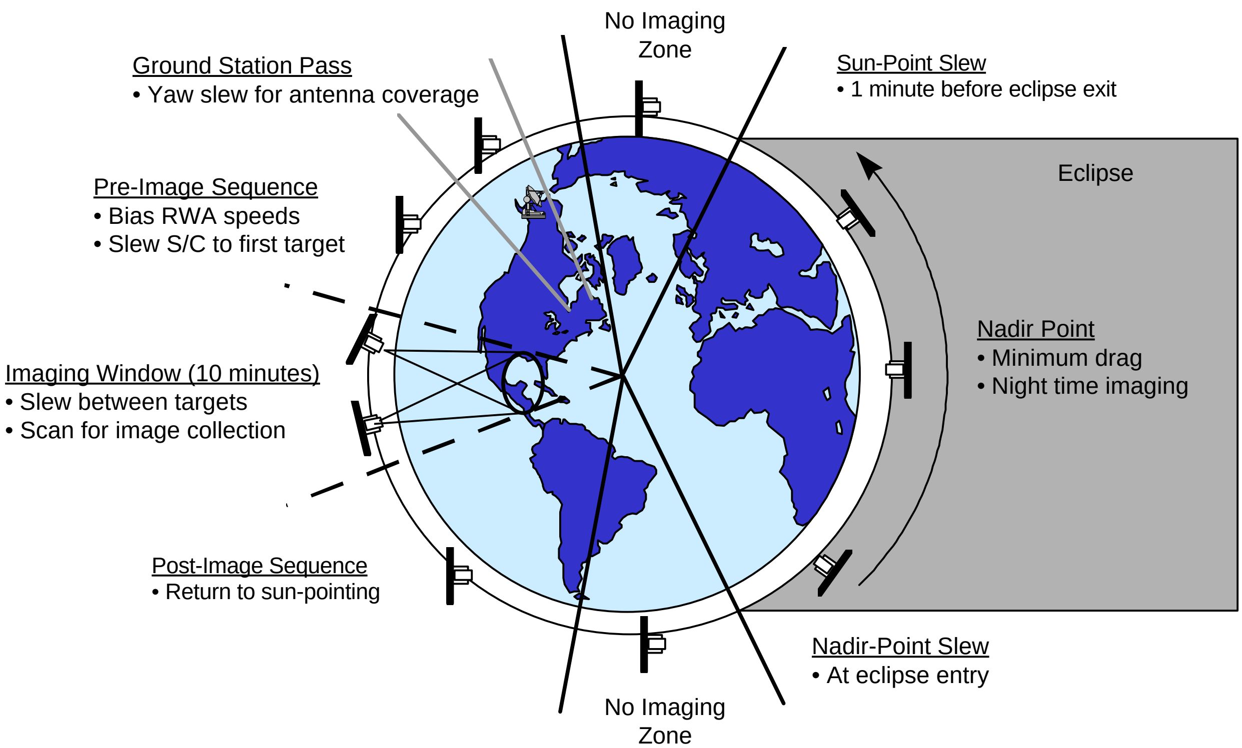

Figure 2. ACS Events Sequence

OrbView-4 Operational Sequence of Events

Spacecraft operations vary as a function of the location within the orbit. The typical spacecraft orbital routine is displayed in Figure 2. On exiting eclipse the spacecraft is oriented to align its fixed solar array panels normal to the sun-line. This provides the optimum attitude for recharging the batteries that were slightly depleted during the eclipse. During this charging period the spacecraft is rotated about its yaw axis to provide a favorable geometry for pointing the spacecraft high gain antenna toward a ground receiving station. Once image tasking commands are uploaded, the spacecraft, remains in its inertially fixed sunbathing orientation until a few minutes before the scheduled imaging window opens.

Prior to imaging initiation the attitude control system spins-up the reaction wheels (to avoid zero-speed crossing during imaging) and slews the spacecraft to an orientation that aligns the camera boresight to the first target and yaws the spacecraft to orient the camera's imaging array with the direction of scan. When the imaging window opens the spacecraft attitude is controlled in accordance with previously uploaded open-loop parameters that control the scanning motion during image gathering and slew commands to quickly acquire subsequent targets.

Upon imaging completion, the spacecraft is slewed back to the sunbathing attitude to recharge the batteries and the reaction wheel speeds are reduced to conserve power. On entering eclipse, the spacecraft attitude is reoriented so that the camera boresight is nadir pointing. This provides a favorable geometry for data downlink and maintains a minimum drag orientation to maximize mission life by minimizing the magnitude of orbit maintenance maneuvers. This orientation also facilitates payload calibration requirements. Approximately one minute before exiting eclipse, the attitude is reoriented to align the solar arrays with the sun-line from thence the process repeats.

ACS Overview

The ACS is formulated with high performance components to provide precise attitude and orbit determination while achieving fine pointing control as well as high speed slew capability to achieve rapid target acquisition. A functional block diagram of the ACS is shown in Figure 3.

Two star trackers are mounted, in a thermally isolated manner, on the spacecraft optical bench perpendicular to one another to allow precise attitude determination about each of three orthogonal reference axes. The star trackers provide an inertial attitude reference accurate to within 6 arcsec (1σ) while scanning at rates up to 1.5 deg/sec. The star trackers are capable of maintaining track at rates up to 6.0 deg/sec thereby facilitating rapid target acquisition slew maneuvers.

The star trackers are complemented with the Orbital Inertial Reference Unit (IRU) that utilizes fiber optic gyro technology to provide highly accurate body motion measurements. The Fiber Optic Gyros (FOG) have been specially designed for the OrbView-4 mission. Each FOG is comprised of two identical fiber optic windings stacked along the axis of rotation and is mounted to the optical bench using a single-point attachment. This allows thermal expansion to occur without distorting the optical bench while allowing the FOG to sense high frequency optical bench motion and thus preclude the need for angular displacement sensors. The FOGs are remotely located from the IRU electronics unit thereby removing all heat generating elements from the optical bench. The Orbital IRU is ideally suited for this application as it is free of dither disturbances typically associated with ring laser or mechanical gyros. The FOG IRU scale factor is less that 0.04 arcsec/bit, angular random walk less than 0.005 deg/rt-hr, bandwidth greater than 150 Hz and its data output frequency is 400 Hz. The IRU data is stored onboard for subsequent downlink to facilitate image post-processing.

Four reaction wheels are arranged in a pyramid about the spacecraft yaw axis. Each wheel is 65 degrees from the yaw axis thereby providing high roll and pitch control torque. Each reaction wheel is capable of producing a torque of 0.3 Nm and storing 19.5 Nms of angular momentum. The reaction wheels are divided into three components to allow the reaction wheels to fit inside a small spacecraft with tight volumetric constraints and to dissipate the heat generated during the imaging period. The reaction wheel assembly contains the motor, rotor and bearing assemblies. The electronics unit contains the motor drive and electrical interface to the spacecraft. The ballast assembly contains diodes used to dissipate, as heat, back-emf generated power during wheel deceleration. To minimize jitter, each wheel rotor is balanced to better than 0.5 gm-cm (static) and 5.0 gm-cm^2 (dynamic) and mounted to the spacecraft with vibration isolators.

GPS Onboard Orbit Determination Software (GOODS) provides a spacecraft position reference in the J2000 coordinate system in each of the along track, cross track and altitude directions accurate to within 25 meters (1σ). The GPS antennas have been mounted on the zenith side of the spacecraft and oriented to maximize the contact duration with each acquired GPS space vehicle. The GPS antennas nominally look toward the orbit normals so that tracking duration is limited primarily by GPS space vehicle motion and spacecraft slews. The mean contact time of greater than 25 minutes for each tracked GPS space vehicle allows pixel geodetic knowledge to be determined within 12 meters (1σ) during image post processing. Two GPS receivers and two dual antennas are provided for redundancy.

Ten coarse sun sensor detectors strategically positioned about the spacecraft provide the failsafe means of attitude determination in the Safe Hold mode. The detectors provide near 4π steradian coverage. In the event of an anomaly, this detector arrangement allows optimal spacecraft slewing, in the presence of shadowing and Earth albedo, to orient the solar array panels toward the sun. The detector placement also protects the camera from sun damage.

A three-axis magnetometer and three magnetic torquer bars are used for momentum control. The magnetometer sense range is -600 to +600 milliGauss and the magnetic torquer dipole in nominally 12 amp-m^2. Each torquer bar is mounted on one of the three control axes. A simple M cross B control law is employed to maintain the momentum level to less than 0.5 Nms per control axis throughout the orbit. This allows the spacecraft to be slewed with minimal gyroscopic coupling induced by maintaining high levels of stored momentum in the reaction wheels.

The ACS sensors and actuators are linked by the Attitude and Power Electronics (APE). The APE acts as a Remote Terminal (RT) on a dual redundant Mil-

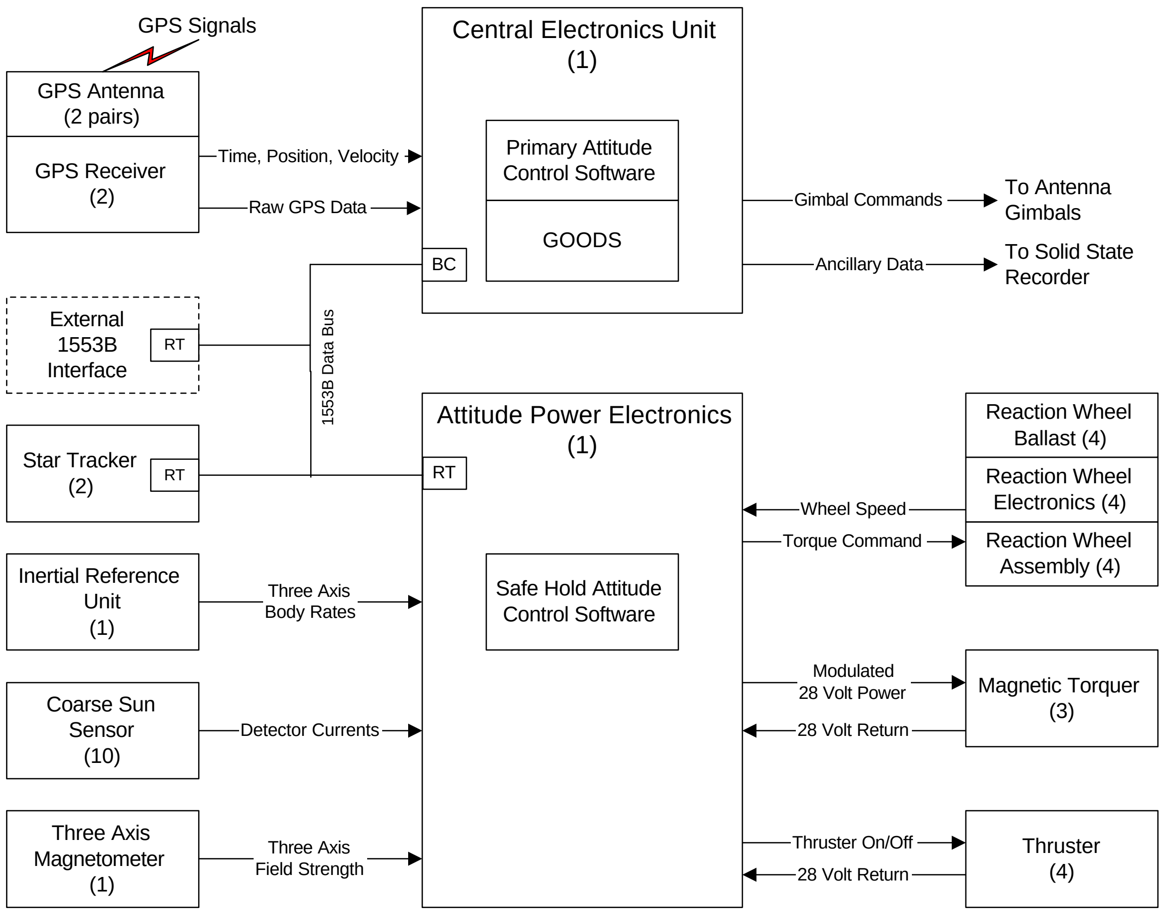

Figure 3. ACS Block Diagram

Std-1553B bus and contains a 69R000 processor used for Safe Hold mode processing as well as power and thermal management. The APE is used to decode and distribute command, control and data request signals between the Central Electronics Unit (CEU) and interface electronics for attitude sensors and actuators and general purpose telemetry conditioning. The CEU contains a RAD6000 processor which is used to perform all the primary attitude determination and control as well as the GOODS processing. The CEU acts as the 1553 Bus Controller (BC) and also contains uplink and downlink control functions and regulates the flow of payload and ancillary data to the solid state recorder.

ACS Control Modes

The ACS utilizes six separate and distinct control modes. The Launch, Normal, Imaging, Orbit Adjust and Contingency control modes are executed by the CEU processor and the Safe Hold control mode is executed by the APE processor. At all times, either the APE or the CEU is the attitude control computer. In each processor, there is always one ACS control mode active. When the APE is the control computer, the attitude control commands from the Safe Hold mode are supplied to the ACS actuators, while the APE inhibits CEU attitude control commands from being supplied to the ACS actuators. When the CEU is the control computer, the APE inhibits the control commands from the Safe Hold mode and delivers commands received from the active CEU control mode to the ACS actuators. The ACS control mode and submode can be selected by command or autonomously following detection of a system fault or an attitude or rate error in excess of predefined thresholds. The attitude control mode switching diagram is shown in Figure 4.

Safe Hold mode orients the spacecraft Z_S-axis parallel to the sun vector with the negative Z-axis oriented toward the sun such that the spacecraft solar array panels are illuminated. Once the sun orientation is achieved a commanded rotation rate about the spacecraft Z-axis is maintained. During eclipse the nominal sun orientation is maintained.

Contingency mode provides a means of operating the spacecraft with the CEU computer in the event that both star trackers are off-line or the spacecraft has an invalid ephemeris due to a GOODS fault. Contingency mode is also used following launch vehicle separation to provide a power positive attitude while the star trackers and GOODS are each initialized.

Normal mode provides a means of operating the spacecraft during non-imaging and non-thrusting operation. Three submodes are used to point the spacecraft to the Earth, sun or an arbitrary inertial attitude, while the fourth submode is used to provide a means of slewing the spacecraft attitude from one orientation to another. Typically the Earth Target submode is used during eclipse periods; the Sun Target mode is used either before or after imaging; and the Inertial Target submode is used both to position the spacecraft near its initial imaging attitude and prior to orbit maintenance maneuvers.

Imaging mode orients the camera boresight toward ground based targets defined by an uploaded attitude maneuver command file. The star tracker is used in conjunction with the GPS derived orbit to provide the attitude reference and the IRU is used to provide body rate estimates. Reaction wheels are used to reorient to the target attitude and to control the motion of the spacecraft as commanded by the attitude maneuver command file. A reaction wheel bias speed and initial attitude are commanded before Imaging mode is entered. The attitude is slewed to the initial imaging attitude using the Normal mode, Slew submode prior to the start of imaging. Ancillary data (i.e. attitude determination and control data needed for post facto image enhancement) processing is started before beginning imaging and terminated once imaging is complete.

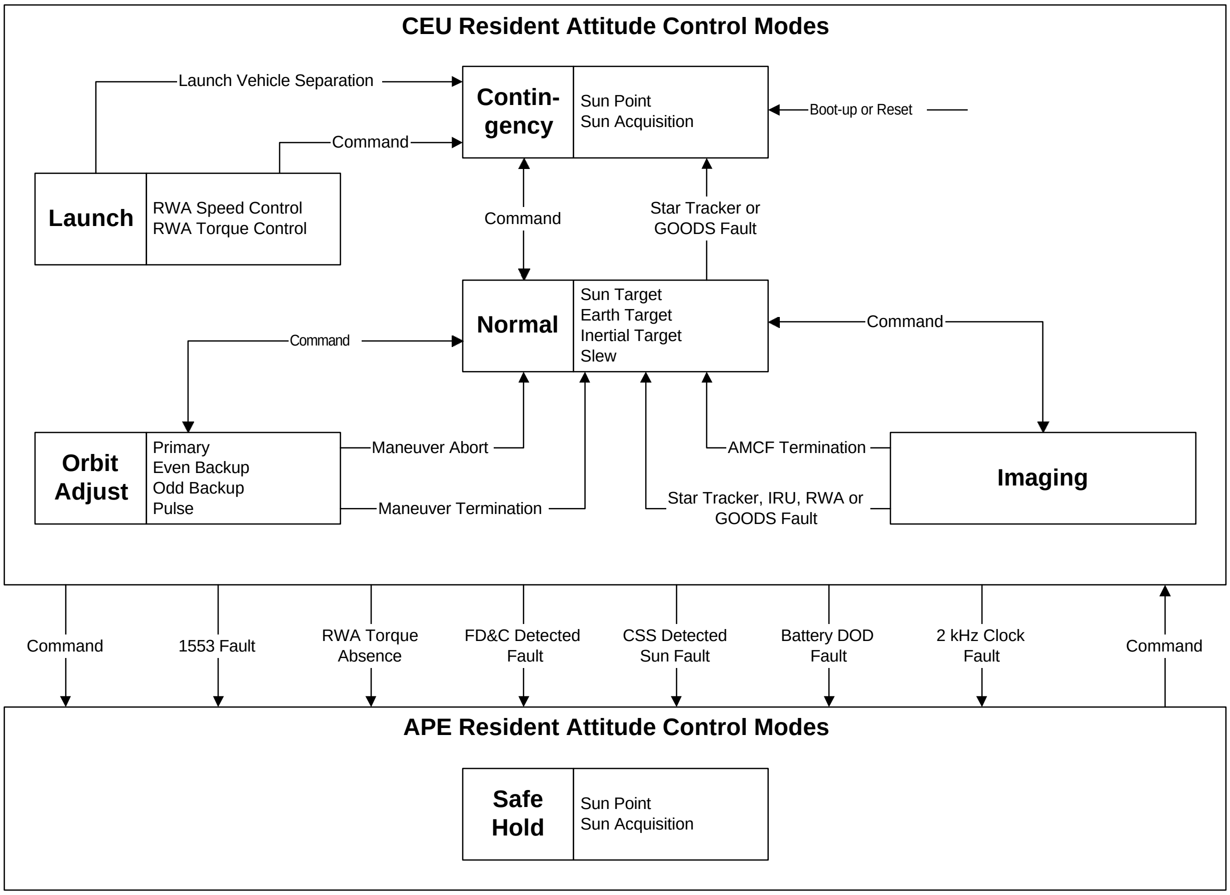

Figure 4. ACS Control Mode Switching Diagram

The Orbit Adjust mode provides closed-loop attitude control during thruster firing. The ACS having previously been oriented to the desired attitude, fires the selected thrusters for the commanded number of jet-seconds. The attitude is controlled in this mode using the reaction wheels with thruster augmentation, based upon IRU sensed body rates. Four 4.45 N hydrazine thrusters are off-pulsed for attitude control.

The Launch mode is used to provide a known, benign and controlled state of the ACS during spacecraft test as well as during pre-launch and launch mission phases. In Launch mode the ACS sensors are decoupled from the ACS actuators. The ACS sensor and actuator data outputs are provided in telemetry. Launch mode has two submodes allowing control of either RWA speed or torque.

Attitude Determination System

The OrbView-4 attitude determination system uses data from the two star trackers and the IRU to estimate the inertial-to-body attitude quaternion and body rates for input to the attitude control system. Data from both star trackers is used in normal operation, but the system is also configured for single-tracker operation in the event of a data loss from either of them. The attitude determination logic is implemented as a conventional Kalman filter updated with star tracker data at 1 Hz. Between filter updates the attitude quaternion is propagated with gyro data at 10 Hz.

The four logic components are identified on Figure 5, a functional diagram of the attitude determination system, along with their software execution rates. In addition to using data from the star trackers and IRU, the logic also uses data from the GOODS to correct the tracker data for velocity aberration.

The IRU data is sampled and processed at 10 Hz. For each axis, the accumulated counts are converted to incremental angles that are corrected for the estimated gyro bias from the Kalman filter. These incremental angles are used to propagate the inertial-to-body attitude quaternion, also at 10 Hz. The IRU processing logic also contains a discrete differentiator to compute the body rates from the bias-corrected incremental angles. These estimated rates are provided to the Kalman filter for covariance propagation, and also to the attitude control logic for rate control.

The star tracker processing logic reads the measured attitude quaternions at 1 Hz and corrects them for velocity aberration and transport delay. The aberration correction is computed based on the instantaneous star tracker line-of-sight vector in the inertial frame, and the spacecraft velocity vector and the sun position vector from the GOODS. The data transport delay is corrected by propagating the measured attitude quaternions forward through the delay time using the estimated rates from the IRU processing logic. The corrected measurements are output to the Kalman filter logic.

A six-state Kalman filter is used to estimate the incremental corrections to the current attitude and gyro bias estimates. Filter updates occur at 1 Hz. The error covariance is propagated with the estimated rates from the IRU processing logic. Positive definiteness and divergence checks are performed on the covariance matrix prior to the residual computation and covariance state updates. For each star tracker, the corrected measured quaternion is used together with the current propagated attitude quaternion to form the residuals in the star tracker frame. In normal operation, when data from both star trackers are available, the boresight axis residual for each tracker is set to zero so that only the more accurate horizontal-vertical axis data from both trackers is used to update the state estimate. However, the boresight axis residual is used if data from only a single tracker is available. Spurious data is rejected by comparing the residuals to a pre-selected threshold. The covariance and state are then updated sequentially with the data from the two trackers. The attitude quaternion is updated with the first three elements of the estimated state and the gyro bias estimate is updated with the second three elements. The resulting inertial-to-body attitude quaternion is output to the attitude control system and the gyro biases to the IRU processing logic.

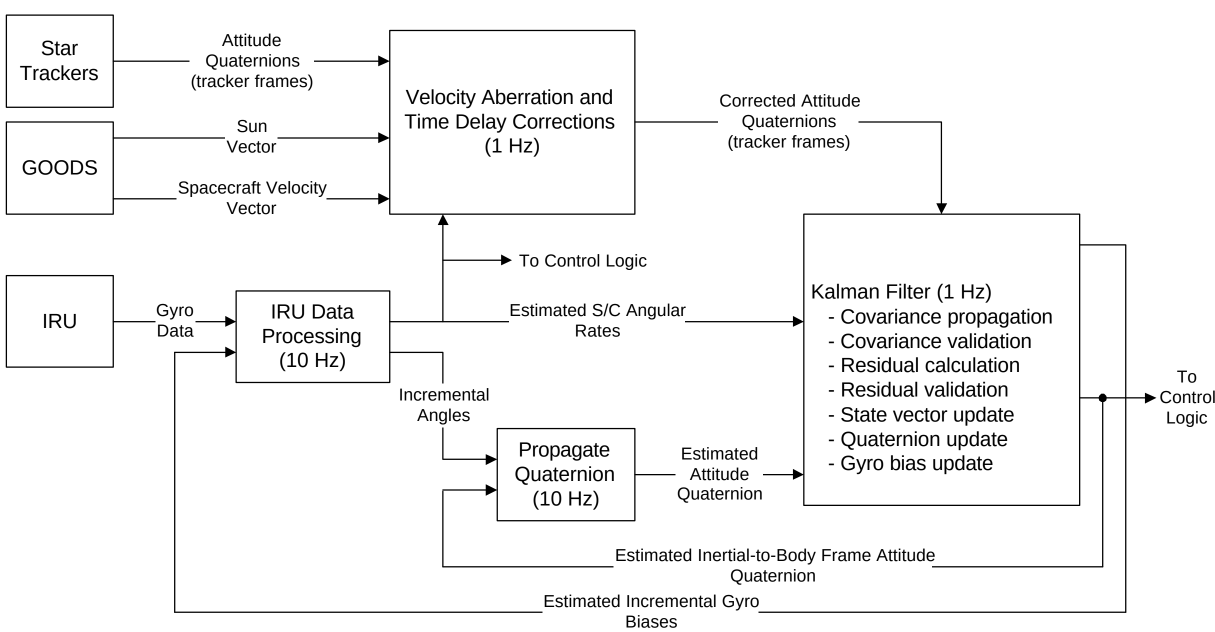

Figure 5. Attitude Determination System Functional Diagram

Figure 6 displays the result of a simulation of the attitude determination system performance in Imaging mode. A ten-minute imaging pass was simulated by computing the required three-axis rate profiles for five different scan directions. Each scan is preceded by a 45 second acceleration profile to achieve the desired initial rates and this is included in the two minutes allotted per scan. The top frame shows the estimated gyro rates from the IRU processing logic and shows the rate profiles for the five scans. The first and last 300 seconds of the simulation occur in Earth pointing mode, with the imaging pass occurring in the middle 600 seconds. The middle frame shows the attitude estimation errors during the imaging pass. As shown, these remain within ±8 arcseconds even during the acceleration preceding each scan. This performance is achieved through the capability of the star trackers to maintain accuracy over the entire range of scan rates required for the mission, and by weighting their measurements more heavily in the computation of the Kalman gains. The bottom frame shows the gyro bias estimation errors. For each axis, a bias with constant and orbit rate-varying components was modeled in the simulation. As shown, the bias estimation errors remain within ±0.3 arcsecond/second during the imaging pass.

Orbit Determination

To meet mission pointing requirements, OrbView 4 utilizes a GPS receiver plus estimation software known as GOODS to achieve better than 25 meter (1σ) real-time position knowledge. Two GPS receivers are provided. One is active and the other is cold redundant. The GPS receiver supports full 12 channel tracking and on-orbit reprogramming. Each receiver is independently connected to its own pair of antennas, pointed generally in opposite directions to maximize the field of view. A simplified block diagram of the GOODS is shown in Figure 7.

GOODS is based on NASA/Goddard's GPS Enhanced Orbit Determination Experiment (GEODE) software. The original GEODE software processes raw GPS pseudorange and Doppler measurements through a Kalman filter to estimate position, velocity, an

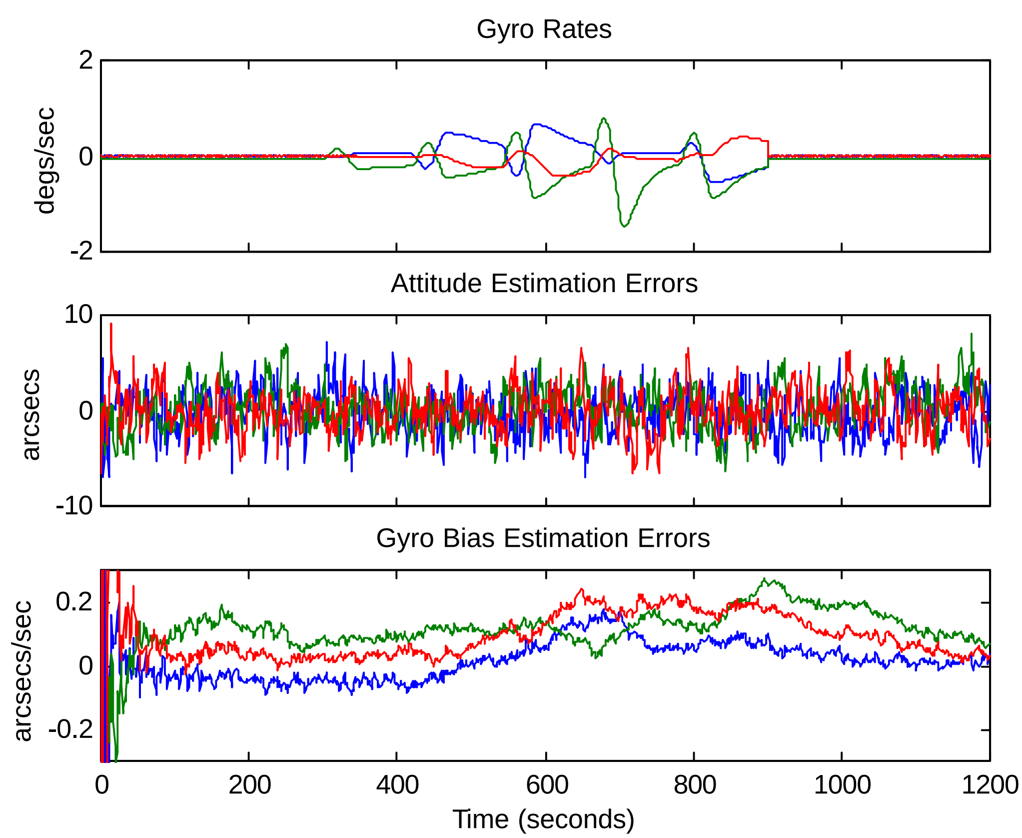

Figure 6. Attitude Determination Performance in Imaging Mode

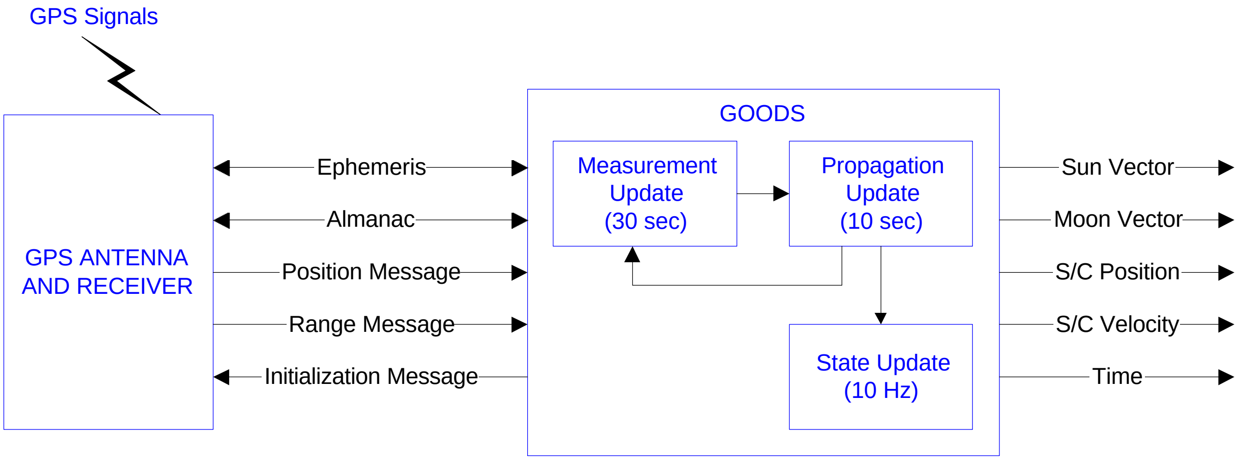

Figure 7. GOODS Block Diagram

atmospheric drag coefficient, receiver bias, and receiver bias drift. Editing is performed on the GPS measurements to reject data with high ionospheric corruption.

GEODE models spacecraft accelerations with a 30x30 gravity model; Earth, sun, and moon point-mass accelerations; a Harris-Priester based atmospheric density model; and a solar radiation pressure model. GEODE performs GPS raw measurement processing in a 30 second loop. Propagation updates occur every 10 seconds. Simplified real-time propagation for control usage nominally occurs at a 1 second rate. GEODE can be used in a propagate-only mode if GPS measurements are unavailable. GEODE was licensed from NASA/Goddard and modified by Orbital to create the GOODS.

The GOODS is integrated into the OrbView-4 flight software which runs on a RAD6000 processor. Simplified real-time propagation was increased to conform with the 10 Hz control rate. GOODS utilizes pseudorange and range rate as inputs. Separate interface software converts the receiver time measurements and integrated carrier phase data into pseudorange and range rate. GOODS internal quantities are also used for other calculations within the attitude control software, including a sun vector and the transformation between the WGS-84 and J2000 Earth-Centered Inertial coordinate systems.

Orbit determination requires initialization of GOODS and the receiver via a boot-strap method. GOODS is initialized by uploading a state vector and entering propagate mode. An initialization vector for the receiver is then created from a GOODS-propagated state. Once the receiver acquires and outputs valid data, GOODS is allowed to use the measurements in state updates. GOODS then converges to its full performance level. If GOODS diverges, it is reinitialized using the receiver state output. If the receiver fails to acquire or loses lock at any time, GOODS continues propagating until the receiver acquires. If receiver re-initialization is required, the receiver initialization procedure is followed again. GOODS is allowed to propagate without GPS inputs for up to several hours after which Fault Detection and Correction logic commands the spacecraft into Safe Hold mode that does not require orbit position knowledge.

Attitude Control

The OrbView-4 attitude control system uses the attitude determination system for spacecraft attitude and rate estimates, and four reaction wheels mounted in a pyramid configuration for attitude control. The nominal mission uses all four wheels to maximize agility along the roll and pitch axes. However, the system can be configured for three wheel operation. A 10 Hz control frequency is used together with a Proportional-Integral-Derivative (PID) controller to meet the stringent pointing requirements during imaging. A control loop bandwidth of 0.37 Hz provides sufficient robustness in presence of parameter variations, structural modes, and fuel slosh. The key functions of the attitude control system, as displayed graphically in Figure 8, are command generation, error signal generation, a simple PID controller, and reaction wheel torque distribution.

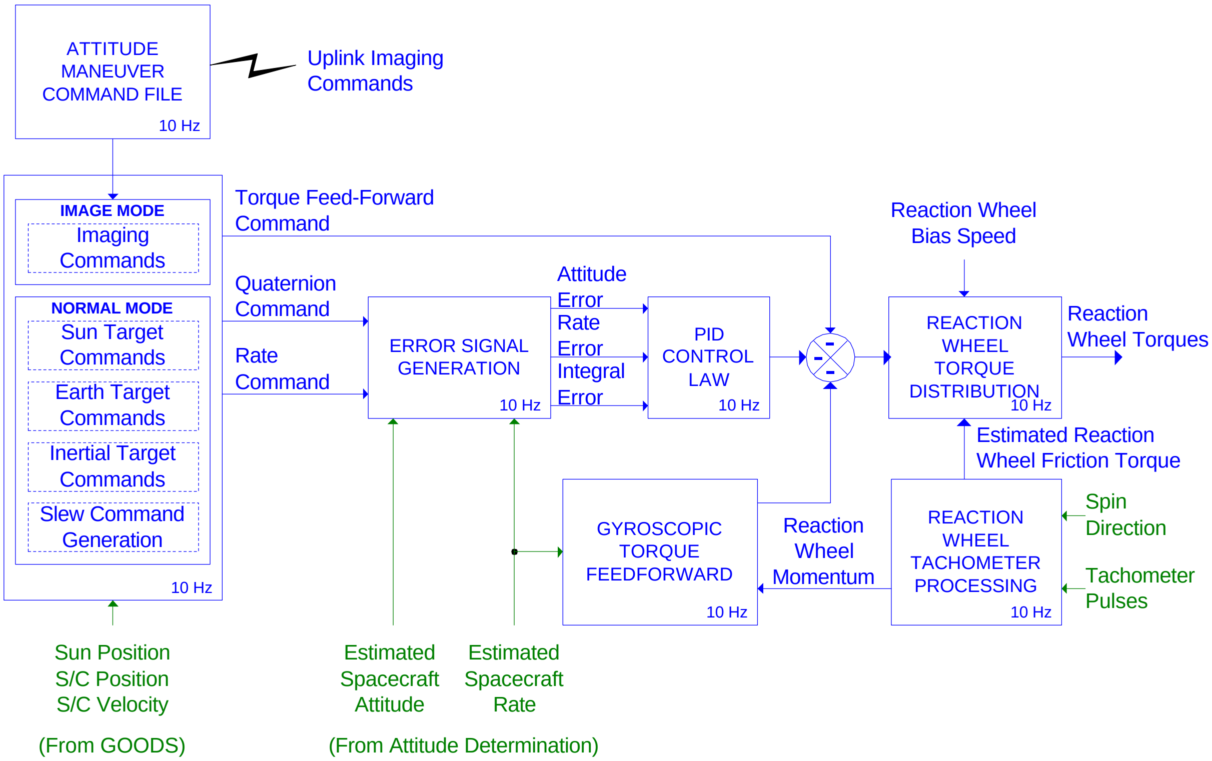

Figure 8. Attitude Control System Functional Diagram

The command generation algorithm generates spacecraft attitude, rate, and torque feedforward commands to point the spacecraft in the desired direction. The attitude commands are generated in the form of a quaternion which represents the desired orientation of the spacecraft with respect to an inertial frame.

During imaging, these commands are generated from a ground uplinked Attitude Maneuver Command File (AMCF). The AMCF contains data to point the camera optical boresight at the specified ground target. This includes location of the ground target in WGS-84 Earth Centered Earth Fixed coordinates, yaw rotation about the camera's optical boresight, and torque feedforward commands in spacecraft coordinates.

During Normal mode operations spacecraft commands are generated using spacecraft and sun ephemeris from GOODS. These commands point the spacecraft at local nadir (Earth target submode), at sun (sun target submode), or in an inertially fixed orientation (inertial target submode). Slews between these targets are performed autonomously using either a ramp-ramp or a ramp-coast-ramp rate profile.

The error signal generation algorithm computes the attitude, rate, and integral errors by comparing the commanded state with the estimated state. During imaging and slews, the integral error is set to zero to improve spacecraft pointing performance.

The PID controller generates three axis control torques used to orient the spacecraft in the commanded attitude. The control torque is generated by applying proportional, derivative, and integral control gains to the attitude, rate, and integral errors, respectively. Then, a gyroscopic torque feedforward term is added to enhance pointing.

The reaction wheel torque distribution algorithm converts the required control torque along spacecraft axes to be applied to each reaction wheel. With four wheels in use, an extra degree of freedom in distributing a three-axis torque in spacecraft coordinates among the four wheels exists. To provide the additional constraint, a pseudo-inverse distribution law is used. This law minimizes a quadratic form of the control torques (i.e., the sum squared of all the wheel torques). With this approach the wheel torques tend to equalize within the constraint of producing the requisite torque while minimizing wheel power

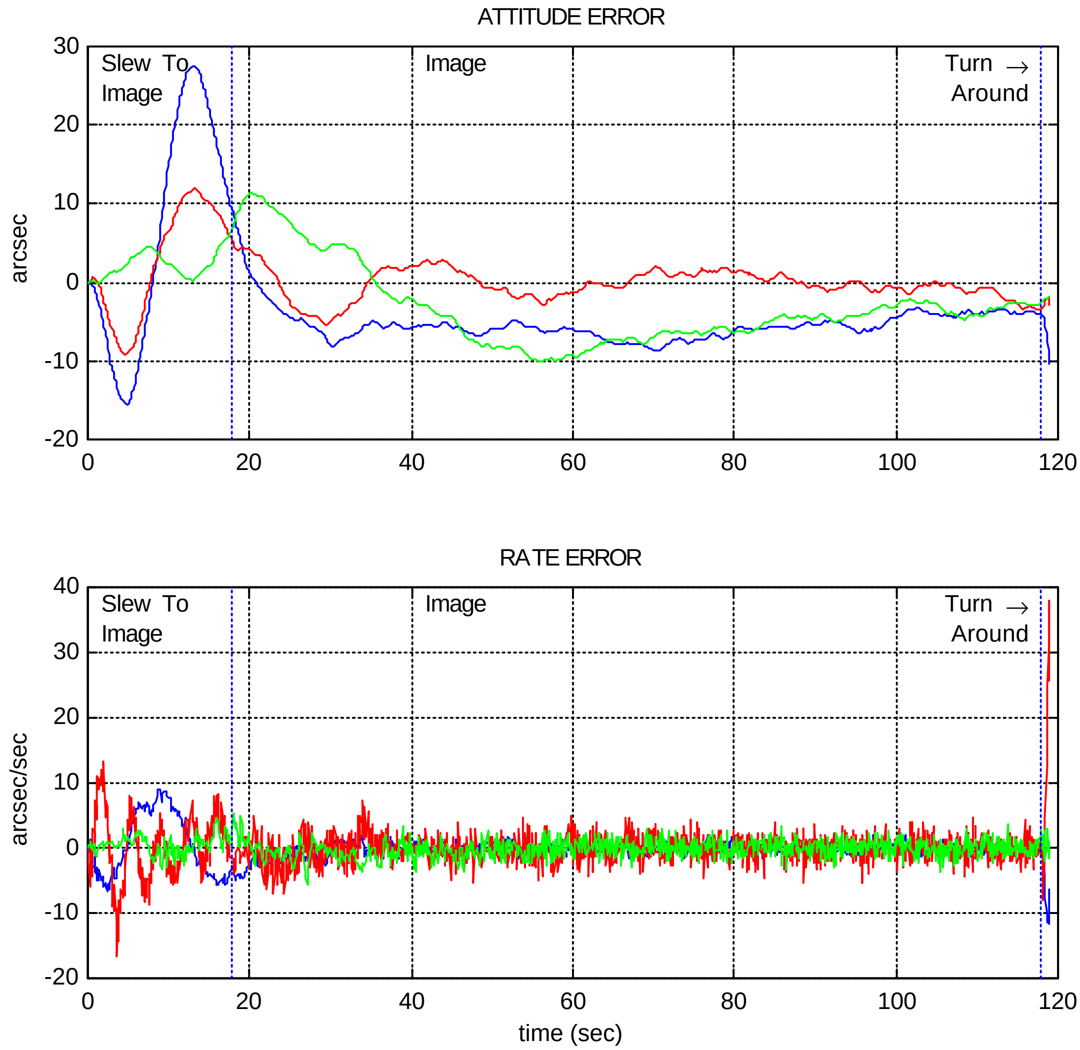

Figure 9. Control Errors During Imaging

consumption. The general form of the pseudo-inverse law is used to distribute spacecraft torque among the four wheels, thus allowing easy management of the reaction wheel bias speed.

The results of a simulation performed to assess attitude control system performance during imaging are shown in Figure 10 and Figure 9. In this scenario the spacecraft is slewed from an initial parking attitude to an imaging attitude. An imaging scan is then performed starting at an initial rate of 1.5 deg/sec. At the end of the scan the spacecraft is reversed to scan in the opposite direction.

Summary

The OrbView-4 ACS combines precise attitude and orbit determination with high performance control actuators to meet the stringent attitude control requirements imposed by a high resolution, body scanning, Earth imaging spacecraft. The ACS is completely autonomous, requiring only imaging tasking commands generated from customer imaging requests to be uplinked. Utilization of a modular development approach for attitude determination, orbit determination and attitude control functions allows the system to be easily reconfigured for a wide variety of missions.

Author Biographies

Dewey Adams is a Senior Principal Engineer in the Attitude Determination and Control group at Orbital Sciences Corporation. As the OrbView-4 lead ACS engineer he is responsible for assuring that the ACS is designed to meet performance requirements, developed within cost and schedule constraints and tested to guarantee successful performance once in flight. Prior to joining Orbital, Mr. Adams was employed at Lockheed Martin Astro Space where he was the lead ACS engineer on a number of low Earth orbiting imaging and geosynchronous communications spacecraft. Mr. Adams holds a B.S. degree in Aeronautical and Astronautical Engineering from the Pennsylvania State University, and a M.S. degree in Mechanical and Aerospace Engineering from Rutgers University.

Dominick Bruno is a Senior Staff Engineer in the Attitude Determination and Control group at Orbital Sciences Corporation. He is responsible for the design of the attitude determination system, and also participated in the initial overall subsystem definition. Prior to joining Orbital, Mr. Bruno was an attitude control systems engineer at Lockheed Martin Astro Space. He has also worked at the Aerospace Corporation, the Charles Stark Draper Laboratory, and Grumman Aerospace. Mr. Bruno holds a S.B. and Engineer degrees in Aeronautics and Astronautics from M.I.T. and a M.S. degree in Aeronautics and Astronautics from Polytechnic University. He is a Senior Member of the AIAA.

Piyush Shah is a Principal Engineer in the Attitude Determination and Control group at Orbital Sciences Corporation. He is responsible for the design of the attitude control system, and also participated in the initial overall subsystem definition. Prior to joining Orbital, Mr. Shah was an attitude control subsystem engineer at Hughes Space and Communications. He has also worked at TRW. Mr. Shah holds a B.S. degree in Electrical Engineering from Ohio State University, and a M.S. degree in Electrical Engineering from University of Michigan.

Dr. Brian S. Keller received his B.S.E. in Aerospace Engineering from the University of Michigan (1986) and his M.S. (1987) and Ph.D. (1993) in Aeronautics and Astronautics from Stanford University. He has held engineering positions with JPL, Ford Aerospace, and Lockheed-Martin working on various satellites including Galileo, Landsat 7, DMSP, and TIROS. Dr. Keller started at Orbital in 1997 and is currently the ACS lead for the OrbView-3 spacecraft.

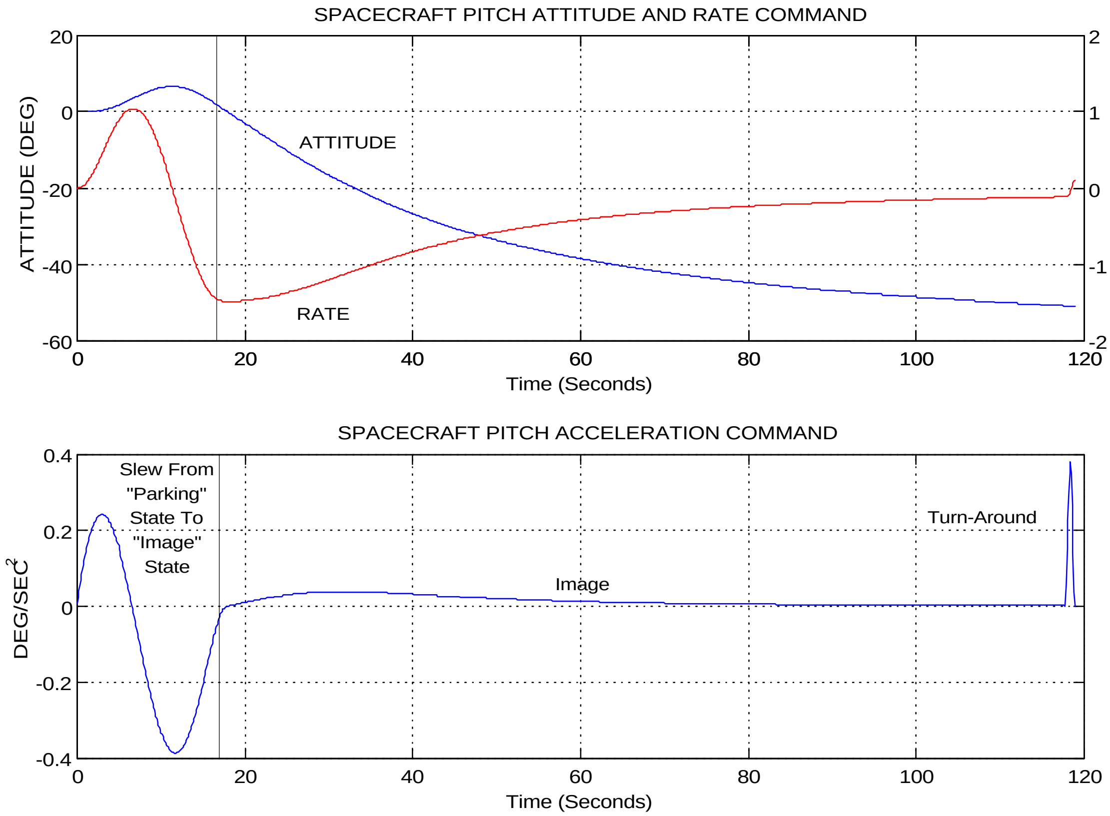

Figure 10. Commanded Spacecraft Motion During Imaging