Design and Performance of the OrbView-2 Attitude Control System

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Abstract. The OrbView-2 satellite, launched on August 1, 1997, is the world's first commercially owned imaging satellite. Because of the commercial nature of the mission, design of the OrbView-2 attitude control system was constrained by cost as well as the normal physical parameters. In addition to maintaining a nadir-pointing momentum-biased mission mode, the spacecraft maintains a wide variety of operating modes including an extended orbit-raising sequence. The mission requirements were met without the use of gyros or other high-cost attitude sensing hardware. This paper provides an overview of the attitude control system design as well as a description of the post-launch system performance.

OrbView-2 Mission Description

The OrbView-2 spacecraft is the world's first privately-owned satellite designed to provide multi-spectral images (in the visible and near-infrared portions of the spectrum) of the Earth's ocean and land surfaces. During the course of a projected five-year mission (with a 10 year goal), these images will be used both by commercial customers and scientific researchers. OrbView-2 carries the eight-channel Sea-Viewing Wide Field of View (SeaWiFS) imaging instrument, built by Hughes Electronics Corporation at the Santa Barbara Research Center, which produces these multi-spectral images to the resolution of 1 km/pixel.

The OrbView-2 spacecraft bus was constructed by the Orbital Sciences Corporation for its Earth imaging subsidiary, the ORBIMAGE Corporation. NASA's Goddard Space Flight Center is ORBIMAGE's anchor customer of imagery data for scientific research purposes. NASA scientists will use OrbView-2 imagery to better understand the Earth's carbon cycle processes and their effect on global warming trends. ORBIMAGE also offers satellite imagery to organizations involved in climate research, environmental monitoring, and commercial fishing.

OrbView-2, shown in Figure 1 (originally known as SeaStar), was launched on August 1, 1997 aboard an Orbital Pegasus XL rocket from the Vandenburg Air Force Base in California. The Pegasus injected OrbView-2 into a 300 x 302km parking orbit, inclined at 98.2°. Within several weeks after launch, OrbView-2 used a series of thruster burns to raise its orbit to a 705 km, sun-synchronous orbit with a 12:05 p.m. descending node.

In this paper, the attitude control system (ACS) of the OrbView-2 will be presented. The ACS hardware will be presented as well as the mission requirements to which the hardware was de-

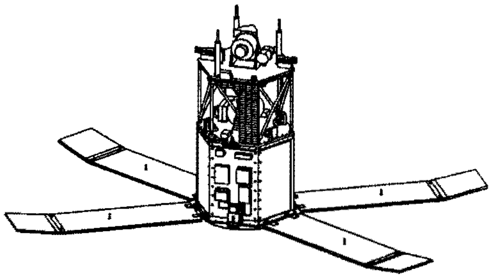

Figure 1 - The Orbview-2 Spacecraft

Table 1 - OrbView-2 Attitude Hardware

Component	Vendor	pecification
Momentum Wheels (2)	Matra (formerly British Aerospace)	0.03 N-m, 3 N-m-sec
Magnetic Torque Rods (6)	Fokker	35 Am^2 dipole
Magnetometer (2)	NanoTesla	+/- 60,000 nT
Horizon Sensors (2)	Ithaco (formerly Space Sciences Corp)	0.05° accuracy
Sun Sensors (3)	Ithaco (formerly Space Sciences Corp)	0.006° accuracy
GPS	Motorola	12 channels

signed to meet. This paper will also present the OrbView-2 mission history including the spacecraft on-orbit performance, anomalies, and the ensuing solutions.

OrbView-2 Attitude Control System

As the mission of the OrbView-2 spacecraft was that of a commercial nature, there was a significant incentive to reduce costs without compromising the mission objectives. For this reason, the attitude control system was designed using inexpensive hardware components.

The OrbView-2 ACS hardware complement is shown in Table 1. The location of the attitude hardware components on the spacecraft is shown in Figure 2.

The nature of the OrbView-2 imaging mission dictates that the spacecraft fly in a nadir-pointing orientation. As a result, the spacecraft operates in a momentum-biased orientation with the momentum wheels spinning along the y-axis and the magnetic torque rods controlling the spacecraft about roll, pitch and yaw.

The spacecraft contains a fully redundant Attitude Control Electronics (ACE) box. The ACE box contains an A and a B side, each with its

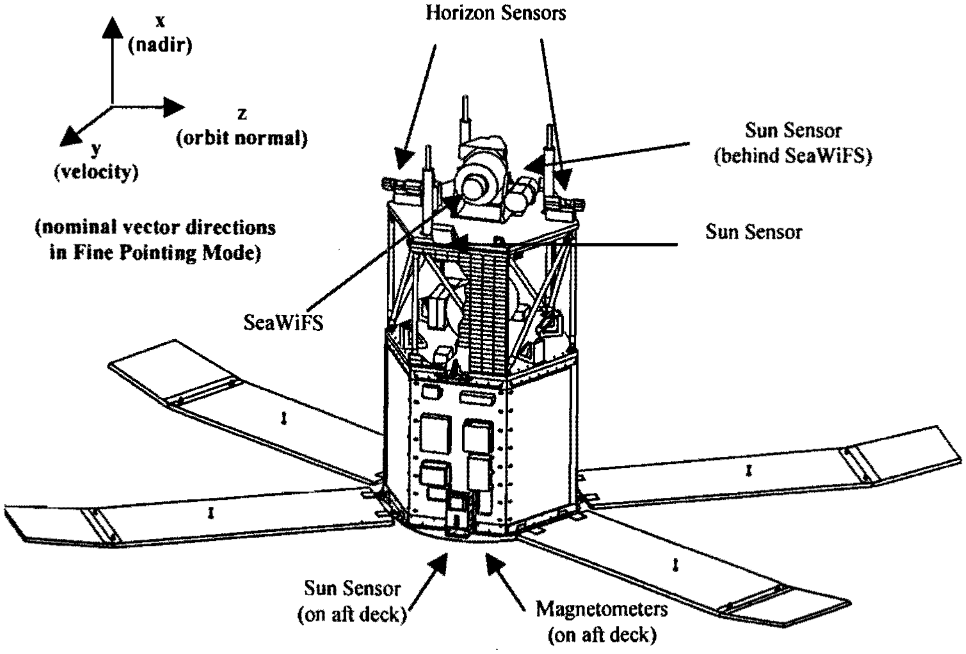

Figure 2 - OrbView-2 Attitude Sensor and Actuator Locations

own power supply (each power supply slice has 2 DC-DC converters for another level of redundancy). Also, each of two Central Processing Units (CPU's – with 80C186 processors), can control either, or both sides of the ACE. Thus, only one CPU slice is powered on at a given time. This allows either side of the ACE box to be turned off, selectively, to reduce power consumption and increase reliability. As a result, each sensor and actuator pair has a designated primary and redundant side.

OrbView-2 has three fine 2-axis sun sensors, two on opposite sides of the nadir side of the spacecraft and one on the aft deck pointing out towards zenith. Each sun sensor has a 64° x 64° field of view giving significant overlap in sun coverage. Unlike the other sensors, there are two primary sun sensors, located on opposite sides of the spacecraft, whereas the sensor on the aft deck is redundant.

As shown in Figure 2, there are two scanning horizon sensors located on either end of the spacecraft. These sensors provide measurement of the phase and chord of the earth presence signal. Along with information about the spacecraft altitude, obtained from the onboard orbit propagator, the earth sensor information enables determination of the nadir vector in the spacecraft coordinate frame.

The spacecraft also maintains two redundant, three axis magnetometers. These sensors determine the magnetic field vector in the spacecraft frame. Comparing the onboard magnetic field model, which calculates the inertial orientation of the magnetic field, with the magnetometer output yields a coarse attitude determination.

Both momentum wheels and all six of the torque rods can be activated, provided that both ACE power supplies are turned on. Nominally, only one side of the actuator suite (one wheel and one side of the torque rods) is active. Yet, both sides were utilized after separation from the launch vehicle, during the initial acquisition phase, giving the spacecraft extra torque and momentum storage to attenuate possibly high body rates resulting from an off-nominal tip-off condition.

The ACS software obtains the spacecraft state vector from the GPS receiver once every second. This state vector is used for attitude determination in a manner described later in this paper. During such time that the GPS receiver is offline, whether from receiver anomalies or inadequate number of visible GPS satellites, the state vector is propagated by a Kalman filter to provide accurate initial values with which to feed the onboard orbit propagator. OrbView-2 uses two GPS antennae to improve the likelihood of receiving signals from visible GPS satellites. The 12-channel receiver output is also used for attitude determination and on the ground for accurate orbit determination.

ACS Operational Modes

In addition to raising the spacecraft orbit, the OrbView-2 flight control system performs several other functions. For this reason, the flight software was compartmentalized into 12 different operational modes as shown in Figure 3.

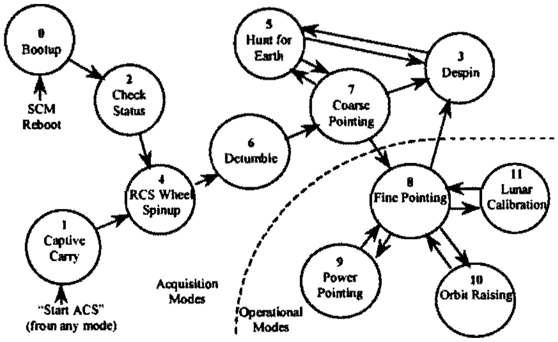

Figure 3 - OrbView-2 Operational Modes and Transitions

These modes are described as:

0. Bootup - The mode from which the spacecraft processor reboots.
1. Captive Carry - Where the spacecraft operates prior to separation from the launch vehicle.
2. Check Status - Spacecraft uses this mode for brief failure detection and correction.
3. Despin - Spacecraft nulls spin rate slowly, using a B-Dot algorithm.
4. RCS Wheel Spinup – The momentum wheels are spun up to their operating speeds.

5. Hunt for Earth - Spacecraft executes slow spin until Earth comes into field of view of the Earth sensors.
6. Detumble - Spacecraft nulls high spin rates, using momentum wheels, in case there is an off-nominal tip-off from the launch vehicle.
7. Coarse Pointing - An earth-pointing safe-hold mode.
8. Fine Pointing – Nominal mission mode during which nearly all of SeaWiFS imagery is recorded.
9. Power Pointing - Spacecraft points arrays at prescribed angles to the sun, at certain points of the orbit, in order to preserve a positive power margin.
10. Orbit-Raising - Thruster-based mode used to control attitude while orbit altitude is raised.
11. Lunar Calibration - Periodic slew in which the Moon is imaged by the SeaWiFS instrument.

Nominally, the spacecraft operates in a nadir-pointing orientation so as to facilitate SeaWiFS imaging; however, this is not the case during every mode. During Orbit Raising, the spacecraft pitches over 90° so as to align the thrusters with the velocity vector. After the thrusters complete their operation, the spacecraft slews back to a nadir-pointing orientation.

The OrbView-2 arrays are fixed with respect to the spacecraft body. As a result, the array normals are nearly perpendicular to the sun line upon emerging from, or entering into, eclipse; therefore the arrays produce little power during those portions of the orbit. During the course of the mission, it is expected that the efficiency of these arrays will degrade and they will produce less power in the current mission scenario.

For this reason, the Power Pointing mode was designed. During the Power Pointing mode, the spacecraft departs from the nadir-pointing orientation and reorients the spacecraft so that the arrays point at a prescribed angle to the sun, during a desired portion in the orbit. In this manner, the arrays provide more power to the spacecraft at high latitudes than they would during a nominal Fine Pointing orientation. The SeaWiFS instrument images the Earth's surface while the spacecraft is between +/- 70^0 latitude in the daylight portion of the orbit. During Power Pointing, OrbView-2 emerges from eclipse in the Northern Hemisphere and orients the solar arrays at the Sun. In the Southern Hemisphere, the spacecraft again slews towards the Sun once SeaWiFS imaging ceases.

The Lunar Calibration mode was designed to provide a means by which the SeaWiFS instrument could be calibrated against a well-known color source. Roughly once a month, OrbView-2 is commanded from Fine Pointing to Lunar Calibration mode, resulting in a 360° slew maneuver in pitch. The timing of the maneuver is planned so that the Moon passes through the field of view of the SeaWiFS instrument. In this way, SeaWiFS scientists can examine the Moon's image and calibrate the instrument settings accordingly.

The Coarse Pointing mode is a mode with degraded pointing performance that acts as an earth-pointing, safehold mode. This mode purely uses the Horizon Sensors for attitude information and does not require position knowledge. As a safety precaution, in off-nominal conditions, the ACS software contains a flag that gives the spacecraft operators an option to prevent any autonomous transitions from Coarse Pointing to Fine Pointing modes.

The Fine Pointing operational mode is where the spacecraft accumulates SeaWiFS imaging data and where the spacecraft will operate during the majority of its lifetime. Therefore, the pointing requirements are tightest in this mode than any of the other modes. In the nominal mission scenario, the spacecraft operates in Fine Pointing mode during the entire orbit, even when SeaWiFS is not imaging; the only exception is when Power Pointing is enabled.

ACS Requirements

The major requirements for the Fine Pointing mode are listed in Table 2.

The 0.1° knowledge requirement, at the 705 km OrbView-2 altitude, translates to slightly over 1km at the Earth's surface. This 0.1° requirement is also the size of the smallest pixel of the SeaWiFS image. As a result, the size of each SeaWiFS pixel is roughly 1 km^2. With this sensor suite, this knowledge requirement proved to be a challenging one to meet as described later in this paper.

The requirements for the Orbit-Raising mode proved to be equally challenging to meet. However, the design of this mode and performance of the OrbView-2 satellite during the orbit-raising period is described in the literature[1] and will not be covered in detail in this paper.

Table 2 - OrbView-2 Fine Pointing Reqmts.

Requirement	Performance Criteria
Pointing Knowledge	0.1° at 705 km, 2σ
Position	On-board propagation errors not to exceed 100 m
Pointing Control (derived requirement)	0.5° during SeaWiFS imaging

ACS Algorithms and Software

The ACS software resides on a MC68302-EP processor known as the Spacecraft Control Module (SCM). The SCM communicates with various subsystems including:

- ACE box - to poll the attitude sensors and actuators for data that is used in the ACS algorithms.
- Spacecraft Maintenance Unit - provides information on the propulsion system including heaters, thruster drivers, as well as other deployables.
- GPS receiver - receives state vector information as well as a 1 pulse/sec. clock timing signal.

The SCM runs several autonomous tasks including the high-level algorithms needed to control the spacecraft attitude. During Fine Pointing, the spacecraft runs a MIMO roll/pitch/yaw controller at a 2 second sample period; the controller gains were derived using an LQR procedure. As the spacecraft is momentum biased, the roll/yaw dynamics are coupled. Roll and yaw errors are corrected using torque created by the magnetic torquer bars. However, the pitch loop is much tighter because of the presence of the momentum wheel.

OrbView-2 Attitude Determination

The low-cost nature of the OrbView-2 mission precluded the use of an IRU for rate sensing. Furthermore, as mentioned in the Power Pointing mode discussion earlier, the power margins are small enough that the spacecraft could not support a standard IRU. For this reason, spacecraft rates are derived from the magnetometer, sun sensor, and horizon sensor measurements.

The attitude errors are determined by the deterministic estimation algorithm, QUEST[2]. Information from the horizon sensors and GPS are used to calculate the nadir vector in the body frame. Similarly, the magnetic field vector is found using the magnetometer data. If available, the fine sun sensors are used to generate a sun vector. The ACS software uses various models to determine the Earth-centered inertial orientation of these vectors. The QUEST algorithm compares the modeled vectors in inertial space to the sensed vectors in the body coordinate system and iterates to find the best attitude solution. This attitude transformation is then compared to the nadir-pointing frame yielding errors in roll, pitch, and yaw.

Limitations of the OrbView-2 Attitude Determination System

The QUEST algorithm presents a robust attitude determination solution that is widely accepted in the industry as well as simple to implement in the flight code. However, as the algorithm is deterministic, the quality of the attitude solution will suffer if the problem is poorly posed.

As seen in Reference 2, the covariance matrix of the state containing the three Euler angles can be calculated as such:

$$\mathbf{P}_{body} = -\sum_{i=1}^{n} \sigma_i^{-2} \left(\mathbf{b}_i^{x}\right)^2 \tag{1}$$

where

$\mathbf{P}_{body}$ = the Euler angle covariance,

σ_i = error associated with the ith sensor,

$\mathbf{b}_i$ = the ith vector measurement.

The superscript on the $\mathbf{b}_i$ vector denotes a 3x3 skew-symmetric representation of the vector as seen below:

$$\mathbf{b}^{\times} = \begin{bmatrix} 0 & b_3 & -b_2 \\ -b_3 & 0 & b_1 \\ b_2 & -b_1 & 0 \end{bmatrix} \qquad (2)$$

As seen in Eq. 1, the Euler angle covariance matrix is a summation of the squares of the skew-symmetric form of the input attitude vectors, i.e. - sun, magnetic field, nadir, as weighted by the square of each sensor noise component. The skew-symmetric representation shown in Eq. 2 results in a rank-deficient 3x3 matrix. If two or more **b** vectors are nearly co-aligned (in the absence of another independent measurement), the resulting covariance matrix is poorly-conditioned. The QUEST algorithm inverts the covariance matrix during the solution process; solving the QUEST algorithm with nearly collinear vector inputs will therefore generate an ill-conditioned solution.

This is illustrated geometrically in Figure 4. As the OrbView-2 orbit is sun-synchronous, its inclination is nearly polar. During the course of a 24-hour period, the spacecraft will pass over both the North and South Magnetic Poles. At these points of the orbit, the Earth's magnetic field points downward and is almost aligned with the nadir vector sensed by the horizon sensor.

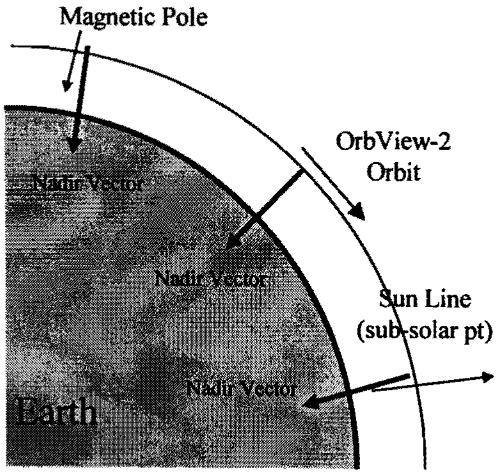

Figure 4 - Illustration of the OrbView-2 Sun/Nadir/Magnetic Field Co-alignment Problem

If the sun is visible, a robust attitude solution can still be obtained by the QUEST algorithm. However, the sun is not always illuminating these points of the orbit. In the summer months, the Sun illuminates the North Magnetic Pole nearly continuously while the South Magnetic Pole can be in darkness. The reverse is true in the winter months of the year. Without the sun sensor reference, the QUEST algorithm cannot resolve the position around nadir, which in Fine Pointing, turns out to be yaw. As a result, large yaw excursions of over 10° are seen when the spacecraft passes over the Earth's Magnetic Poles while in eclipse.

A similar problem occurs when the sun and nadir vectors are involved. As mentioned previously, the OrbView-2 satellite is in an 12:05 p.m. orbit plane. This means that depending on the time of year, the spacecraft can pass within a few degrees of the *sub-solar point*, or the point on the Earth's surface directly underneath the Sun. Near the sub-solar point, the nadir and sun vectors are almost aligned. While the magnetometer will deliver a magnetic field measurement, it is an inherently less accurate sensor than either the sun or horizon sensors. As a result, the magnetometer's contribution to the QUEST algorithm is weighted less, compared to that of the horizon sensor (higher weighting) and the sun sensors (highest weighting). With the magnetometer making an ineffectual contribution to the solution at the sub-solar point in the OrbView-2 orbit, the accuracy of the attitude determination solution breaks down. For this reason, the ACS code performs a "yaw smoothing" maneuver, bypassing the QUEST algorithm, when the angle between the sun and the nadir vectors is less than 3° in magnitude.

It was decided, because of limitations of the MC68302-EP flight processor, not to include a Kalman filter which would have provided smoothing of the attitude at the Magnetic Poles and sub-solar point. Without an IRU, to propagate rates into position errors, or a Kalman filter, the OrbView-2 ACS provides extremely poor results at certain points of the orbit as mentioned above. However, this concern is ameliorated by the fact that the SeaWiFS is not imaging during the times that the spacecraft is passing over the Magnetic Poles; as mentioned previously, imaging only occurs when the spacecraft is between +/- 70° latitude. During the subsolar point, the SeaWiFS instrument executes a certain articulating maneuver; no imaging occurs during this brief *tilt* maneuver.

Mission History

OrbView-2 was launched on August 1, 1997 onboard a Pegasus XL rocket from Vandenburg Air Force Base into a 300 x 302 km orbit. With S-band tracking stations in Alaska, Antarctica, and West Virginia, contact with the spacecraft was frequent and regular during the early part of the mission. Shortly after launch, the ACS was unable to determine a proper attitude solution because of a corrupted GPS state vector and the first contact found the spacecraft in Hunt for Earth mode. Once a ground-processed state vector was uploaded to the spacecraft, the ACS was able to propagate the correct orbit. After initial checkout, lasting about 12 hours, the command was uploaded to allow the spacecraft to transition to Fine Pointing mode.

Almost immediately, the flight operations team noticed that the momentum wheel torque commands were tripping pre-defined telemetry limits. Both momentum wheels were being commanded at their maximum torque values. Upon closer inspection, it became evident that the wheel torques were limit cycling between +/- 0.03 N-m, in a bang-bang fashion. This prompted concern regarding adverse effects on the wheels' life expectancy in addition to thermal concerns, such as higher ACE temperatures, brought about by excessive wheel activity.

A simple analysis was quickly undertaken and it was determined that a time delay greater than expected was present in the control loop. This time delay negated phase margin designed into the system. The source of the time delay is suspected to result from extra processing inherent in a last-minute addition to the flight code. To correct the situation, the momentum wheel control loop gain was reduced to 25% (-12 dB). This alleviated the limit cycling problem and allowed flight controllers to turn off the redundant momentum wheel.

At this point, the first priority was to raise the orbit altitude to the prescribed 705km. Worst-case orbital decay studies showed that the spacecraft would have re-entered the Earth's atmosphere within a few weeks, without orbit raising burns, starting at the parking orbit altitude. A sequence of 32 thruster burns, each lasting up to 500 sec, were planned to raise the spacecraft to the mission orbit over a 1 month duration.

Initial GPS Anomaly

However, shortly before the first burn was to occur, roughly nine days into the mission, the GPS receiver sent a series of bad state vectors to the ACS without sending a prescribed error flag. This caused the ACS to accept and propagate the corrupted state vectors and attempt to process an attitude solution. Needless to say, this attitude solution quickly diverged and the spacecraft transitioned out of Fine Pointing mode, and eventually entered Coarse Pointing mode.

Although the GPS receiver soon recovered, the flight operations team decided to sever the link between the GPS and the ACS in order to keep the orbit-raising process free of future anomalies of this sort; this was accomplished by uploading a single flag to the spacecraft telling the ACS software not to accept GPS updates to the onboard orbit propagator. To substitute for those updates, the following process was instituted by the flight operations team.

- GPS-derived state vectors were downloaded from the satellite and checked by the flight operations team for validity.
- Using a high-fidelity ground-based orbit propagator, new state vectors were propagated up to a certain point in time.
- At that point in time, the propagated state vector was uploaded to the spacecraft for the purpose of updating the onboard orbit propagator.
- Several such state vectors were uploaded each day in a stored command schedule to augment the performance of the onboard orbit propagator.

This labor-intensive procedure continued for roughly four months until a software patch was written, tested, and uploaded to the onboard SCM flight code. This software patch rejects those state vectors that are outside certain criteria, and monitors and resets the GPS receiver, if necessary. Before the patch was uploaded, the above procedure provided the ACS with a spacecraft position that was outside the specified 100m error budget. However, the ground upload process was sufficiently accurate to allow orbit-raising to occur.

Initial Pointing Performance

The performance of the OrbView-2 spacecraft during Orbit Raising mode is detailed in Reference 1. However, it is sufficient to say here that the orbit-raising sequence performed as planned and within five weeks after launch, OrbView-2 reached its desired operational altitude and inclination. At that point, the SeaWiFS was turned on and test imagery was downloaded to ORBIMAGE and NASA scientists on September 18, 1997.

Upon receipt of the initial SeaWiFS images, it became apparent that the ACS needed further tuning and calibration. The spacecraft was experiencing large yaw excursions at the point of the orbit nearest the sub-solar point. The spacecraft would react to a perceived jump in calculated yaw error, arising from the ill-conditioned orbit geometry described above. Furthermore, the control system appeared to be underdamped, causing the spacecraft to spend a good portion of the orbit in the Southern Hemisphere recovering from this condition, in a slow oscillation about yaw.

This is shown in Figures 5 and 6; Figure 6 shows a detailed history of the Euler angle response for a single orbit. The sub-solar oscillation in roll and yaw can be first seen occurring at roughly 0545 GMT with a considerable amount of lightly-damped ringing following the disturbance. Similar disturbances can be seen in the following orbits. This ringing is shown in greater detail in Figure 6. The large yaw excursions occur when the spacecraft moves into eclipse near the South Pole; at this point, the sun sensors no longer provide their accurate contribution to the attitude solution and errors in the magnetometer and horizon sensor calibrations become more predominant.

This underdamped behavior was evident in the attitude telemetry but was noticeably affecting SeaWiFS imagery. Linear analysis was performed that tightened the Fine Pointing control bandwidth, attenuating the response to the yaw excursion as shown in Figures 7 and 8. Note that in contrast to the behavior shown in Figures 7 and 8, the sub-solar yaw disturbance, which first occurs slightly before 0530 GMT, exhibits improved damping.

On-Orbit Attitude Sensor Calibration

At this point in the mission, the ACS provided a stable enough platform to allow commercial SeaWiFS imaging to occur. However, over the next few months, Orbital and NASA Goddard personnel attempted to determine the misalignments and bias information on several of the attitude sensors that would attenuate the sub-solar point yaw excursions and increase the accuracy of the attitude determination process.

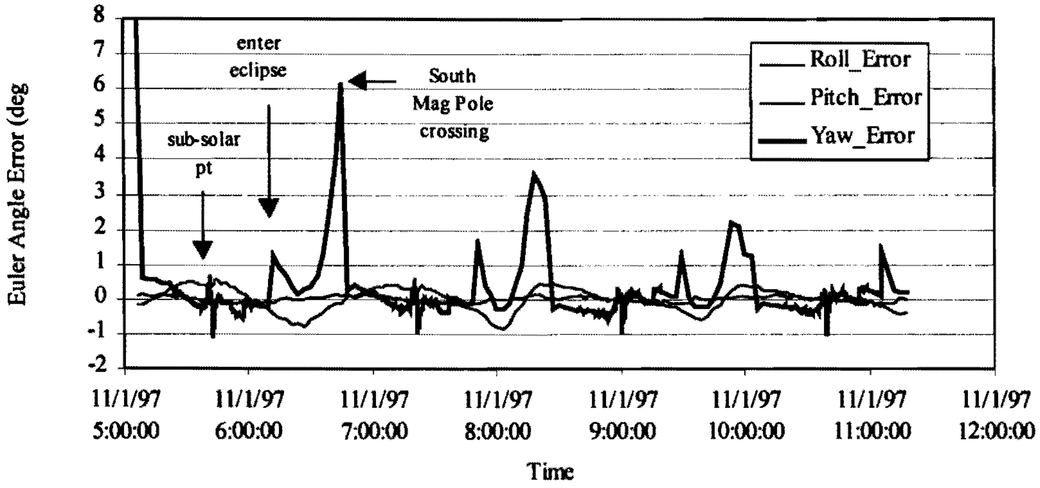

Figure 5 - Attitude History Showing Underdamped Controller Behavior

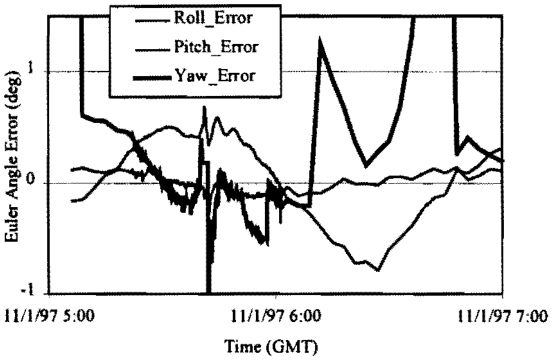

Figure 6 – Attitude History Showing Under-damped Controller Behavior

Gradually, the following variables were updated onboard the spacecraft:

- magnetometer biases
- torque rod control gains
- sun sensor misalignment angles
- horizon sensor phase biases

These gains were a small subset of those ACS parameters that can be adjusted on-orbit. Over 500 parameters, such as control gains, sensor biases, scale factors, and other elements can be adjusted on-orbit with justification by ground simulation. This provides the flight operations team with a great amount of flexibility to adjust the on-orbit ACS performance.

The gains and variables were adjusted through repeated test runs of a high-fidelity ACS software simulation in addition to repeated testing of a real-time, hardware-in-the-loop simulation, before they were uploaded to the spacecraft. The initial sub-solar point yaw excursions were attenuated by over an order of magnitude with the very first misalignment change. While the on-orbit calibration process is ongoing as of this writing, the ACS meets its specified requirements and performs as shown in Figure 9. In this figure, the spacecraft first passes near the sub-solar point at roughly 0515 GMT. There is a minor disturbance in yaw and a barely noticeable glitch in roll and pitch. The yaw errors still spike upon entering eclipse which means that further calibration needs to be performed on the magnetometers and horizon sensors to eliminate inherent processing errors.

Note that in Figure 9, the Euler angle errors

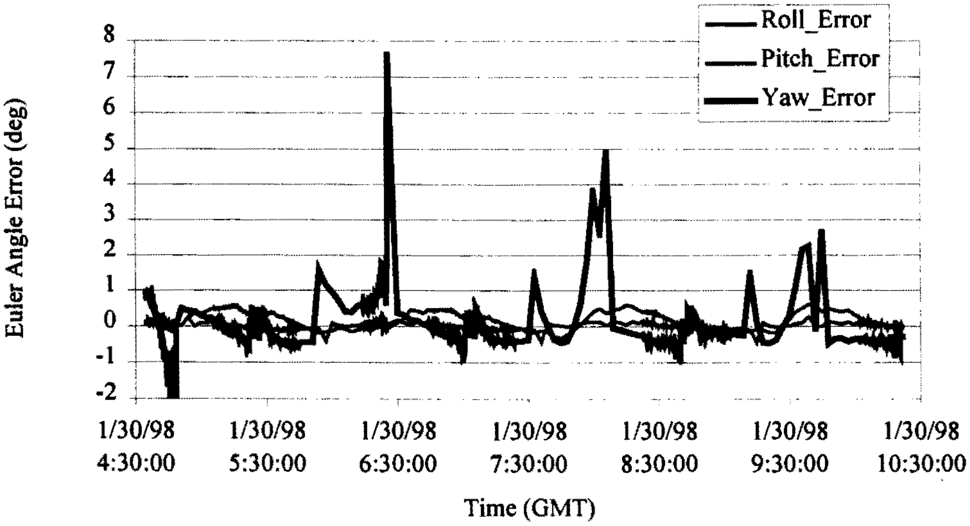

Figure 7 – Attitude History Showing Improved Damping Performance

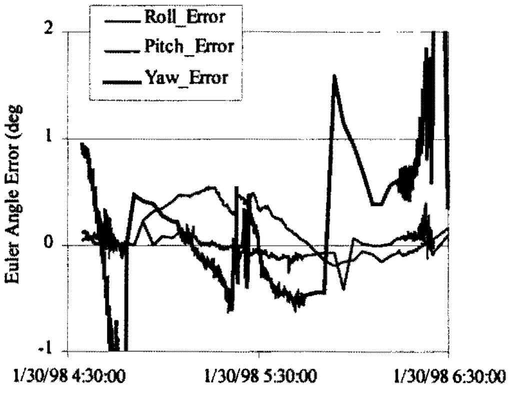

Figure 8 – Attitude History Showing Improved Controller Behavior

exceed the derived requirement of 0.5°. In conjunction with analysts from NASA Goddard's SeaWiFS project, more emphasis was placed on reducing spacecraft jitter than in reducing error from the nadir orientation. Note that the jitter in the curves in Figure 10 is attenuated with respect to Figure 6 and 8. While the roll and yaw errors exceed 1°, the pitch error is on the order of 0.5°. The reduction of spacecraft jitter resulted in satisfactory images whereas the increased attitude errors can be compensated through ground processing of the attitude data.

ACS Accuracy

The SeaWiFS project at NASA Goddard maintains a high-fidelity OrbView-2 attitude estimation capability. Using the raw sensor inputs and other data telemetered from the spacecraft, the attitude solution can be processed, using algorithms and computers more powerful than what exists within the ACS, to a higher fidelity. As a result, the SeaWiFS project personnel can improve the location accuracy of the SeaWiFS imagery.

This high-fidelity solution also allows comparison between the ground-processed attitude solution and the solution calculated on the spacecraft. Figures 11 and 12 show this comparison. In Figure 11, the ground-processed and spacecraft-processed yaw are compared. The spacecraft flies through the sub-solar point at around 1200 seconds. Note that except for the area around the sub-solar point, the spacecraft angle is within 0.1° of the ground-computed yaw angle therefore meeting the prescribed accuracy requirements. Note that in Figure 12, however, the ground- and spacecraft-processed attitude

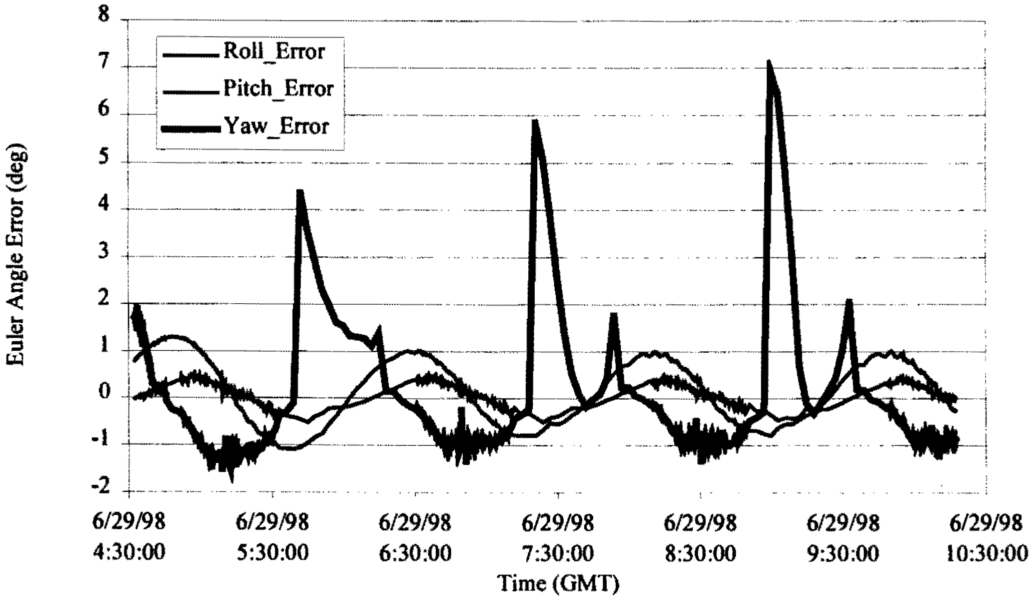

Figure 9 - Recent Attitude Error History

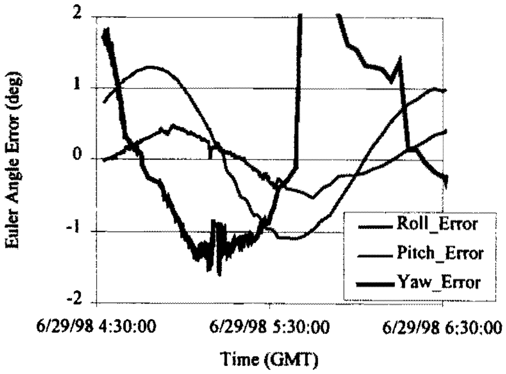

Figure 10 – Recent Attitude History

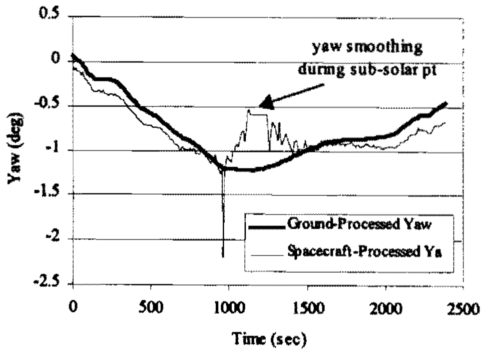

Figure 11 – Ground-Processed Yaw vs. Spacecraft Processed Yaw History

solutions diverge once the spacecraft passes through the sub-solar point. This may result from misalignments of the sun sensor used at that portion of the orbit.

Future Work

Currently, work is in progress which will further reduce attitude jitter and error resulting in more accurate SeaWiFS imagery. As seen in Figures 11 and 12, further work is also required to reduce errors in the pointing accuracy; this may require further sun sensor alignments. Further magnetometer calibration is expected to reduce the large yaw errors seen upon entering eclipse. Efforts will also be undertaken to reduce the roll and yaw attitude errors to the level of the 0.5° derived requirement.

In addition, there is a desire to turn off one of the ACE processors. As mentioned previously, it is expected that the power provided to the spacecraft via the solar arrays will diminish with time. The second ACE processor provides redundancy but requires additional power. Some redundant sensors will be turned off when the second ACE is shut down so calibration of the remaining sensors will need to be redone in order to produce a good attitude solution.

Conclusions

The OrbView-2 spacecraft is currently operating as planned providing valuable SeaWiFS imagery to government and commercial customers. Despite GPS and control system anomalies, the flight operations team was able to reconfigure the ACS to allow it to meet specified performance requirements. Despite the lack of an IRU or a Kalman filter in the attitude determination loop, the ACS performs well enough to provide 0.1^{0} accuracy despite the awkward geometry of the OrbView-2 orbit. Much of the ability to adjust the performance of the OrbView-2 ACS lies in the large number of parameters, built into the flight code, that can be altered through command uploads. Performance of the OrbView-2 ACS proves that a low-cost innovative approach to control system design can provide a viable platform for commercial imaging and other applications.

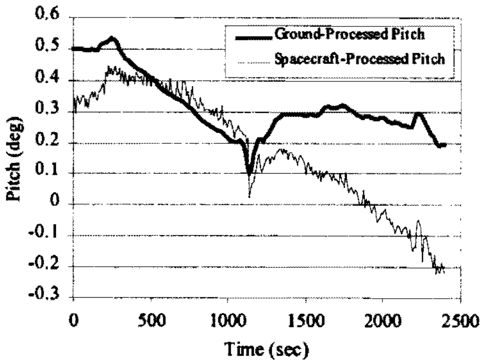

Figure 12 – Ground-Processed Pitch vs. Spacecraft Processed Pitch History

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Biography

Tobin Anthony holds three degrees in Aerospace Engineering including a Ph.D. from the University of Texas at Austin. He spent 12 years at NASA Goddard developing attitude control systems for several spacecraft including TRMM, XTE, and MAP. He now works at Orbital Sciences Corporation as an ACS lead engineer.

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