AAS 99-073

AMERICAN ASTRONAUTICAL SOCIETY

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21st ANNUAL AAS GUIDANCE AND CONTROL CONFERENCE

February 3-7, 1999
Breckenridge, Colorado

Sponsored by
Rocky Mountain Section

AAS Publications Office, P.O. Box 28130 - San Diego, California 92198

AAS-99-073

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This paper presents an overview of the Tropical Rainfall Measuring Mission (TRMM) Attitude Control System (ACS) along with detailed in-flight performance results for each operational mode. The TRMM spacecraft is an Earth-pointed, zero momentum bias satellite launched on November 27, 1997 from Tanegashima Space Center, Japan. TRMM is a joint mission between NASA and the National Space Development Agency (NASDA) of Japan designed to monitor and study tropical rainfall and the associated release of energy. Launched to provide a validation for poorly known rainfall data sets generated by global climate models, TRMM has demonstrated its utility by reducing uncertainties in global rainfall measurements by a factor of two.

The ACS is comprised of Attitude Control Electronics (ACE), an Earth Sensor Assembly (ESA), Digital Sun Sensors (DSS), Inertial Reference Units (IRU), Three Axis Magnetometers (TAM), Coarse Sun Sensors (CSS), Magnetic Torquer Bars (MTB), Reaction Wheel Assemblies (RWA), Engine Valve Drivers (EVD) and thrusters. While in Mission Mode, the ESA provides roll and pitch axis attitude error measurements and the DSS provide yaw updates twice per orbit. In addition, the TAM in combination with the IRU and DSS can be used to provide pointing in a contingency attitude determination mode which does not rely on the ESA. Although the ACS performance to date has been highly successful, lessons were learned during checkout and initial on-orbit operation. This paper describes the design, on-orbit checkout, performance and lessons learned for the TRMM ACS.

TRMM MISSION OVERVIEW

TRMM is a joint mission between NASA and the National Space Development Agency (NASDA) of Japan designed to monitor and study tropical rainfall and the associated release of energy shaping both weather and climate around the globe. TRMM is the first mission dedicated to measuring rainfall through five microwave and visible infrared sensors, including the first spaceborne rain radar. Launched to provide a validation for poorly known rainfall data sets generated by global climate models, TRMM has demonstrated its utility by reducing uncertainties in global rainfall measurements by a factor of two. A sample image taken by one of the TRMM instruments is shown in Figure 1.

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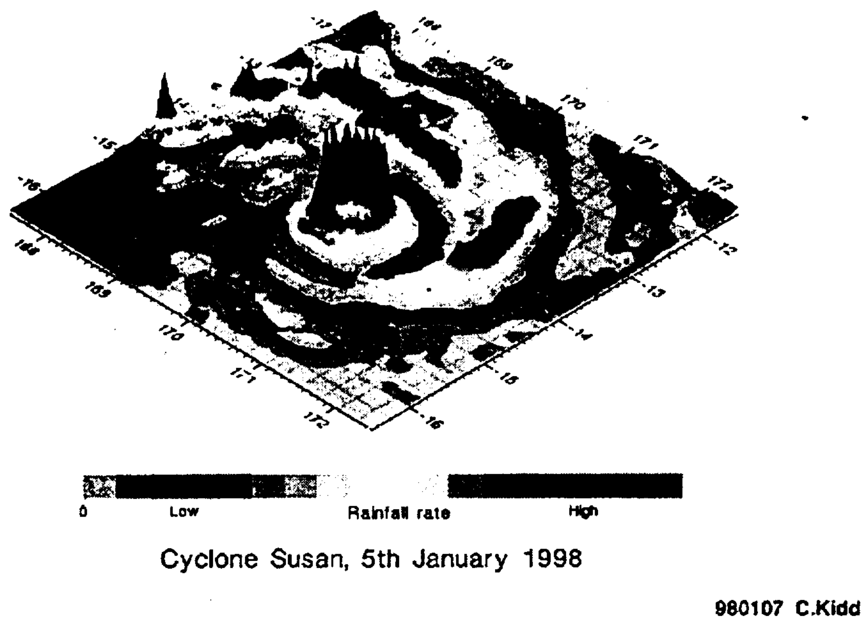


Figure 1 TRMM Science Image

The TRMM spacecraft, shown in Figure 2, was launched on the H-II Expendable Launch Vehicle on November 27, 1997 from Tanegashima Space Center, Japan. The spacecraft is three-axis stabilized, in a near circular 350 km orbit with inclination of 35°. At launch, the spacecraft had a mass of 3,523 kg including 903 kg of fuel and pressurant. Solar arrays are canted at a 26.5 angle from the YZ plane and track about the Y-axis via a Solar Array Drive Assembly (SADA).

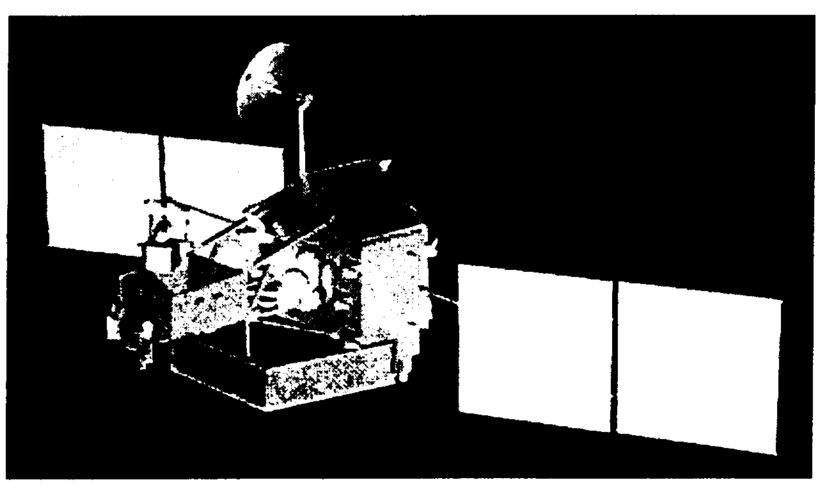


Figure 2 TRMM Spacecraft

TRMM ATTITUDE CONTROL SYSTEM DESIGN

The TRMM Attitude Control System (ACS) is required to maintain a nadir pointing attitude with requirements shown in Table 1[1]. Since there was no science requirement for either a geocentric or geodetic reference, for convenience the nadir reference was defined by the output of the chosen Earth sensor. This resulted in a nadir reference defined by a horizon bisector of the CO_2 horizon of the Earth, so that spacecraft pointing is provided with respect to a quasi-geodetic position . The ACS is required to provide the ability to acquire Mission Mode given worse case H-II tip-off rates and any spacecraft attitude.

Table 1
TRMM ACS MISSION MODE POINTING REQUIREMENTS

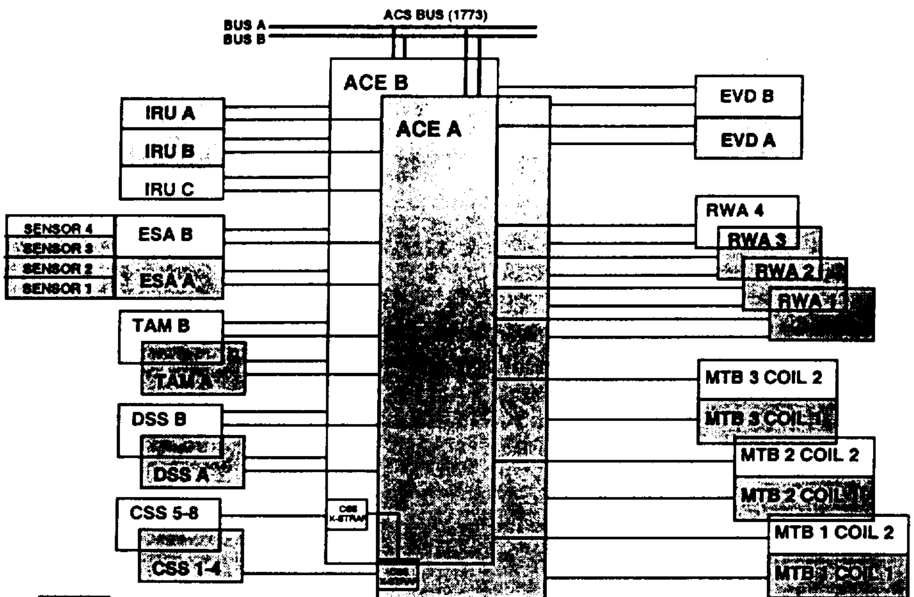
Characteristic	Requirement (per axis)
Pointing Knowledge, on-board (3σ)	0.2^0
Pointing Accuracy (3σ)	0.4^0
Stability (peak to peak)	0.1^0 over 1 sec

Due to an instrument thermal requirement that the –Y side of the spacecraft stay cold, the Mission Mode is required to operate in either a +X forward or –X forward orientation. The spacecraft is required to rotate 180^0 about nadir (yaw) every few weeks whenever the Sun crosses the orbit plane. Due to these yaw rotations, the spacecraft maintains an angle between the Sun and the spacecraft X-Z plane of roughly between 0^0 and 58.4^0.

The TRMM mission requires an orbit of 350 km altitude with tolerance of +/- 1.25 km. The ACS is required to provide thruster-based control modes to maintain the orbit and provide backup momentum unloading and slew capabilities. The ACS is also required to provide solar array tracking and High Gain Antenna (HGA) pointing throughout the mission.

The TRMM ACS architecture is shown in Figure 3. The ACS is comprised of Attitude Control Electronics (ACE), an Earth Sensor Assemble (ESA), Digital Sun Sensors (DSS), Inertial Reference Units (IRU), Three Axis Magnetometers (TAM), Coarse Sun Sensors (CSS), Magnetic Torquer Bars (MTB), Reaction Wheel Assemblies (RWA), Engine Valve Driver (EVD) and thrusters. Each EVD can drive up to 12 hydrazine thrusters. The ACE is comprised of an 80c86 processor, DC-DC converters, and actuator and sensor interface electronics. The ACE processor formats raw sensor data, decodes commands and contains Safe Hold flight software. The ACE transmits the sensor data over a 1773 fiber optics data bus to a 80386 processor, referred to as the ACS processor, for use by the ACS software and to be down-linked in telemetry. The flight software for initialization, attitude determination and control, momentum management, ephemeris generation, solar array commanding, High Gain Antenna (HGA) commanding, mode management and Fault Detection and Correction (FDC) are implemented in the

ACS Processor. The computed control torques are sent back to the ACE, which sends the appropriate commands to the actuators. The TRMM ACS operates at a 2 Hz control rate while in all modes with the exception of the thruster-based modes which operate at 8 Hz. All TRMM ACS components are fully redundant and cross-strapped with the exception of the MTBs which are redundant but not cross-strapped. The FDC software provides tolerance of a single point failure with minimal interruption to science data gathering.



Note: Shading denotes number of each component required to perform mission.

Figure 3 TRMM ACS Architecture

Table 1 shows the various ACS modes of operation, associated equipment used, and function of each mode. While in Mission Mode, the ESA provides roll (X) and pitch (Y) axis attitude error measurements. Yaw (Z) position is determined with DSS updates and propagated between updates using gyro output. Four RWAs arranged in a pyramid configuration are used for control. The TAM and three MTBs are used for momentum management.

Table 1
TRMM ACS MODES

Mode	Equipment Used	Function
Standby	80386, ACE CSS, IRU, TAM	ACS Mode entered during launch or while ACE in Safe Hold.
Sun Acquisition	80386, ACE CSS, IRU, TAM RWA, MTB	Acquire Sun-pointing attitude. Solar arrays commanded to index position.
Earth Acquisition	80386, ACE ESA, IRU, TAM RWA, MTB	Point +Z axis to nadir.
Yaw Acquisition	80386, ACE ESA, DSS, IRU, TAM RWA, MTB	Align +X or –X axis with velocity vector. Solar arrays commanded to track Sun when yaw attitude is within 10^0.
Mission	80386, ACE ESA, DSS, IRU, TAM RWA, MTB	Provide nadir pointing orientation for Science operation. Solar arrays track Sun. Orientation Submodes: +X forward, -X forward, -Y forward, Yaw Maneuver Attitude Determination Submodes: Normal, Contingency (does not use ESA)
CERES Calibration	80386, ACE IRU, TAM RWA, MTB	Maintain spacecraft inertially fixed for CERES instrument calibration.
Delta V	80386, ACE IRU VDE, Thrusters	Control spacecraft attitude during orbit adjust maneuvers. Submodes: +X forward, -X forward
Delta H	80386, ACE IRU VDE, Thrusters	Control spacecraft momentum. Backup yaw maneuver.
Safe Hold	ACE CSS, IRU, TAM RWA, MTB	ACE mode to acquire Sun-pointing attitude. Solar arrays commanded to index position. ACS resides in Standby.

The initial mode entered upon separation from the launch vehicle is the wheel-based Sun Acquisition Mode. In this mode, solar arrays are commanded to an indexed position and the spacecraft acquires a Sun-pointing attitude. Sun Acquisition Mode uses the full capability of both MTBs to increase momentum loading capability over Mission Mode. If spacecraft momentum is above a set limit when entering Sun Acquisition, RWA control to the Sun is not attempted while the MTBs unload momentum in order to conserve power. Once a valid ephemeris has been loaded in Sun Acquisition mode, the spacecraft may be commanded to Earth Acquisition Mode at any point in the orbit. Transition through Yaw Acquisition Mode to Mission Mode is autonomous.

Mission Mode is a wheel-based mode where all instrument science is performed. This mode allows the +X, -X or -Y spacecraft axis to be flown along the velocity vector. The –Y orientation is used occasionally throughout the mission for the instrument Precipitation Radar (PR) pattern mapping. Roll and pitch attitude is nominally computed by the ESA. Yaw attitude is propagated over the orbit by the IRU and updated twice per orbit by each DSS. A contingency attitude determination algorithm using a Kalman filter with DSS, TAM and IRU data (no ESA) can also provide pointing slightly degraded pointing from the 0.2^0 knowledge requirement. This mode was provided due to concerns that the ESA may have a single point failure. Yaw maneuvers to and from the +X, -X or –Y orientations are accomplished while in Mission Mode.

Delta V Mode is commanded for all orbit adjust maneuvers. This mode autonomously transfers through Earth Acquisition and Yaw Acquisition to Mission Mode once the burn has been completed. A Delta V may be performed in either the +X or -X direction. Four thrusters are located on the Instrument Support Platform (ISP) with thrust directions nominally along the +X axis and four other thrusters are located on the Lower Bus Structure (LBS) with thrust directions nominally along the –X axis. Either the ISP or LBS thrusters provide pitch and yaw control during the burn through off-modulation. Roll control during the burn is provided by on-modulation of four additional roll control thrusters with thrust directions radial to the X-axis.

CERES Calibration Mode is an inertial-fixed, wheel–based mode designed to be entered at orbit noon for one orbit. This mode provides calibration of the CERES instrument. CERES Calibration Mode is exited by command to Earth Acquisition Mode.

Delta H Mode is the only mode on TRMM that has not been entered to date. This mode allows the spacecraft to unload a set amount of momentum and can be used a backup to momentum unloading with magnetics at low altitudes during controlled re-entry. The Delta H Mode also provides backup yaw slews.

All ACS modes autonomously transfer to Standby Mode if the ACE enters Safe Hold Mode. Safe Hold Mode is functionally equivalent to Sun Acquisition Mode, but utilizes independent software coded in a different software language. Safe Hold Mode resides in the ACE processor, which provides hardware independence from the ACS processors. Safe Hold Mode was designed to be wheel based to avoid large changes in spacecraft momentum state which can result from the misuse of thrusters. While in Standby Mode, attitude is provided by the ACS processor through a TRIAD algorithm using TAM, DSS and IRU data. Figure 4 illustrates valid mode transitions.

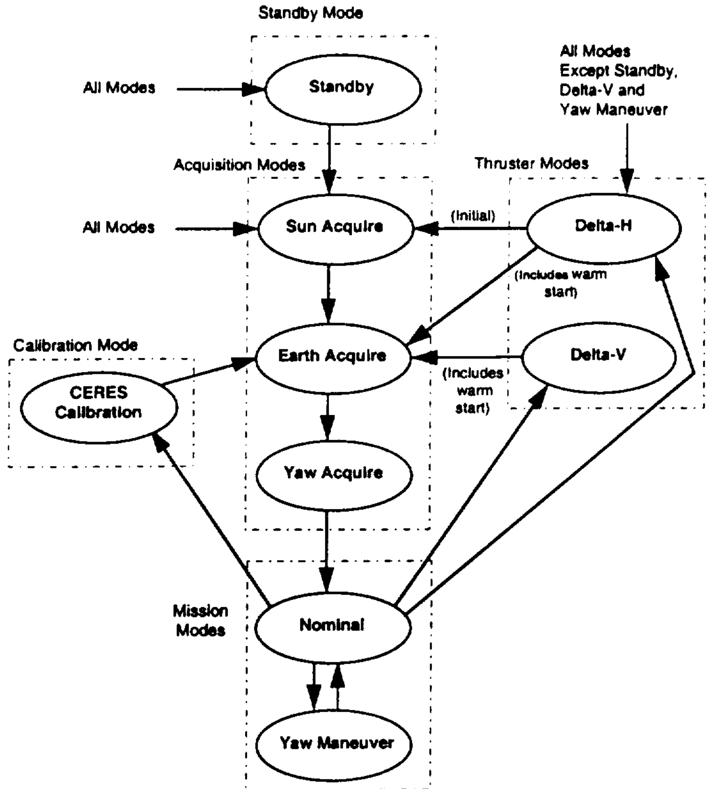


Figure 4 TRMM ACS Mode Transitions

LAUNCH AND ON-ORBIT CHECKOUT

Launch and initial operation of the TRMM ACS was very smooth. Upon separation from the H-II and deployment of the TRMM solar arrays and HGA, the RWAs were autonomously powered by the spacecraft sequencer and the spacecraft transitioned from Standby Mode to Sun Acquisition Mode. The H-II tip-off rates, as monitored by the IRU, were -0.02, -0.13 and 0.04 degrees/second for roll, pitch and yaw, respectively. These were well below even the 1-σ tip-off rates specified for the H-II. Due to the low spacecraft system momentum, four RWAs were immediately used to acquire the Sun in less than 10 minutes. Figure 5 shows gyro rates during the launch and acquisition. Figure 6 illustrates position errors while in Sun Acquisition Mode.

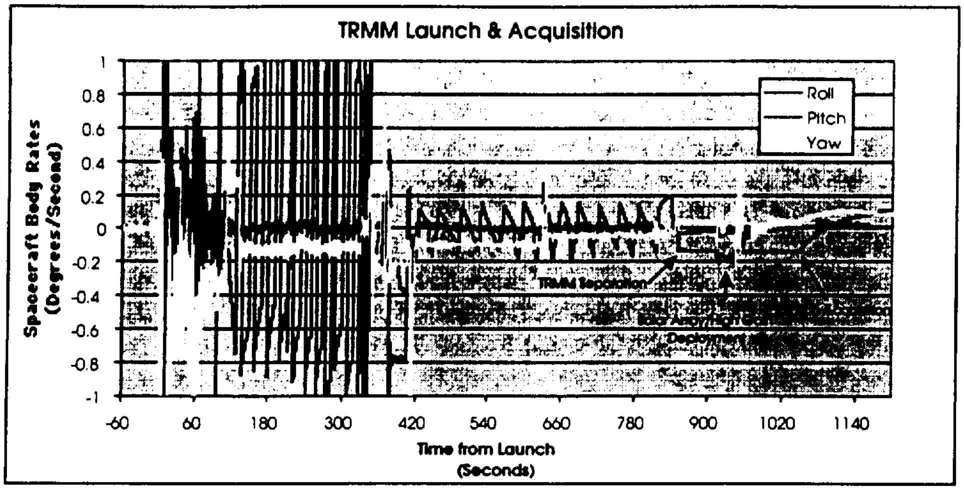


Figure 5 Launch and Acquisition: Gyro Rate

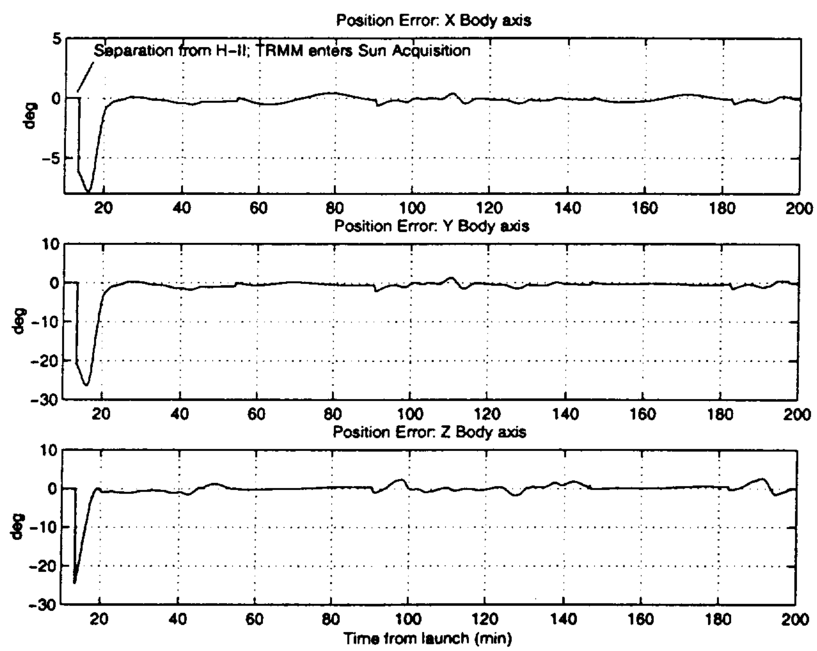


Figure 6 Sun Acquisition Mode: Position Errors

The only ACS anomaly acquisition occurred within the first orbit, when the FDC marked the TAM A as static and autonomously switched to TAM B. This occurred because the on-orbit noise on both TAMs was lower than the static threshold that is used to decide if the TAM data is updating correctly. Although this did not present a problem, because TAM B also had lower noise than expected the next FDC action would have transitioned the spacecraft to Safe Hold Mode. This was avoided to due quick ground diagnosis and command of the spacecraft to disable the TAM FDC test. The static threshold has since been lowered and TAM A is again being used.

Most of the TRMM ACS subsystem checkout was performed over a five day period during which time the spacecraft was transitioned to Mission Mode. On-orbit checkout consisted of observing system performance during nominal operation and performing three special tests to checkout Safe Hold, Contingency, and thruster modes of operation. Further Contingency Mode testing was done after descent burns were performed to reach the mission altitude of 350 km. Table 2 gives the timeline of events during on-orbit checkout.

Table 2
LAUNCH AND ON-ORBIT CHECKOUT TIMELINE

Time	Event
97-331-21:27:00	Launch
331-21:30:34	Fairing Separation
331-21:41:12	TRMM/H-II Separation
331-21:42:12	Solar Array and HGA pyros fire
331-21:42:42	RWAs powered ON
331-21:42:46	Entered Sun Acquisition Mode
331-21:44:00	+Y Solar Array is indexed
332-01:25	Isolation Valve #5 opened
332-13:17:29	Start of ACS Safe Hold test
332-14:48	End of ACS Safe Hold test
332-15:48	RCS Pyrotechnic Isolation Valve pyro fired, opening valve
332-16:21	Contingency Mode test performed
332-20:30	Exited Contingency Mode. Returned to Sun Acquisition Mode
332-21:03:06	Entered Earth Acquisition Mode
332-21:14:15	ESA Processing transition from Course to Fine
332-21:16:06	Entered Yaw Acquisition Mode
332-21:25:28	Entered Mission Mode
333-14:15:46	Roll thruster 1-shot calibration firings
333-17:58:00	ISP thruster calibration firings
334-15:11:01	10 sec Delta V ISP thruster calibration firing
335-15:03:01	10 sec Delta V LBS thruster calibration firing
337-19:35:01	60 sec Delta V descent burn
338-20:07:01	180 sec Delta V descent burn
339-19:05:01	180 sec Delta V descent burn
339-20:37:01	180 sec Delta V descent burn
340-18:54:01	180 sec Delta V descent burn
340-20:26:01	60 sec Delta V descent burn
341-17:43:38	81 sec Delta V descent burn
341-19:28:42	69.625 sec Delta V descent burn
341-19:29:52	Mission orbit reached
341-20:45:45	Precipitation Radar enters observation mode at mission altitude
346-14:33:00	DSS Alignment Table uploaded
347-13:11:02	First 180° Yaw Maneuver

ACS Safe-Hold Test

One day after launch, TRMM was transitioned from Sun Acquisition to Safe Hold during a planned special test of the Safe Hold operation. This test was performed to ensure that the spacecraft had a safe state to enter should an anomaly occur in the future. The test was done early in the mission to ensure that the mode was fully checked out with engineers familiar with the design who may not be present should the spacecraft transition to Safe Hold in the future.

ACS Contingency Mode Test

While in Sun Acquisition, the ACS Contingency Mode was tested. In Contingency Mode the ACS uses the DSS and TAM data to estimate spacecraft attitude and gyro biases using a Kalman filter algorithm. While in Sun Acquisition Mode the Kalman filter output is available, but it is not used to point the spacecraft. This allowed the performance of the Kalman filter to be tested without affecting spacecraft performance.

Contingency Mode was tested using DSS and TAM data, and during eclipse when only the TAM data was available. When the Kalman filter was reinitialized in eclipse, it did not accept the DSS data when it became available. The algorithm overestimated its accuracy without the DSS data and underestimated the accuracy of the DSS data. Thus it was not as accurate as it could have been if it had used the DSS data. The Kalman filter was re-tuned based on this test in preparation for the Contingency Mode test in Mission Mode.

In reviewing the performance of the Contingency Mode, it was discovered that the magnetic field model on-board was not internally consistent. The coefficients were from a 1995 model, but the epoch time for computation of the secular variations was set to 1990. An attempt was made to update the magnetic field model, but it was discovered that the epoch for the magnetic field model could not be changed using a table load because it was hard coded in the software. The coefficients were set back to correspond to the 1990 epoch for the test in Mission Mode. If Contingency Mode is ever required for the TRMM mission, a software patch will be loaded to allow change of the epoch time.

The Contingency Mode was tested while in Mission Mode after all sensor calibration was complete. The best measure of performance of the Contingency Mode is the attitude derived from the ESA. Although ESA data is not processed while in Contingency Mode, the data is available in telemetry. Figure 7[2] show the attitude errors derived on the ground from ESA telemetry while the spacecraft is controlled to the attitude derived from Contingency Mode. Transients occur when Contingency Mode is entered and when the Kalman filter is reset by the ground during this test. The initial attitude transients are on the order of 1^0 in roll and 0.2^0 in pitch. The steady state performance is on the order of 0.25^0.

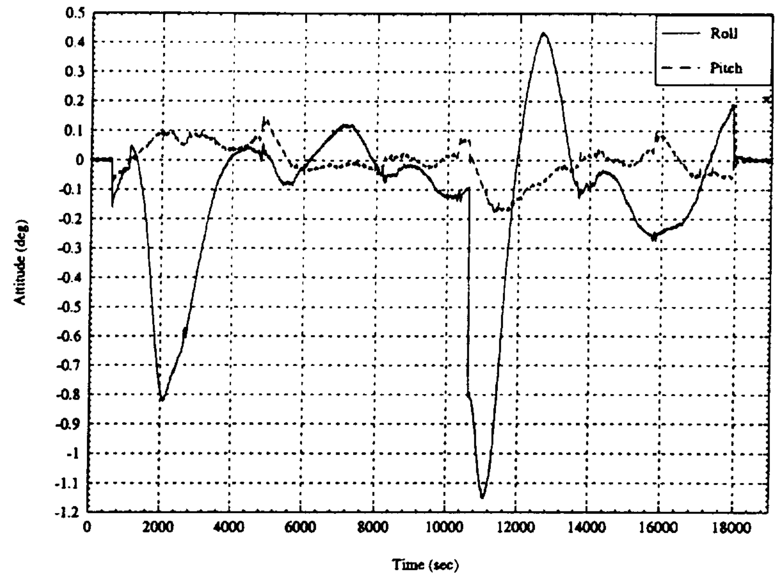


Figure 7 Mission Mode Contingency Mode Test: ESA Attitude

Earth Acquisition

Earth acquisition performance is shown in Figure 8. Within approximately 12 minutes, a nadir attitude was reached and the spacecraft autonomously transitioned to Yaw Acquisition Mode. Mission Mode was autonomously entered within approximately 22 minutes.

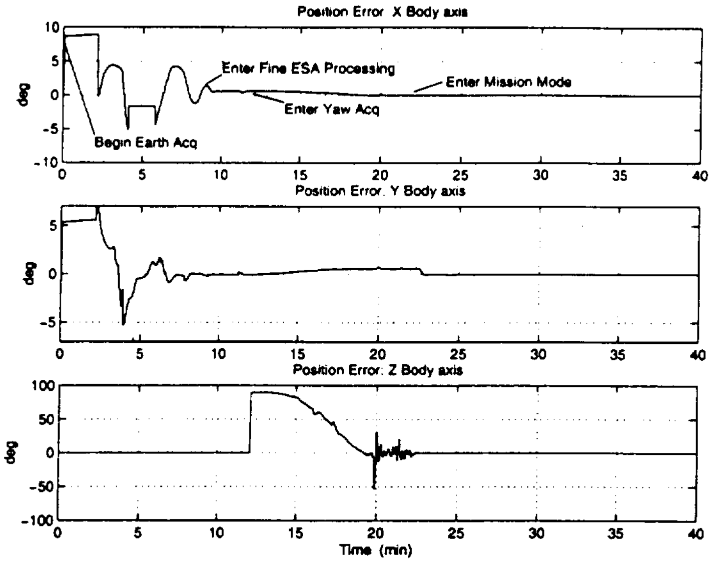


Figure 8 Earth Acquisition: Position Errors

Mission Mode

Upon first entering Mission Mode, the spacecraft attitude showed larger DSS yaw updates than expected. Corresponding to these changes, the on-board estimate of the gyro bias showed similar changes which resulted in significant drift in the yaw direction until the next yaw update. This pattern of attitude fluctuation was traced to not just sensor misalignment but also to a misalignment between the two heads within each DSS. In order to avoid alteration of the flight software, DSS transfer function coefficients were determined to minimize the error due to head misalignment. Figure 9[3] shows how alignment and DSS coefficient uplinks improved the attitude determination performance while in Mission Mode.

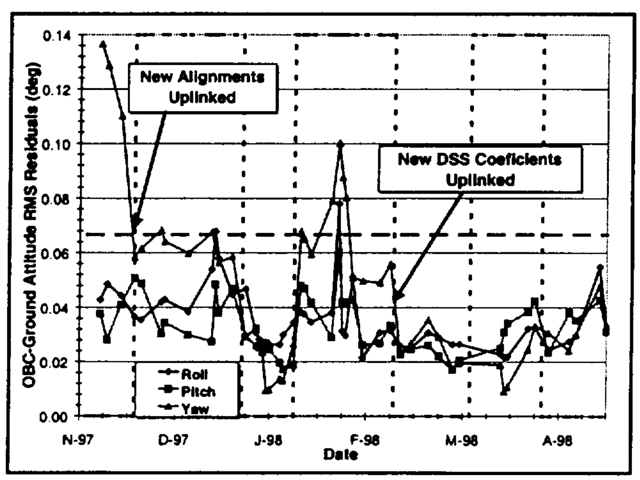


Figure 9 Mission Mode Performance

Another unexpected spike in position error was found to occur in roll and pitch during periods of time when the Sun was in one the ESA quadrant's Field of view (FOV), as shown in Figure 10. It was determined that these spikes were caused by the on-board ESA processing. When the Sun is predicted to intrude into an ESA quadrant FOV, that quadrant is not used in attitude computations and the output for that quadrant is not filtered. When the Sun is predicted to leave the quadrant FOV, it is then again used in attitude computations and filtering resumes. The spikes in position error resulted from an error in the on-board algorithm which did not reset the filter properly when it was turned back on. The bottom plot in Figure 10 illustrates the position error with filtering turned off during a period of time when the Sun passes through the same ESA quadrant FOV. It can be seen that the removal of the filter has greatly minimized the effect of spikes due to Sun intrusion. A flight software change could be made to correct the filter initialization; however, the performance with the filter turned off was deemed to be adequate.

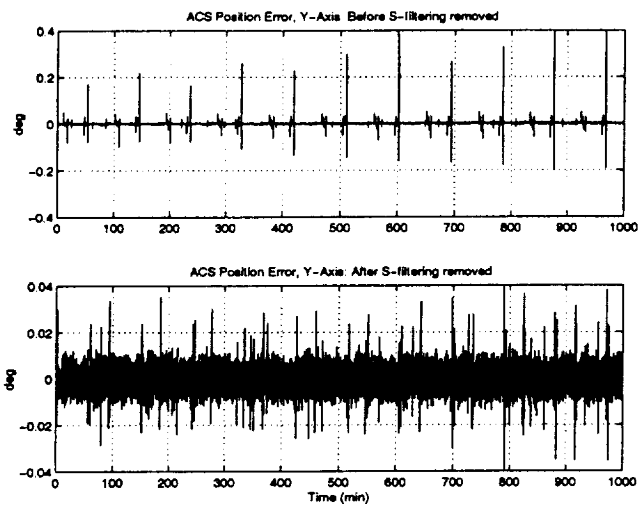


Figure 10 Mission Mode: Position Error

Thruster Calibration and Delta V performance

The TRMM thruster calibration consisted of one-shot firings of each of the 4 roll control thrusters, two 10 second firings of the 4 thrusters located on the ISP, and one 10 second firing of the 4 thrusters located on the LBS. One shot firings consisted of a single 200 msec pulse commanded by the ground. The 10 second ISP and LBS firings were accomplished by entering Delta V Mode.

The ISP thrusters were tested during a 10 second Delta-V calibration firing. The delta-V was successful, but the -Pitch thruster was only on for about 7 seconds. A retest resulted in the same performance. Initial simulations predicted that all four delta-V thrusters would be commanded on for the entire 10 seconds. For such a short duration burn it was not believed that the disturbances would cause the attitude errors to reach the switching limits. When these switching limits are reached, the ACS automatically offmodulates the appropriate thruster. Slight differences in the assumptions for center of mass, thruster alignment, thruster positions, and thrust levels will cause slight variations in the time required to reach the -pitch switching limit. It should be noted that the center of mass is above the X-Y plane, so some net -Pitch torque is expected. The 10 second test of the LBS thrusters resulted in no off modulation of any of the thrusters. Table 3 gives actual and expected thruster accelerations.

Table 3
THRUSTER ACCELERATIONS

Acceleration	Actual (deg/sec^2)			Expected (deg/sec^2)		
ISP disturbance	-2.99E-06	-6.15E-04	1.39E-05	-9.64E-08	-4.64E-04	7.43E-05
ISP control	-3.46E-06	1.18E-03	-2.88E-05	-4.65E-06	1.01E-03	7.73E-05
ISP-Pitch	4.68E-07	-1.80E-03	4.27E-05	4.56E-06	-1.48E-03	-2.98E-06
LBS disturbance	-9.56E-06	5.32E-04	-9.12E-05	6.84E-06	4.67E-04	-9.65E-05

Although the ISP pitch disturbance acceleration was higher than expected, and the ISP yaw acceleration was almost nonexistent, the controller worked as expected on the actual disturbances. A typical phase plane plot for one of the 3 minute descent burns is shown in Figure 11. The one LBS thruster burn also showed a larger pitch disturbance acceleration than expected, but the yaw disturbance was accurately predicted.

Based on the commanded firing times and the computed thruster accelerations, the ISP -Pitch thruster is off modulated about 34% of the time. The attitude hangs off about 3.4 degrees, which is comparable to the predicted 3.6 degrees. The rate error is controlled to +/- 0.1 deg/sec. The system reaches a steady-state duty cycle in about 60 seconds.

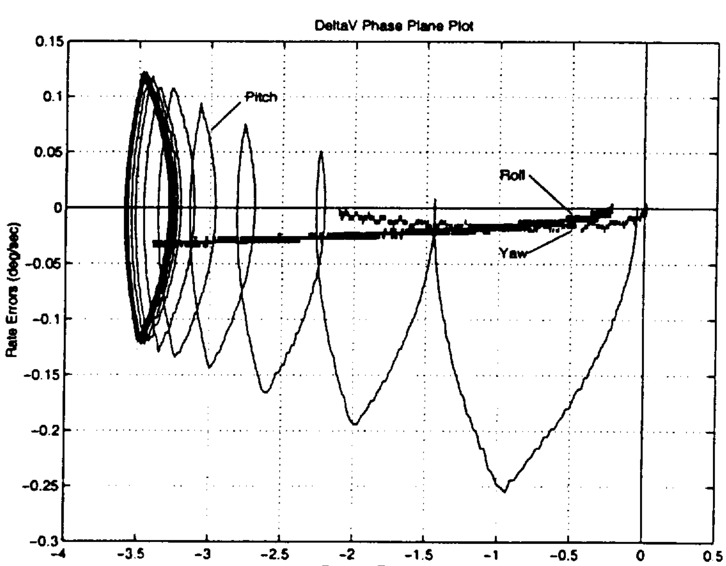


Figure 11 Delta-V Mode: IRU Rate

ON-ORBIT PERFORMANCE

Mission Mode

Once all sensor calibration was complete, the Mission Mode performance was evaluated by performing a ground solution. The ground solution was obtained from a batch least-squares computation of the attitude using all sensor data. The major source of DSS errors was found to be the remaining uncompensated misalignment of the sensor heads. The major source of ESA errors appears to be variation in horizon radiance. The ESA performance was slightly degraded during periods in which one or two of the sensor quadrants could not be used because of the proximity of the Sun or Moon image to the field-of-view. Figure 12 illustrates the ground solution showing performance of the TRMM Mission Mode over a typical orbit. Performance is well within the 0.2^{0} knowledge requirement.

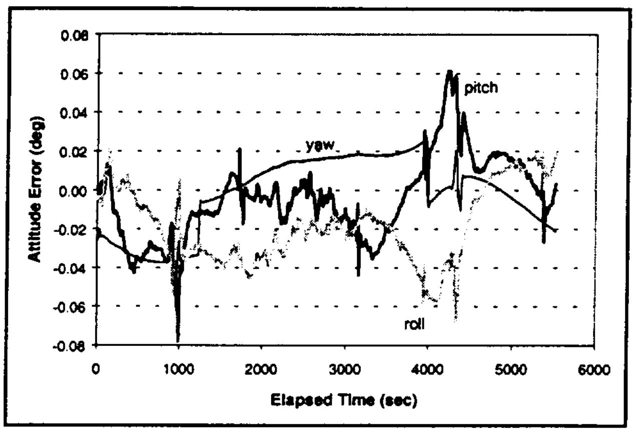


Figure 12 Mission Mode: Ground Solution Attitude

LESSONS LEARNED

A number of lessons learned were derived during on-orbit checkout of the TRMM ACS. One lesson learned deals with the importance of communication between engineers and the importance of allowing flexibility in the ACS flight software. More thorough communication between the ACS and Mechanical engineers could have prevented a misunderstanding of the importance of mounting the DSS heads orthogonal with high precision. More attention during integration and test to the detail of the alignment measurement summary on the part of the ACS team could have identified the problem prior to launch. Finally, the ACS flight software should have been designed with the flexibility to accommodate misalignments of each head rather than each DSS. Extra DSS coefficient tables or alignment matrices for each DSS head would have reduced the amount of effort spent calibrating the DSS post-launch.

Another lesson learned deals with the importance of sensor model fidelity and correlating test data with model assumptions. The autonomous FDC configuration change to the redundant TAM during initial on-orbit operations could have been avoided if a better representation of the TAM noise had been used during design. The post launch removal of the filter in ESA processing could also have been avoided if a thermal dependent model of the ESA had been used in simulations. The problem with the filter reset when switching from 3 back to 4 quadrant processing was not uncovered because a non-thermal dependent ESA model was used in all simulations and flight software qualification tests. Alternatively, a high fidelity stimulator of the ESA capable of stimulating 3 and 4 quadrant processing could have uncovered the problem during test.

Another lesson learned dealt with the importance of a table design that allows parameters to be changed in flight software without software patches. The DSS misalignment errors were successfully calibrated through table up-link; however, the epoch update for the on-board magnetic field model could not be accomplished without a software patch. Software patches require a significant development and testing effort and impose an additional risk to spacecraft health.

CONCLUSION

The on-orbit performance of the TRMM ACS has been presented along with the mission level requirements. Flight data results show that the TRMM ACS is meeting all of the imposed requirements. Although the TRMM Mission Mode continues to meet pointing requirements and the mission has been very successful to date, lessons learned were realized.

ACKNOWLEDGMENT

The authors wish to thank Marty Frederick, whose leadership of the TRMM ACS effort was a major factor in its success.

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