MICROWAVE ANISOTROPY PROBE LAUNCH AND EARLY OPERATIONS

James R. O'Donnell, Jr., Ph.D., Stephen F. Andrews, Scott R. Starin
Flight Dynamics Analysis Branch

David K. Ward, Systems Engineering Branch

NASA Goddard Space Flight Center
Greenbelt, MD 20771 USA

The Microwave Anisotropy Probe (MAP), a follow-on to the Differential Microwave Radiometer (DMR) instrument on the Cosmic Background Explorer (COBE), was launched from the Kennedy Space Center at 19:46:46 UTC on June 30, 2001. The powered flight and separation from the Delta II appeared to go as designed, with the launch placing MAP well within 1σ launch dispersion and with less than 7 Nms of tip-off momentum. Because of this relatively low momentum, MAP was able to acquire the sun within only 15 minutes with a battery state of charge of 94%. After MAP's successful launch, a six week period of in-orbit checkout and orbit maneuvers followed. The dual purpose of the in-orbit checkout period was to validate the correct performance of all of MAP's systems and, from the attitude control system (ACS) point of view, to calibrate the performance of the spacecraft ACS sensors and actuators to maximize system performance. In addition to the checkout activities performed by the MAP team, the other critical activity taking place during the first six weeks after launch were a series of orbit maneuvers necessary to get the spacecraft from its launch orbit out to its desired orbit about L2, the second Earth-Sun Lagrange point.

As MAP continues its standard operations, its ACS design is meeting all of its requirements to successfully complete the mission. This paper will describe the launch and early operations summarized above in greater detail, and show the performance of the attitude control and attitude determination system versus its requirements. Additionally, some of the unexpected events that occurred during this period will be discussed, including two events which dropped the spacecraft into its Safehold Mode and the presence of an "anomalous force" observed during each of the perigee orbit maneuvers that had the potential to cause these critical maneuvers to be prematurely aborted.

INTRODUCTION

The Microwave Anisotropy Probe (MAP), one of the first two Medium-Class Explorer (MIDEX) missions, will measure the anisotropy of the Cosmic Microwave Background (CMB), which is believed to be a remnant of the Big Bang marking the birth of the universe. This anisotropy was first measured by the Differential Microwave Radiometer (DMR) instrument on the Cosmic Background Explorer (COBE) satellite.[1–4] MAP has been designed to measure the spectrum and spatial distribution of the CMB with sensitivity 50 times greater than that of the DMR and angular resolution 20 times finer, specifically 0.3° or 18 arc-minutes.[5] These increases in sensitivity and resolution should enable MAP to determine the values of key cosmological parameters and to answer questions about the formation of structure in the early universe.[6]

MAP was launched on June 30, 2001, and, after three phasing loops about the Earth, a gravity assist from the moon, and five orbit adjust maneuvers, entered its planned Lissajous orbit around the second Earth-Sun Lagrange (L_2) point in October, 2001. This paper will describe the experience of the MAP attitude control system (ACS) team during the launch and early orbit period of MAP, concentrating on the in-orbit checkout (IOC) activities performed to test the spacecraft ACS hardware and software. It will also describe the orbit maneuvers performed to keep MAP on its way to L_2, and describe the two Safehold events that have occurred on MAP since launch. (For more detail about the MAP ACS design, see references 7 and 8.)

LAUNCH AND IOC TIMELINE

To reach its planned orbit about the second Earth-Sun Lagrange point (L_2), MAP first performed three phasing loops about the Earth. An orbit maneuver was planned at perigee of each of the phasing loops. After the third phasing loop, MAP performed a lunar swingby and used the gravity assist from the moon to send it on its way to L_2. This trajectory divided up MAP's in-orbit checkout (IOC) period into the approximately one week periods for each phasing loop. The launch and IOC timeline for MAP was structured as follows:

- *Pre-Launch and Launch*: Launch day began 12 hours before the scheduled launch time, as the spacecraft was powered on and configured for launch. There were a few issues that crept up during this period—the most serious of which being a period of intermittent telemetry caused by a ground station problem—but all issues were resolved in time to allow the Delta II rocket carrying MAP to launch at 19:46:46.183 UTC, 183 milliseconds into the beginning of its launch window.

- *Separation and Initial Acquisition*: As with most spacecraft, the period from launch until spacecraft separation from its launch vehicle was one of the most tense periods of the mission. After an expected post-launch communications gap of over an hour, a low rate command and telemetry link was established with MAP about 10 minutes before separation. The spacecraft telemetry revealed that MAP was in a nominal state, though the rocket third stage had yet to perform it yo-yo despin. The despin went off without a hitch, the spacecraft separated and its solar arrays deployed, and MAP very quickly was declared safe with stable pointing of the solar arrays to the sun.

- *Phasing Loop and Perigee Maneuver 1*: The first week of MAP's mission was its busiest time. During this time, there were three major ACS related activities going on concurrently. First, all of MAP's ACS sensors and actuators were tested, along with all ACS software and control modes. Second, operations were conducted on the spacecraft that were used to calibrate and determine post-launch alignments for MAP's ACS and propulsion sensors and actuators. Finally, preparations were made for the first orbit maneuver, performed at the first perigee.

- *Phasing Loop and Perigee Maneuver 2*: With most IOC activities completed, the second phasing loop period was relatively quiet. A lot of analysis, however, was performed investigating an anomalous force phenomena observed during the first perigee maneuver. Also, because of moon albedo interference in MAP's star trackers, the spacecraft was not able to be placed into Observing Mode, its nominal science mode, which uses a dual spin motion canted 22.5° off of the sun line. A "shallow" spin mode was developed to avoid the moon albedo interference and give a better thermal environment for the instrument. A second thruster calibration burn was performed at the second apogee (A2) and the second perigee maneuver was performed at the end of this phasing loop.

- *Phasing Loop and Perigee Maneuver 3*: MAP was able to be placed in Observing Mode during most of the third phasing loop. The final thruster mode calibration was performed at the third apogee (A3) and the final perigee maneuver executed at the third perigee (P3), with a small correction maneuver performed approximately a day later.

- *Lunar Swingby and Midcourse Correction Maneuvers*: Four days after P3, MAP performed its lunar swingby, which put it on its way to L_2. A small midcourse correction maneuver was performed a week later. After this maneuver, MAP was put into Observing Mode in order to achieve the thermal stability required to generate good science data. Another midcourse correction maneuver was performed about a month later, on September 14, 2001, to place MAP into a trajectory to achieve its planned L_2 orbit.

SEPARATION AND INITIAL ACQUISITION

The MAP spacecraft was launched on June 30, 2001, at the very beginning of its launch window at 19:46:46 UTC. Its ride atop the Boeing Delta II rocket was without incident. After a post-launch communications gap, contact was established with MAP via TDRS-W at 21:03, 77 minutes after launch and 10 minutes prior to spacecraft separation. At the beginning of this contact, MAP was still in the Delta II third-stage spin; gyro rates were saturated (over 5.3°/sec) and the system momentum magnitude measurement was over 90 Nms (Figure 1). At 21:13, the yo-yo despin from the third-stage spin occurred, and MAP separated from its booster. Within one telemetry update (16 seconds), the gyros desaturated with all axes below 1°/second. The measured system momentum dropped in that update to approximately 10 Nms. The solar arrays began to deploy 14 seconds after separation. The spacecraft reported that the arrays were deployed (all arrays deployed to within 25° of their fully deployed state) 8 seconds later. As shown in the inset in Figure 1, the system momentum magnitude changed as the mass properties of the spacecraft changed during array deployment and fuel spin down. It took 4 minutes for the arrays to open fully. At this point, the system momentum magnitude was 7 Nms—well within the maximum level of 55 Nms at which Sun Acquisition Mode could acquire the sun.

Figure 2 shows the coarse and digital sun sensor (CSS and DSS) measured sun angles at separation. Note that the sun was out of the DSS field of view until 5530 seconds of the plot. The spacecraft acquired the sun within 7 minutes of separation. The spacecraft was declared separated and safe on the sun at 21:26. The first ACS activity after this was to power on the two Lockheed Martin AST-201 Autonomous Star Trackers (ASTs), in order to quickly determine that the trackers would successfully track stars and output attitude quaternions. First AST 1 and then AST 2 was powered on. After an expected power up delay, both trackers began to track stars and reported consistent attitude quaternions. However, as the spacecraft rotated at 0.1°/second (because of a Z axis gyro bias loaded pre-launch), both trackers endured periods of lost track. AST 1 was able to recover on its own, but AST 2 needed to be reset from the ground at 22:34. It was determined that this problem was related to the tracker seeing stray light from Earth limb; as MAP's altitude increased, the problem did not recur.

After a thruster pulse test was performed and the Z axis gyro bias removed, MAP's Delta H Mode was used to dump its separation momentum. After 5 seconds, the mode timed out and returned to reaction wheel control, reducing the system momentum from 7.0 to 0.75 Nms.

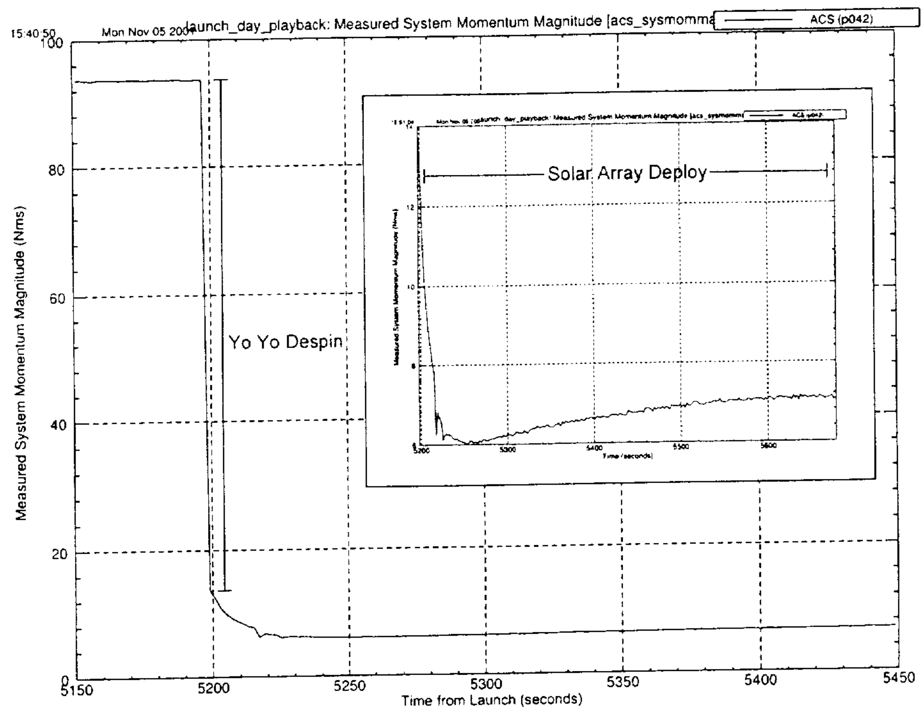

Figure 1: System Momentum Magnitude at Separation

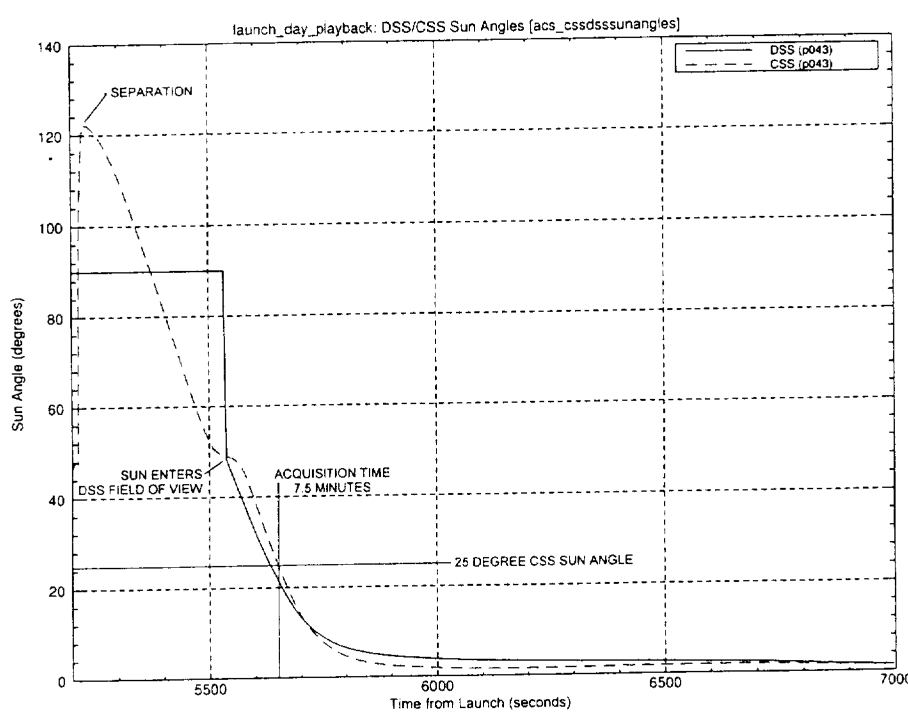

Figure 2: Sun Angles at Separation

SENSOR AND ACTUATOR TESTS AND CALIBRATION

Two sets of reaction wheel based operations were planned for sensor calibration and alignments. The first of these was a set of slow slews to be used for scale factor determination and alignment of MAP's two Kearfott Two-Axis Rate Assemblies (TARAs). After these slews were completed, a series of slow spin operations was planned to generate data to calculate the relative alignments of MAP's two ASTs and its two Adcole DSS heads. Calibration burns for the propulsion system used in MAP's thruster control modes were also planned and conducted; these will be discussed later in this paper.

In addition to these planned activities, two other calibration activities took place during MAP's first week in orbit that were not planned. The first of these was calibration of the tachometer outputs of the three Ithaco Reaction Wheel Assemblies (RWAs); because the tachometer outputs were used in several of the ACS control modes—including Observing Mode—it was important to calibrate them as closely as possible. This calibration will be discussed in the science mode performance section below. Also, after noticing that the sun angle derived from MAP's twelve Adcole CSSs was significantly different than that measured by the DSS, a calibration of the CSS eyes was performed. Rather than upload new parameters to the spacecraft, however, it was decided to relax several failure detection and correction (FDC) limits that used CSS input.

Gyro Calibration Slews

Before the slow slews used to calibrate the TARAs were performed, a polarity check of the Inertial Mode controller was done. This polarity check used a slew profile similar to the calibration slews, using smaller slews to verify the correct polarity of the Inertial Mode controller and to verify that the software command quaternion table (CQT) used to implement the slew profile worked correctly.

The TARA calibration slews were performed the day after launch. The spacecraft had to be slowly slewed about one axis at a time for as large a slew as possible. At the end of each slew the spacecraft was held for at least an hour to collect AST and other sensor data that would be used for the calculation of gyro scale factors and alignments. Because of MAP's 22.5° sun angle constraint needed to thermally protect the science instrument, slews in the X and Y axes were limited to 44°. There were a total of 10 calibration slews; starting and ending in a sun pointing attitude with the slew sequence about each: +22°, –44°, +44°, –22° first about the X and then about the Y axis, and ±90° slews about the Z axis. Figure 3 shows the Y axis attitude error and rate associated with the Y axis calibration slews; note that the slew rate for these slews was reduced from the Inertial Mode nominal value of 0.5°/second to 0.1°/second. The sensor data from these slews was saved and post-processed to develop new alignment matrices and scale factors for the TARAs. There were no anomalies during the slews. The next day, the new TARA parameter data was loaded onto the spacecraft. The calibration series of slews was repeated to verify the new parameters.

Star Tracker and Sun Sensor Alignment Spins

To generate the data needed to coalign the ASTs and DSSs, a series of calibration spins was planned. There would be seven spins; each with a 0.1°/second spin and no precession about the sun line, at scan angles of 22.2–22.8° from the sun in increments of 0.1°. The slow single axis spin would make it easier for attitude determination data to be analyzed in order to determine the post-launch alignments of both the ASTs and the DSS heads. The range 22.2–22.8° was used to cover the 22.5±0.25° range specified in the requirements as the allowable sun angle range in Observing Mode. The table driven ACS flight software design allowed these spins to be implemented using Observing Mode with a handful of parameter changes. The spins were performed on the third day after launch and the new AST and DSS parameters uploaded to the spacecraft two weeks later.

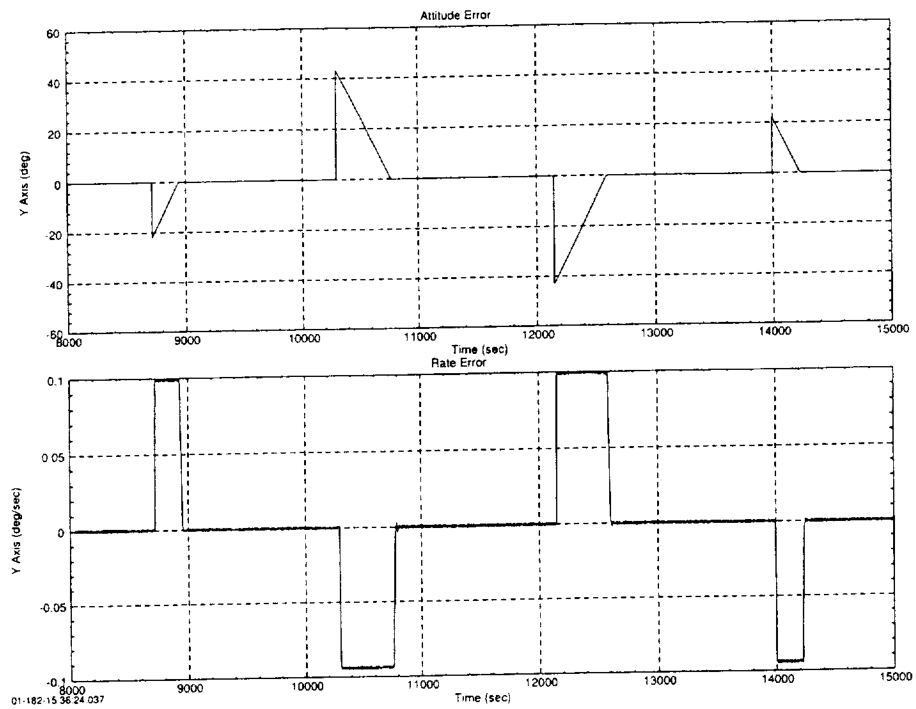

Figure 3: Y Axis Gyro Calibration Slews

SCIENCE MODE ATTITUDE DETERMINATION AND CONTROL

The MAP science instrument includes radiometers at five frequencies, covering two fields of view (FOVs) 135° apart on the celestial sphere. To obtain a highly interconnected set of measurements over a large area of the celestial sphere, the MAP Observing Mode combines a fast spin (2.784 °/second) and a slower precession (0.1°/sec) of its spin axis about the sun line, while the spin axis is held 22.5° off of the sun.

Observing Mode Checkout

On July 2, 2001, two days after launch, the first test of Observing Mode was conducted. This was a first look at many important aspects of the MAP ACS subsystem. In addition to being the initial trial for Observing Mode, it was the first chance provided for seeing how well the ASTs and Kalman filter performed during MAP's approximately 3°/second compound spin. As it turned out, however, the most interesting aspect of this first test did not have to do with either the ASTs or the filter, but with the reaction wheel tachometers.

Figure 4 shows the Euler states—the precession rate, the scan angle, and the spin rate—during the initial spin-up into Observing Mode. Because sensor calibration parameters had not yet been calculated and uploaded to the spacecraft, Observing Mode performance during these initial tests did not satisfy the ACS requirements; this was expected until all sensor calibrations were completed.

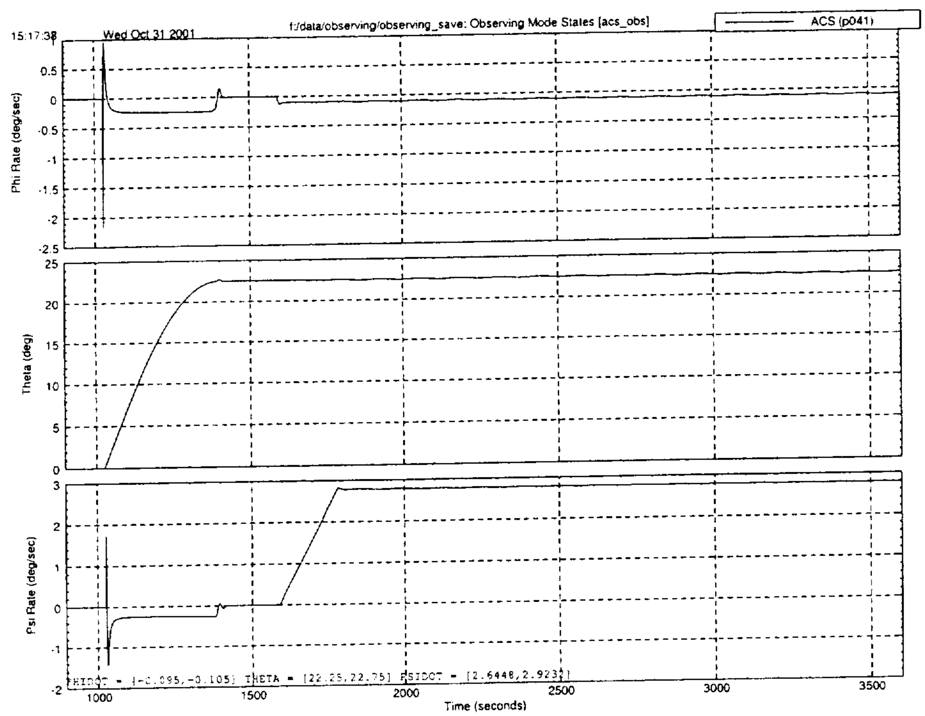

Figure 4: Initial Observing Mode Spinup

Reaction Wheel Tachometer Calibration

Besides the attitude and rate performance requirements for Observing Mode reflected in the measurements of the Euler states, there was, also, an accuracy requirement for the system momentum magnitude measurement in Observing Mode to be within 0.1 Nms, in order to assist in determining when to dump momentum. During flight software testing, this requirement was relaxed because reaction wheel tachometer quantization error and noise prevented the original requirement from being met. Figure 5 shows the system momentum magnitude measurement upon spin-up into Observing Mode. The measurement went from a fairly steady value of approximately 0.8 Nms, when the spacecraft was not moving and had very low reaction wheel speeds, to a sinusoidally varying value (with both spin and precession rate components) with a mean of about 1.65 Nms and a peak-to-peak variation of about 0.24 Nms; other data sets showed this peak-to-peak variation as high as 0.8 Nms.

MAP's system momentum measurement is derived from the spacecraft rates, as measured by the configured rate source (normally the gyros), and the reaction wheel speeds, as measured by the tachometers. Over short periods of time, the system momentum magnitude remains constant, so the highly varying value in Observing Mode showed that there was a problem with one or both of the measurements. Because the measured spacecraft rates are passed through the Kalman filter, it was unlikely that those values were significantly in error. So, the most likely problem was in the tachometer measurement of the reaction wheel speeds. Some error in the tachometer measurement, or in the tachometer measurement compared to the gyro rate measurement, was causing three distinct error effects in the system momentum measurement: a measurement bias, a sinusoidal spin rate error, and a sinusoidal precession rate error.

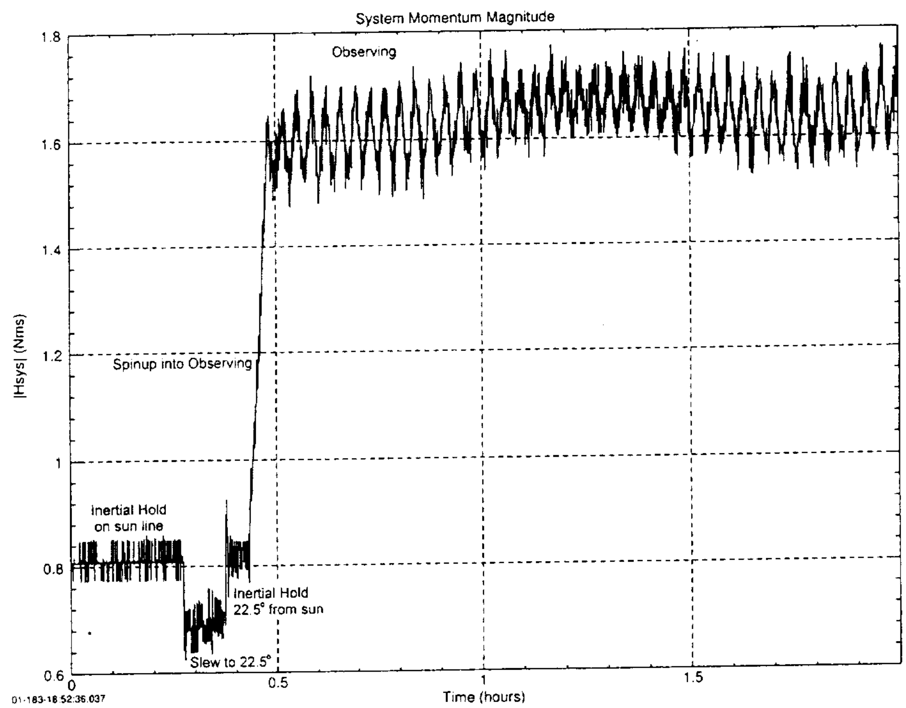

Figure 5: Measured System Momentum Magnitude Entering Observing Mode

By comparing the system momentum magnitude when MAP was stationary to its mean value in Observing Mode, an approximate RWA tachometer scale factor error of 4% was determined. However, the presence of the spin rate component of the measurement error made it apparent that the tachometer scale factors were also in error relative to one another. The tachometer scale factors were calibrated by analyzing flight data and comparing it with data from the MAP high fidelity (HiFi) simulator. It was then possible to compare the actual and ideal RWA tachometer measurements and to calculate a scale factor error for each wheel of 2.4%, 4.2%, and 4.5%, respectively. New scale factors were calculated and uploaded to the spacecraft; Figure 6 shows the Observing Mode system momentum magnitude measurement immediately before and after the upload. The lingering precession rate component of the measurement error can be traced to a small time difference between the body rate and wheel speed measurements; this error is also present in the HiFi simulation system momentum measurement.

Observing Mode Performance

Figure 7 shows the Observing Mode performance from the initial Observing Mode checkout, before any sensor calibrations had been performed and/or uploaded to the spacecraft. The final alignments and calibrations were uploaded on August 7, 2002, followed by nominal values for the onboard Kalman filter parameters. These values were tuned for the nominal operating range of the sensors and were not as large as the values used at launch, which assumed uncalibrated and misaligned sensors. Figure 8 shows the resulting performance of the mode (using the same scales as the plots in Figure 7). It can be seen that the performance is significantly improved. Table 1 shows the pre- and post-calibration Observing Mode performance, verifying that the control mode met its requirements after all of the sensor calibrations were performed.

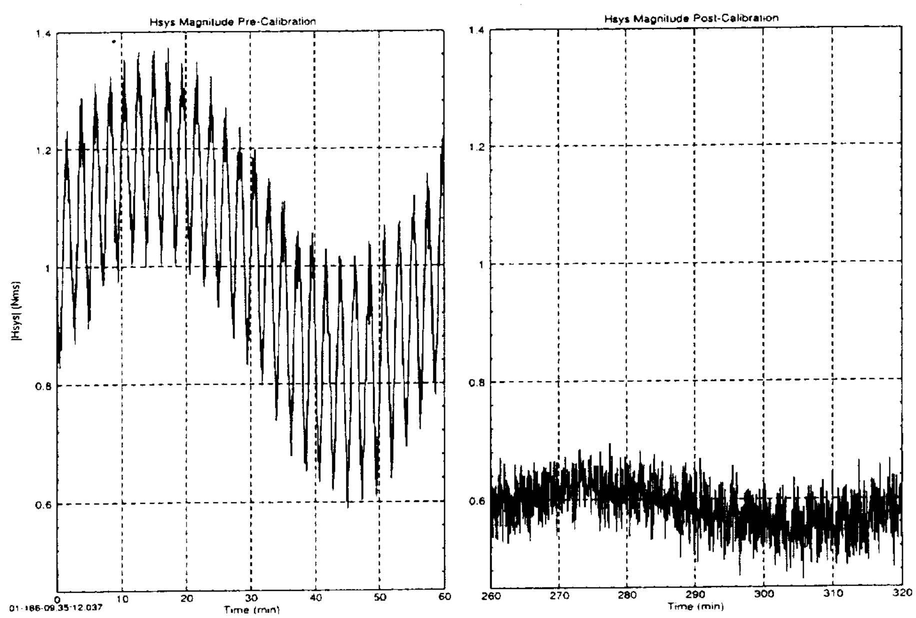

Figure 6: System Momentum Magnitude Pre- and Post-RWA Tach Calibration

Table 1: Observing Mode Performance

Euler States	Requirements	Pre-Calibration	Met?	Post-Calibration	Met?
phi (precession) rate	–0.1°/sec ± 6.3%	–0.1°/sec ± 9%	No	–0.1°/sec ± 3.6%	Yes
theta (sun/scan) angle	22.5° ± 0.25°	22.5° ± 0.064°	Yes	22.5° ± 0.023°	Yes
psi (spin) rate	2.784°/sec ± 5%	2.784°/sec ± 0.32%	Yes	2.784°/sec ± 0.13%	Yes

Observing Mode Variations

As discussed above, the first test of Observing Mode occurred two days after the launch of the MAP spacecraft. Once the mode was checked out, the pre-launch plan was nominally to keep the spacecraft in Observing Mode except when performing any other test or operation. Unfortunately, it was not possible to do this, primarily because of light contamination from the moon or (to a lesser extent) the Earth in the ASTs. The first and third phasing loop had relatively little light contamination. During the second phasing loop, serious light contamination problems were seen in Observing Mode for almost the entire time, and again for the period between the final perigee and the midcourse correction maneuver. The reason these periods were so different

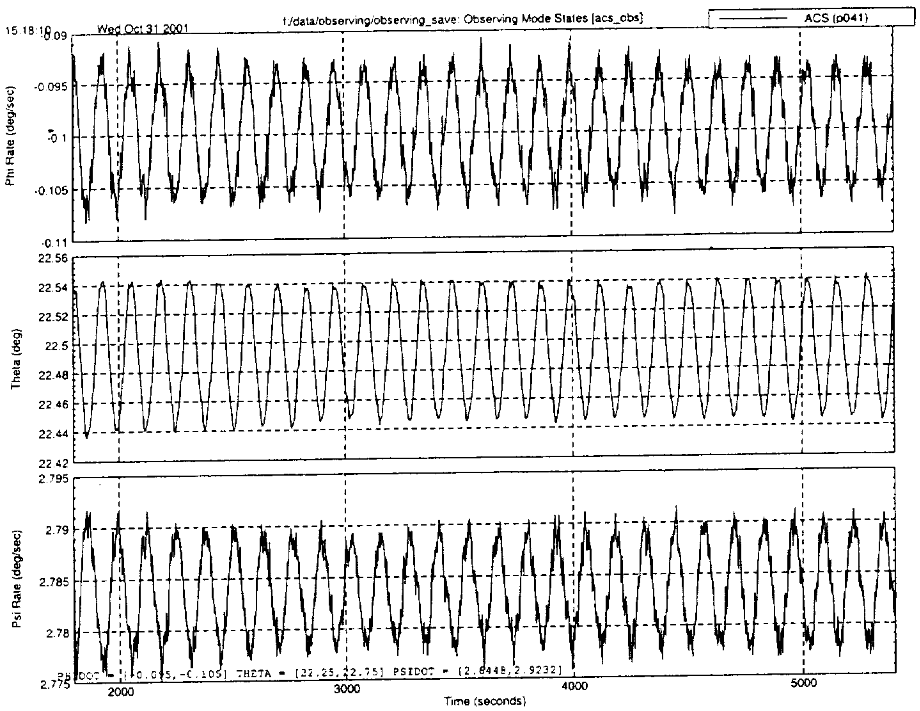

Figure 7: Pre-Calibration Observing Mode Performance

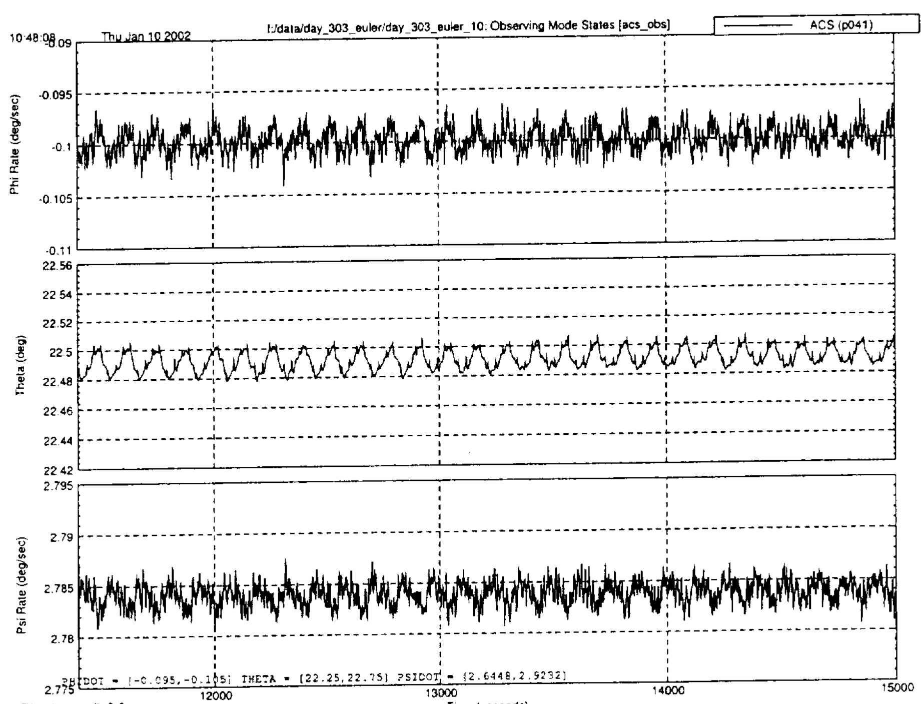

Figure 8: Post-Calibration Observing Mode Performance

is somewhat related to the varying orbit of MAP during each phasing loop, but is mostly a result of the position of the moon in its orbit about the Earth.

During some of the early periods when MAP was in a light contamination region, it was kept in Inertial Mode in an orientation that kept light contamination from the moon from entering the AST boresights. However, there was a desire on the part of the science team to put MAP into Observing Mode, or some sort of spin at Observing Mode rates, to conduct early tests of the science instrument and to help establish its thermal stability. In order to do this, the ACS team came up with two variations of Observing Mode, referred to as "Observing, Jr." and "Observing, III" or "Trey".

Observing, Jr.: The "Observing, Jr." mode was created by making simple changes to values in flight software tables. There was some concern about attempting to use Observing Mode with a 0° scan angle, so "Observing, Jr." was setup to implement a "shallow" Observing Mode, with nominal precession and spin rates and a scan angle of 2°. The spacecraft was kept in this mode for about a day. After that, the nominal Observing Mode was attempted, and MAP was kept in that mode until the second perigee maneuver.

Observing, III, or "Trey": About a day after the third perigee maneuver, when it became obvious that the light contamination region would persist until after lunar swingby, the spacecraft was again put into a modified Observing Mode. With the increased confidence the ACS team had in the flight software, it was decided to implement a version of Observing Mode with a 0° scan angle; this mode was christened "Observing, III", or "Trey". In this mode, the command scan angle was set to 0° and the precession rate was set to 0°/second; the spin rate was kept at its nominal value.

THRUSTER MODE CALIBRATIONS AND ORBIT MANEUVERS

Though there were many other in-orbit checkout activities that occurred within the first month of the MAP mission, the primary focus throughout that time was on the orbit maneuvers and the thruster mode calibrations leading up to them. MAP's planned orbit about L_2 and its limited fuel budget meant that a lunar gravity assist was needed to reach L_2. So, the orbit maneuvers required to get the spacecraft in the right place at the right time for the lunar swingby were critical to mission success. Orbit maneuvers were planned for each of MAP's three perigee passes. Calibration burns of the ACS Delta V Mode used to perform these maneuvers were planned for each apogee, where their disturbance to MAP's orbit would be minimized.

Thruster Mode Pulse Tests

Before any use of either Delta V or Delta H Mode, thruster one-shot pulse tests were performed to determine the correct polarity of the propulsion system and determine if there were any obvious and significant differences between the performance of the eight thrusters, known as Reaction Engine Modules (REMs). The one-shot tests fired each thruster for 400 milliseconds, one at a time, using ground commands while in Sun Acquisition Mode. Given the expected 4.45 N thrust from each thruster and the calculated moment arms, an expected torque response and system momentum change was calculated for each thruster firing and each axis. This expected momentum change was compared with the actual change seen during the test. Each pulse caused a pointing error that was corrected by the Sun Acquisition controller using the reaction wheels. To ensure that no bubbles or other discontinuities existed in the valves, the test was repeated to check for consistent data.

A specific order for the thruster tests was determined by the ACS team so that the tests would tend to decrease rather than increase the system momentum. Figure 9 shows the system momentum magnitude difference caused by the first round of thruster one-shots. As each thruster was fired during the first round of tests, the momentum changes were only 65–75% of the expected values. The propulsion team did not find these results to be of concern, surmising the low value to be caused by the initial lack of hydrazine between the thruster seats, and explained that the rationale for running the test twice took this effect into account. The second round of tests produced results that were similar to the first round. This strengthened the belief in a different theory, that the 400 millisecond thruster firings were not enough for the thrusters to reach a steady-state thrust, so the proof of correct thruster function was actually the consistency of test results rather than 100% torque comparisons. The thruster one-shot test was repeated the next day using the other attitude control electronics (ACE) box. From the standpoint of thruster performance, this test was successful, though it did cause an unexpected FDC failure into Safehold Mode, which will be described later in this paper.

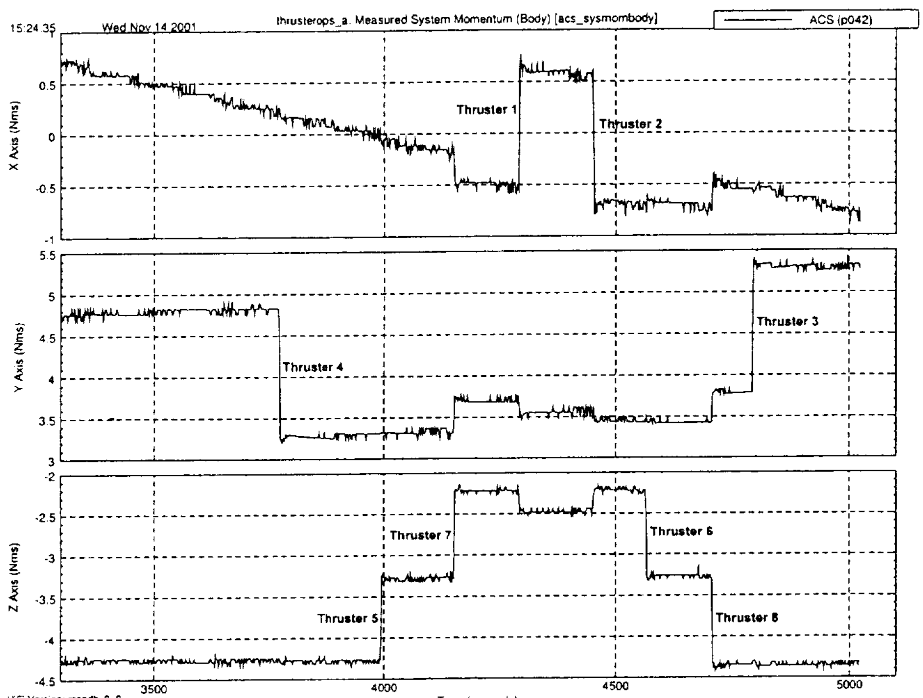

Figure 9: Thruster One-Shot System Momentum Effects

Thruster Mode Calibration

The nominal configuration for all of the perigee maneuvers was a four thruster +X axis burn, so the first calibration burn planned was a two minute burn in this configuration. If this calibration burn and first perigee maneuver proceeded nominally, the other two calibration burns would be +Z and –Z axis burns. The maneuver plan used for the calibration burns was made very similar to the perigee maneuvers to provide practice for the operations and flight support team. An absolute time sequence (ATS) of commands did the bulk of the setup for all burns onboard. For the critical perigee maneuvers, using an ATS would allow the burn to execute even if contact with the spacecraft were lost.

There were two main unknowns that had a direct effect on the performance of Delta V Mode, particularly on +X axis burns. The first of these was the location of the spacecraft center of mass (CM) along the Z axis, and the second was the magnitude of disturbance torques caused by thruster plume impingement. The two quantities that could be observed during a burn that would most clearly reveal the effect of these two unknowns were the Y axis attitude error and the duty cycle of thruster 4. Assuming the expected values of CM and thruster plume, a 45% duty cycle for thruster 4 was expected along with a Y-axis attitude error of 6°.

Figure 10 shows the attitude error from the first Delta V calibration burn, along with the expected performance as determined from HiFi simulation. The performance was much better than expected, with a thruster 4 duty cycle of 28% and a Y axis attitude error just under 4°. This was potentially good news—the lower duty cycle meant less fuel usage along with the smaller attitude error—but there was some concern about finding a viable explanation for the better performance. After analysis, a CM 2.785 cm from its predicted value and a thruster plume 50% of expected was found to allow accurate predictions of thruster mode performance. Figure 11 shows the actual vs predicted performance of the burn after calibration, with much better concurrence.

The other two calibration burns were performed at the second and third apogee and each proceeded nominally. After the last of these burns, the flight data was analyzed to determine the relative scale factors between the eight thrusters to allow predicted performance of the thrusters to match actual flight data. Table 2 shows the values found. It is interesting to note that thrusters 1 and 2, the X axis thrusters, were perfectly balanced in the calibration burns. These two thrusters were canted 10° by bending their tubing after they had been integrated onto the spacecraft as part of a propulsion system redesign made necessary by a CM migration.

Table 2: Relative ACS Thruster Scale Factors

Thruster Number							
1	2	3	4	5	6	7	8
1.0	1.0	0.9619	0.9887	0.9789	1.0031	0.9999	0.9993

Orbit Maneuvers

Figure 12 and Figure 13 show the thruster commands and attitude error flight data from the first perigee maneuver, a 20 minute burn that was the longest performed. As shown, the thruster 4 duty cycle and attitude error performance were consistent with that seen in the calibration burn. Except for some excitement due to the "anomalous force", which is described in the next section, the first perigee maneuver proceeded nominally, both from an ACS and a trajectory point of view. The remaining orbit maneuvers at the second and third perigee and the final correction maneuver were also nominal and put MAP on a good trajectory for its encounter with the moon and its path to L_2.

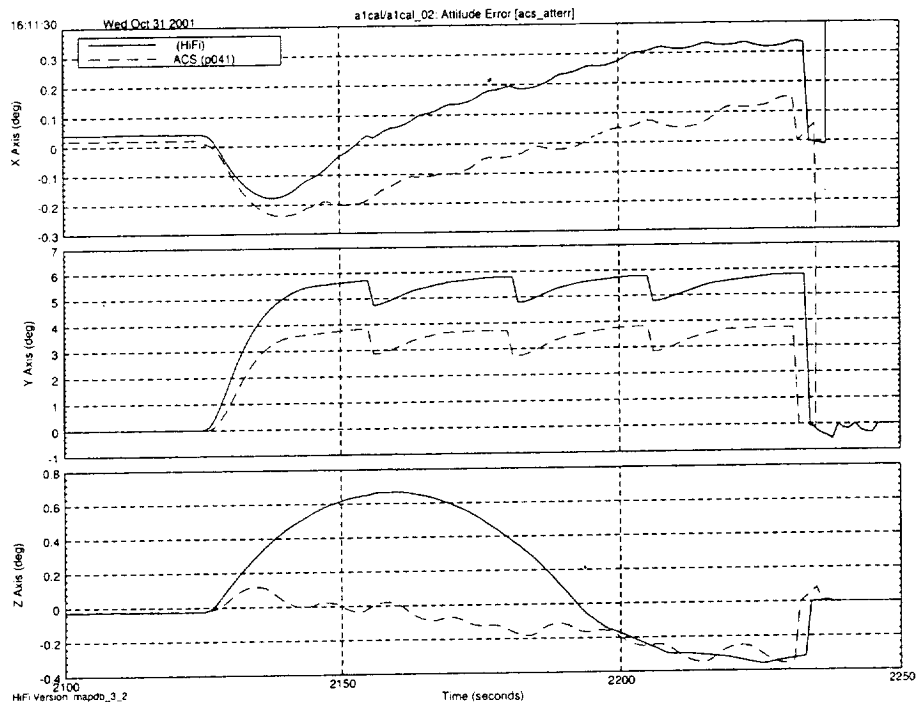

Figure 10: +X Cal Predicted and Actual Attitude Error (Pre-Calibration)

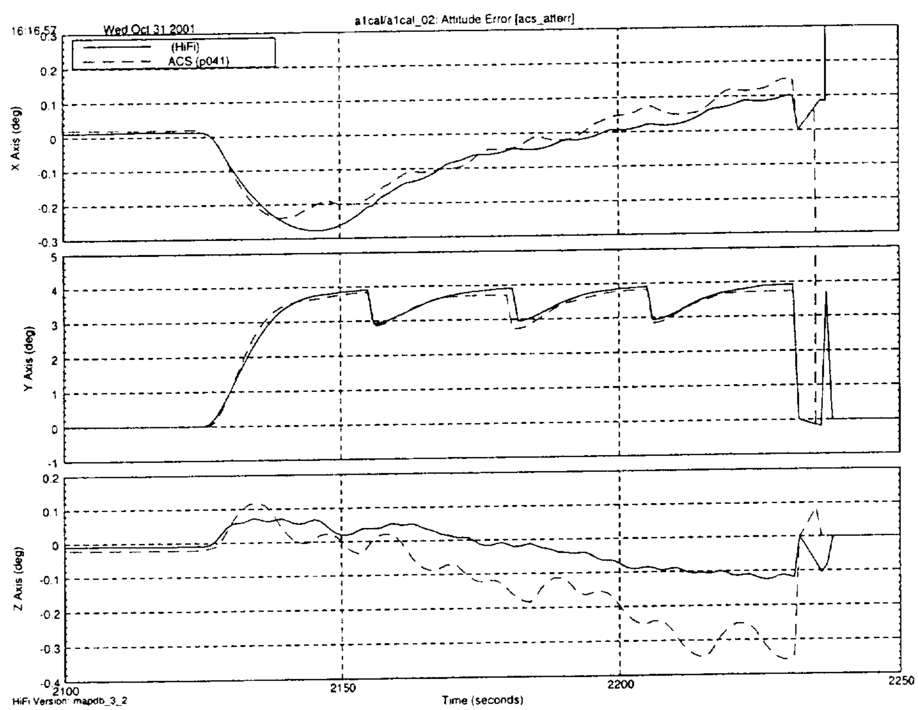

Figure 11: +X Cal Predicted and Actual Attitude Error (Post-Calibration)

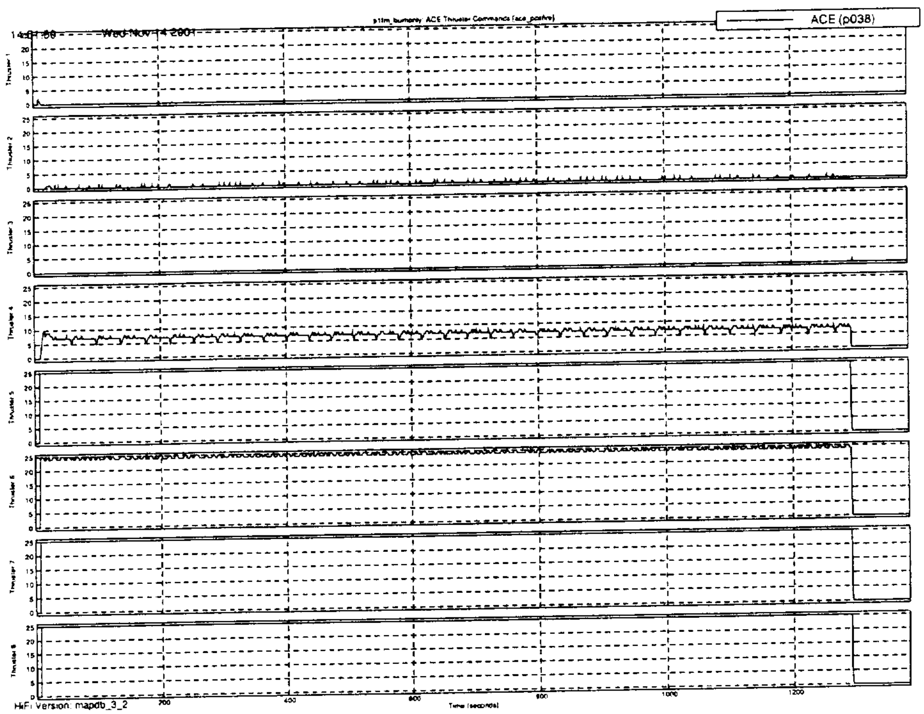

Figure 12: Perigee Maneuver 1 Thruster Commands

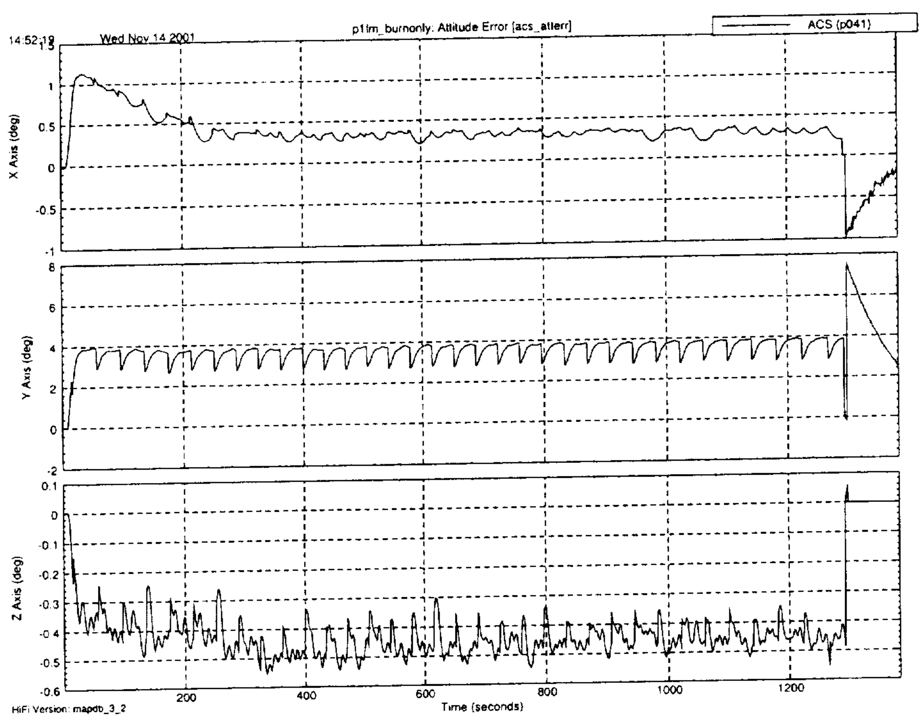

Figure 13: Perigee Maneuver 1 Attitude Error

Anomalous Force at Perigee

Approximately 35–40 minutes before each perigee, MAP telemetry showed a small but significant increase in system momentum. In each case, the system momentum peaked 20–25 minutes before perigee and decreased significantly (but not to its pre-anomaly level) before scheduled Delta V operations started. Because the Delta V mode controls system momentum, it was more difficult to obtain information regarding the momentum changes after the thrusters began to fire; however, there was some evidence that system momentum was still changing slightly after the spacecraft exited Delta H mode after each Delta V.

During the first perigee maneuver, the system momentum increased rapidly for about 10 minutes, going from 0.5 Nms to 2.1 Nms. Figure 14 shows the P1 momentum profile; the time axis displays number of minutes until perigee. Because Delta V mode can only manage a limited range of system momentum values, onboard FDC nominally aborts a maneuver at a value of 5 Nms, and there were concerns at P1 that this would happen. Hurried preparations were made to disable this FDC and possibly manually abort the maneuver. As shown in Figure 14, the system momentum peaked before any problem with the burn would have occurred.

After the first perigee maneuver was successfully completed, attention was focused on explaining the "anomalous force" that had caused the system momentum changes around perigee. Possible causes such as gravity gradient, solar pressure, spacecraft magnetization, and twisting of the solar panels were suggested, analyzed, and discarded one by one after it was shown that they could not have caused the system momentum profile seen. The theory that was finally accepted was that outgassed moisture from the spacecraft had frozen on the back of the solar shield during the phasing loops. Then as the spacecraft approached perigee, the back of the solar shield was illuminated by Earth albedo and sublimated the outgassed materials, causing a predominantly Y axis torque first in one direction and then another as more of the solar shield was illuminated.

Figure 15 shows the outputs of three backward facing CSS eyes superimposed over the X and Y momentum profiles for P1. As expected, the torques appeared to occur as the three dark-side CSSs were illuminated by Earth albedo during the perigee approaches. Furthermore, the order of illumination—first CSS 2, then 6, then 4—indicated a correspondence between albedo varying across the cold side of the solar shield and the sequence of anomalous torques. Subsequent analysis by the thermal and science teams confirmed the possibility of this explanation and further predicted that the anomalous force would reoccur to a lesser degree at each perigee; as percentages of the change seen at the first perigee the predicted value was 35% at P2 and 15% at P3. As shown in Figure 16, the flight data collected at P2 and P3 agreed with this prediction.

SAFEHOLD EVENTS

As mentioned in an earlier section, there was at least one unplanned entry into MAP's Safehold Mode during the IOC period. In addition to a Safehold event that occurred during one of the thruster pulse tests, there was one other Safehold event that occurred in November, 2001, well after the IOC period.

Day 182: Static Gyro Data

At the end of the day on June 1, 2001, the team was performing a set of thruster one-shot tests to confirm proper functionality via the second ACE (known as the LMAC ACE). During the test

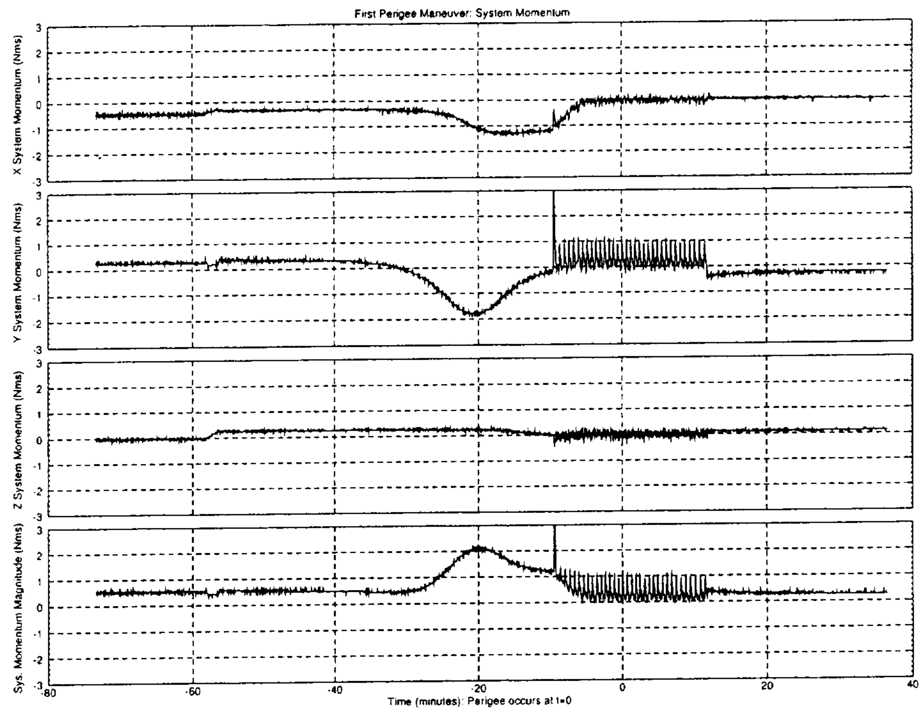

Figure 14: System Momentum Profile, Perigee Maneuver 1

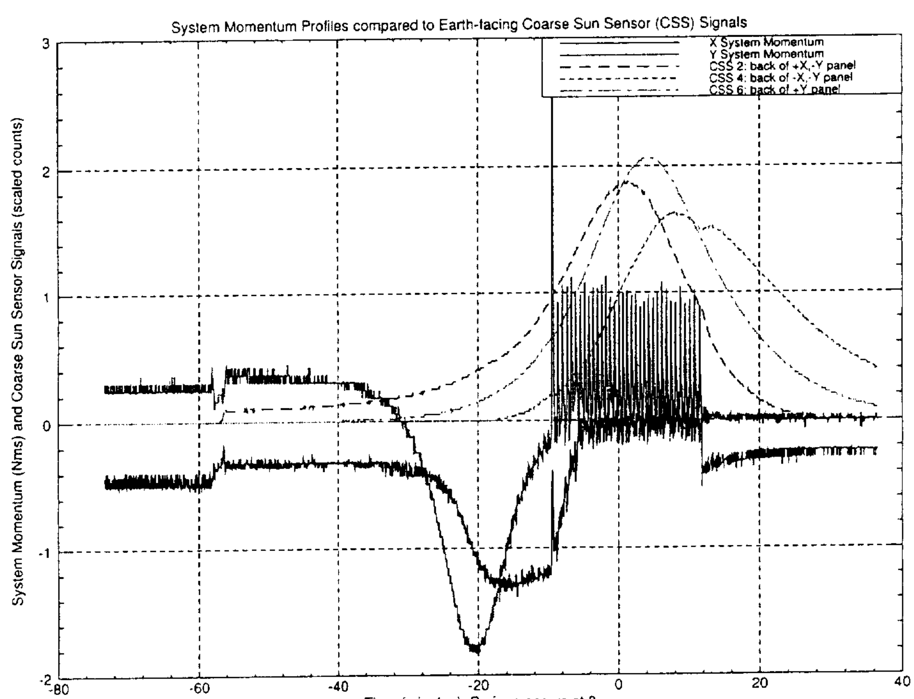

Figure 15: System Momentum and CSS Profiles, Perigee Maneuver 1

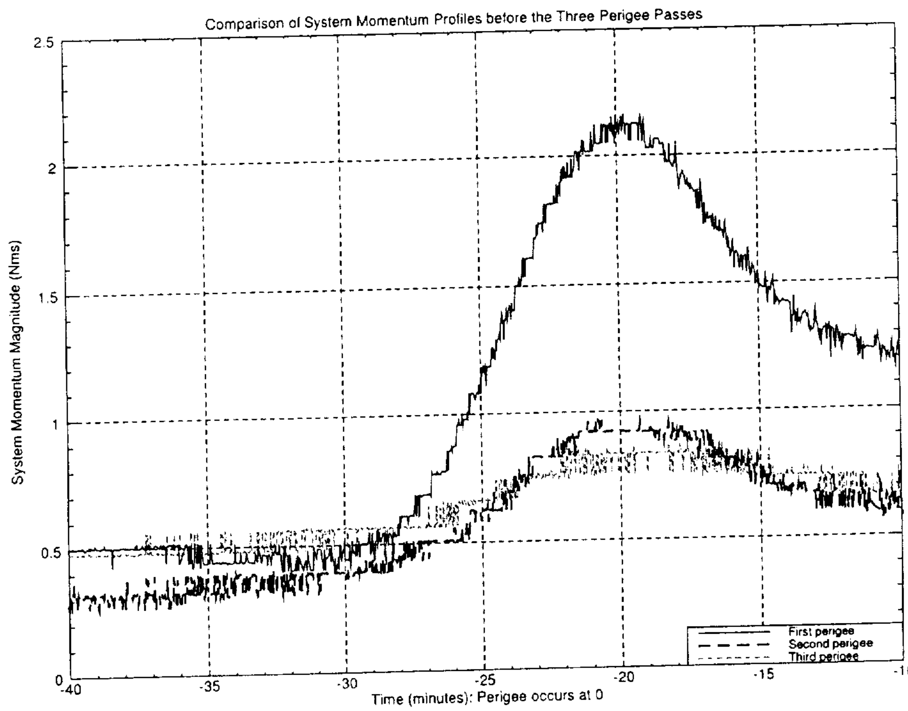

Figure 16: System Momentum Profile, All Perigee Maneuvers

of thruster 7, the fire command appeared to have no effect on system momentum, possibly indicating a problem with the LMAC ACE thruster 7 driver. Instead, telemetry indicated that the Static Gyro Data FDC had tripped, causing the ACS to switch into Safehold on the other ACE (known as the MAC ACE). A review of the command timeline shows that the LMAC ACE thruster 7 was enabled successfully just before the FDC tripped, but the FDC trip caused ACS to switch control and communications to Safehold on the MAC ACE before the thruster fire command was sent. Since the thruster enable and thruster fire commands were sent to different ACEs, the thruster was not fired.

Since Safehold was working correctly, the team focused on determining the cause of the FDC failure. An investigation of telemetry from both ACEs showed that they both appeared to be working correctly. A closer inspection of the gyro data prior to Safehold showed the actual cause of the perceived gyro anomaly. Since the Sun Acquisition controller allowed for a subtle, slow oscillation as the disturbance caused by each thruster one-shot was damped out, the 2°/hour Y axis gyro bias actually cancelled the spacecraft rate for more than 20 seconds, appearing as 0 counts of rate output for that period of time. The Static Gyro FDC was watching for 20 seconds of 0 counts for spacecraft rate as a sign of faulty gyro input, since disturbances would be expected to cause some rate variation over such a long period. The problem would not occur in other modes, since the higher performance that was required by those modes necessitated a higher bandwidth, thus eliminating the slow oscillation. Figure 17 shows the 20 consecutive static gyro counts on the Y axis gyro. Once the cause of the anomaly was determined, the spacecraft was reconfigured to its pre-Safehold state and the Static Gyro FDC threshold increased to 120 seconds, to lessen the chance of it tripping accidentally in the future.

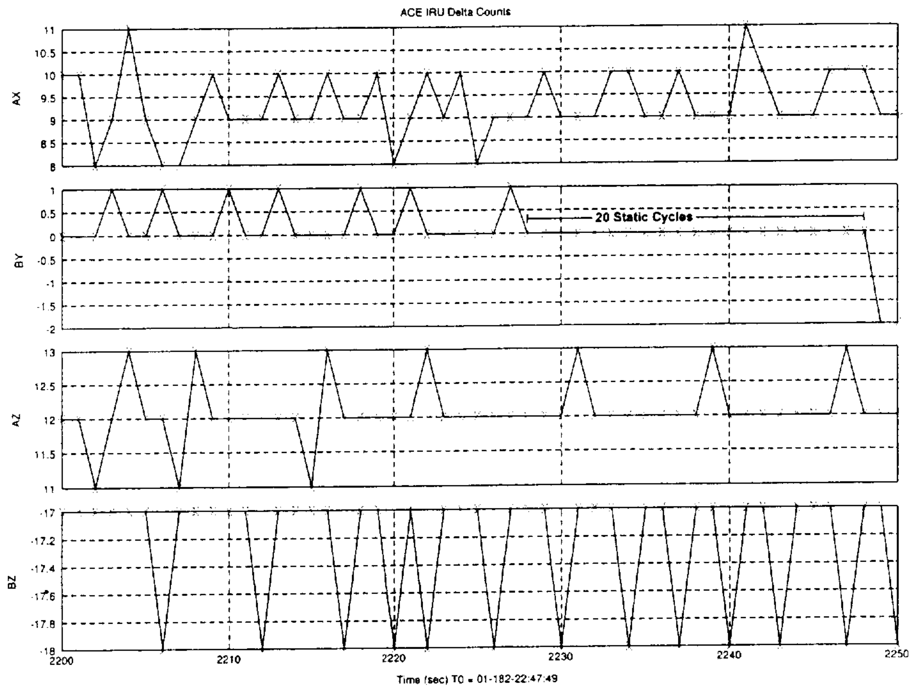

Figure 17: IRU Counts Leading to Safehold Entry

Day 310: Solar Storm

On November 6, 2001, at the beginning of a nominal operations pass, the flight operations team noticed that the ground station's radio frequency automatic gain control was steady, as opposed to the slight variation that is normally seen as a result of the Observing Mode spin and precession. As the telemetry link was being established, the flight operations team contacted members of the ACS and flight software teams to support a possible spacecraft anomaly. When it became available, telemetry showed the Observatory to be in Safehold, the result of an apparent Mongoose power-on reset, most likely the result of a Single Event Upset coincident with a significant solar storm in progress at that time. The ACS responded as designed to the reset by entering Safehold following the loss of the "I'm OK" signal from the Mongoose. As expected, there was no reconfiguration of either ACE during the anomaly, so the LMAC ACE remained in control. A review of available telemetry showed that Safehold was able to hold the spacecraft's Z axis within 1° degree of the sun line, with a very slow drift around the sun line commensurate with the gyro's drift rate.

After a review of spacecraft telemetry showed that there were no apparent problems with any hardware or software, MAP was reconfigured out of Safehold and back into Observing Mode. The Observing Mode motion was monitored for one hour to confirm nominal performance, during which several one second time adjusts were commanded to adjust the on-board clock into sync with ground time. After this time, the spacecraft emergency was declared over and the pass was completed.

CONCLUSION

From its launch on June 30, 2001, to the present time, the attitude control system on the MAP spacecraft has satisfied all of its requirements. Launch, separation, and initial acquisition were nominal. The in-orbit checkout plan conducted during MAP's first month in orbit showed that all of its hardware and software was performing well. At the same time, all orbit maneuvers needed to get MAP to its lunar swingby and on to its final orbit about L_2 were successful. The MAP ACS algorithms and flight software design were well suited to performing their functions and to responding to anomalies or unexpected conditions on orbit. The MAP mission is now well on its way to completing its first full-sky map of the cosmic microwave background.

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