RESTORING REDUNDANCY TO THE MAP PROPULSION SYSTEM

James R. O'Donnell, Jr.*, Gary T. Davis*, David K. Ward*
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA

Abstract

The Microwave Anisotropy Probe is a follow-on to the Differential Microwave Radiometer instrument on the Cosmic Background Explorer. Sixteen months before launch, it was discovered that from the time of the critical design review, configuration changes had resulted in a significant migration of the spacecraft's center of mass. As a result, the spacecraft no longer had a viable backup control mode in the event of a failure of the negative pitch axis thruster. Potential solutions to this problem were identified, such as adding thruster plume shields to redirect thruster torque, adding mass to, or removing it from, the spacecraft, adding an additional thruster, moving thrusters, bending thrusters (either nozzles or propellant tubing), or accepting the loss of redundancy for the thruster. The impacts of each solution—including effects on the mass, cost, and fuel budgets, as well as schedule—were considered, and it was decided to bend the thruster propellant tubing of the two roll control thrusters, allowing that pair to be used for backup control in the negative pitch axis. This paper discusses the problem and the potential solutions, and documents the hardware and software changes that needed to be made to implement the chosen solution. Flight data is presented to show the propulsion system on-orbit performance.

Introduction

The Microwave Anisotropy Probe (MAP) spacecraft was launched on June 30, 2001, as a follow-on to the Cosmic Background Explorer (COBE), which made precise measurements of the Cosmic Microwave Background (CMB) that is believed to be a remnant of the Big Bang marking the birth of the universe.[1-4] MAP was designed to measure the CMB anisotropy with much greater sensitivity and angular resolution than the Differential Microwave Radiometer (DMR) instrument on COBE. In addition to using a more advanced science instrument, the MAP mission was designed to eliminate many of the major error sources in the DMR by using a Lissajous orbit around the Sun-Earth L_2 Lagrange point to minimize magnetic, thermal, and radiation disturbances from the Earth and Sun. Figure 1 shows a sketch of the MAP spacecraft.

MAP attained its Lissajous orbit about L_2 in October, 2001, using maneuvers at the perigee of each of its three phasing loops, a lunar gravity assist, and several smaller correction maneuvers. MAP's path is diagrammed in Figure 2. MAP's orbit made an onboard propulsion system necessary in order to perform the maneuvers required to reach L_2, conduct periodic stationkeeping maneuvers to maintain this orbit, and to unload momentum.

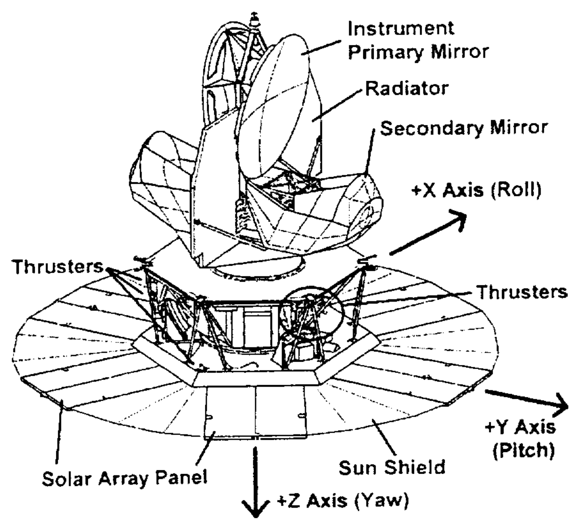

Figure 1: MAP Spacecraft Layout

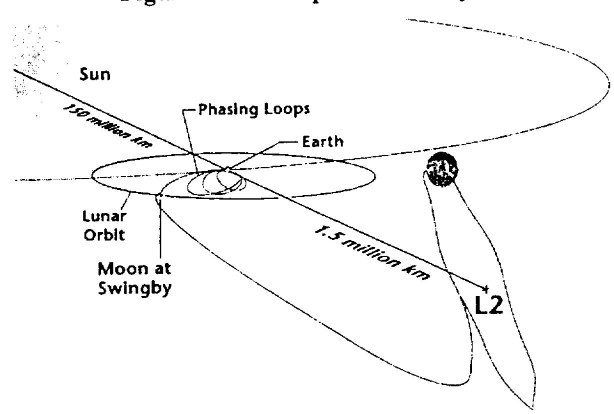

Figure 2: MAP Trajectory to L_2

The preliminary propulsion system design located thruster pairs with both the thrust directions in a plane with the observatory's center of mass. This placement decoupled the torque axes for each thruster, and allowed each thruster pair to be used for nearly torque-free acceleration when used together. Thrusters 1 and 2 were placed on the sunward (+Z) face of observatory along the Y axis, providing a thrust in the –Z direction and ±X torque for attitude control. Thrusters 3 and 4 were placed on the anti-sunward (–Z) face of observatory along the X axis, providing a thrust in the +Z direction and ±Y torque for attitude control.

* Aerospace Engineer, Senior Member, AIAA

Thrusters 5 and 6 were placed on the –X face of observatory along the Y axis, providing a thrust in the +X direction and ±Z torque for attitude control. This design provided both decoupled attitude control thrusters and thrust vectors in three different directions. This feature allowed the observatory to thrust in any direction without exposing the instrument to the sun, critical to maintaining the needed thermal stability during stationkeeping maneuvers at L_2. (The approximate locations of thrusters 1–6 are shown in Figure 3; thrusters 5 and 6 were actually aligned with the center of mass at this point in the design.)

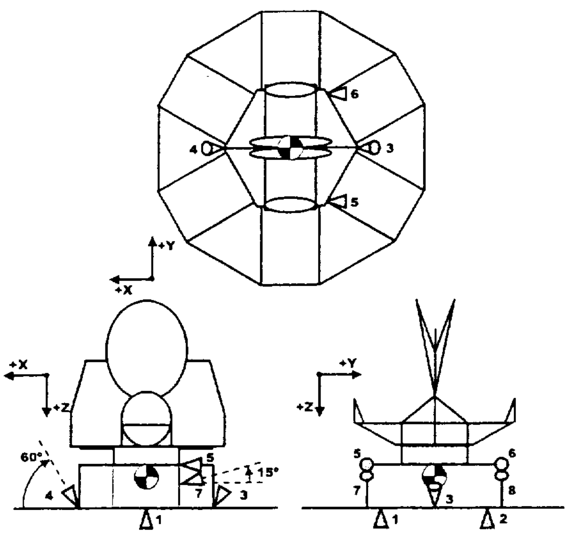

Figure 3: Original Thruster Layout

After MAP's Confirmation Review in 1997, a decision was made to use available programmatic resources to add selected redundancy and increase the reliability of the observatory. Among the components selected for additional fault tolerance were the thrusters, given the criticality of reaching the L_2 orbit and the necessity of performing ΔV maneuvers without exposing the instrument to the sun. Resource and design constraints limited the maximum number of thrusters to eight, so two additional thrusters were added into the propulsion system design.

In order to maximize the utility of the added thrusters, the team decided to mount them in a canted direction to provide functional redundancy for all three thruster pairs. In order to achieve this, thrusters 5 and 6 were moved in the –Z direction with respect to the spacecraft center of mass (CM) and thrusters 7 and 8 were added on the –X face of the observatory with a 15° cant from the XY plane to provide thrust vector in the +X and +Z directions, as shown in Figure 3.

Table 1 shows the primary and backup thrusters used by the attitude control system (ACS) for attitude control during thruster operations and for dumping momentum. Another benefit of the two new thrusters was that because the phasing loop perigee maneuvers were planned to be in the +X axis, these maneuvers could use four thrusters instead of two and thus be approximately half as long, increasing the acceleration and significantly cutting the finite burn penalty (the penalty from applying a finite, rather than impulsive ΔV.)

Table 1: Original Propulsion System Design Primary and Backup ACS Thrusters

Torque Axis	Primary Thruster	Backup Thruster(s)
+X	1	5 + 8
–X	2	6 + 7
+Y	3	7 + 8
–Y	4	5 + 6
+Z	5	7
–Z	6	8

Center of Mass Migration

In March, 2000, a new mass properties update was available for the spacecraft. In addition to the changes in spacecraft inertia that were expected with mass growth during a mission, a significant change in the location of the center of mass was also seen. At the Confirmation Review, the beginning of life (BOL) CM was located 63 cm from the separation plane. The new mass properties analysis showed this beginning of life value to have moved 9 cm in the –Z direction, to 72 cm. At end of life (EOL), the new mass properties estimated a center of mass 76 cm from the separation plane.

CM Migration Backup Thruster Implications

These changes were significant to the propulsion design because thrusters 5–8 had been placed to balance their moment arms about a CM located between 63 and 68 cm. In that case, the combined torque of thruster pair 5 and 6 in the –Y axis was approximately 20% of that of the primary thruster, thruster 4, and the pair was a viable backup in that direction (see Table 2).

Table 2: –Y Axis Torques

Thruster Set		Y Axis Torque (Nm)
Original Design	Primary (4)	–5.13
	Backup (5 + 6)	–1.0
Post CM Migration	Primary	–5.52
	Backup BOL	–0.11
	Backup EOL	+0.25

A CM between 72 and 76 cm in the –Z direction was nearly in the thrust plane for thrusters 5 and 6. As also shown in Table 2, when thruster plume impingement effects were also factored in, thruster pair 5 and 6 could only provide a combined torque 2% that of thruster 4 at the beginning of life. At the end of life, the torque from the thruster 5 and 6 combination was not even in the correct direction. Thrusters 5 and 6 could no longer be used as a backup to thruster 4.

Backup Thruster Solution Options

At this point, a number of redesign options for MAP were studied. Given the strict mission requirement to reach L_2, the loss of thruster functionality was considered a mission-ending failure, so the team agreed to consider all options before falling back to a non-redundant solution. These options fell into two categories: change the location of the center of mass, or redirect the thrust of one or more thruster pairs. The first option was the logical solution: since adding mass in the –Z direction had caused the problem, perhaps it could be fixed by adding mass in the +Z direction. Unfortunately, launch mass constraints limited the available ballast to a maximum of 15 kg, and even that much mass would only move the CM 1.5 cm, less than the 4.5 cm needed to ensure that thruster 5 and 6 could be used as a backup for –Y axis attitude control. Removing mass from the instrument (–Z direction) would have unacceptably impacted the science return through degraded optical or thermal performance. Neither of these options was acceptable, so redirecting the thrust was given more serious consideration.

MAP has an integrated propulsion design, in which the tanks, thrusters, and tubing are all integrated directly onto the main spacecraft structure.[5] This approach saved mass, but meant that the propulsion system was fully welded and integrated in place at the time the CM migration problem was discovered, complicating the prospect of moving or redirecting thrusters.

Two groups of thrusters were considered for redesign: thrusters 5–8 or thrusters 1 and 2. Because thrusters 5 and 7 share a mounting bracket, as do thrusters 6 and 8, redirecting the thrust axis of thrusters 5 and 6 might also change the thrust direction for thrusters 7 and 8. After considering the possibilities of moving or changing the cant of thrusters 5 and 6, this option was eliminated for two reasons. First, the proposed change to both thruster brackets interfered with spacecraft structural members, making the modifications nearly impossible. More importantly, any redirection of the thrust direction for thrusters 5 and 6 in order to create a larger torque in the –Y axis would also create a larger plume impingement torque in the +Y axis. As shown in Figure 4, the plume impingement torque increased faster, eliminating any torque benefits gained by the increased moment arm relative to the CM.

Instead, the team determined that rotating the thrust from thrusters 1 and 2 in the XZ plane allowed them to be used for –Y torque control in place of thrusters 5 and 6 in the event of a thruster 4 failure. A small 5°–10° redirection would not significantly affect the fuel budget, since thrusters 1 and 2 would only be used for ΔV during the shorter stationkeeping burns once MAP reached L_2.

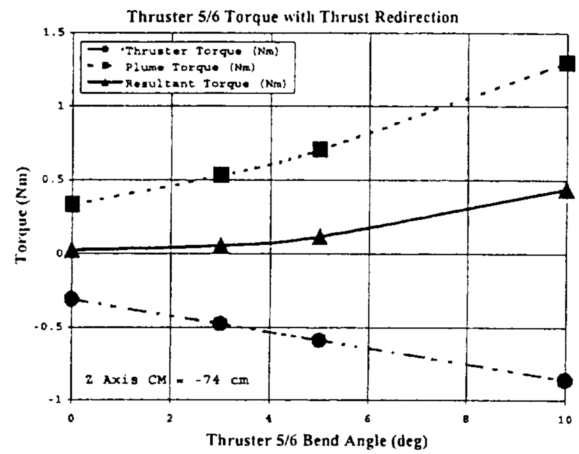

Figure 4: Results of Thruster 5/6 Bend Option

A trade was done between a 5° and 10° redirection, as shown in Table 3. This tables shows the how much additional CM movement or plume impingement would create a 100% duty cycle of thrusters 1 and 2 when being used for –Y axis attitude control during a two thruster +X axis ΔV (in this backup mode, four thruster +X axis burns would not be possible). A further CM movement of only 2.2 cm or plume impingement torques just 26% higher than expected would saturate the thrusters if canted 5°, while the margins were significantly higher for the larger cant. Since the fuel cost for 10° was considered acceptable, its added robustness to changes in mass properties or plume impingement effects made it the team's choice.

Table 3: Thruster 1 and 2: 5° vs 10° Cant

Margins	5° Cant	10° Cant
Z Axis CM (cm)	2.2 cm	10.4 cm
Plume (% Increase)	26%	115%

The final question was how the actual thrust redirection would be accomplished. Plume deflection shields had been considered as the simplest method for thrust redirection, but it was considered the least deterministic method with regard to final thrust direction. Bending the thruster nozzles themselves was also considered, but it was considered a significant risk to the reliability and performance of the thrusters. Instead, bending the tubing upstream of the thruster was selected as the preferred method for redirecting the thrust. Figure 5 shows the final thruster flight configuration.

With the 10° cant added to thrusters 1 and 2, MAP's propulsion system had backups for any single thruster failure. Table 4 shows the primary and backup thrusters and beginning of life torques for each direction. The torque authority for each backup mode represented from 18% to 97% that of the primary, all viable and stable modes.

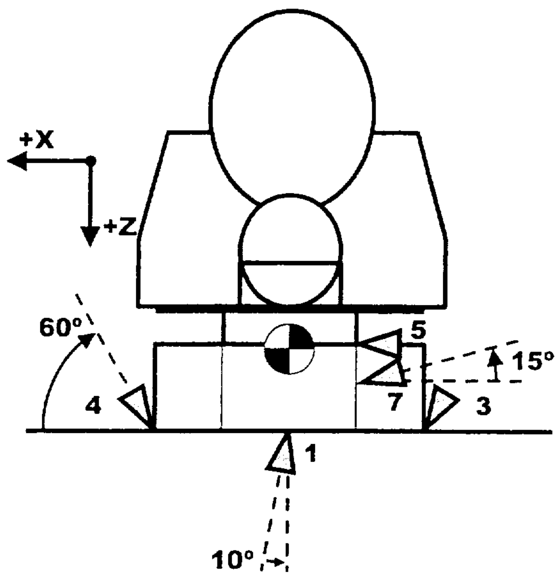

Figure 5: Thruster Layout with Thruster 1/2 Cant

Table 4: Post-Bend Propulsion System Primary and Backup ACS Thrusters and BOL Torques

Torque Axis	Primary Thruster		Backup Thruster(s)	
	#	Torque (Nm)	Set	Torque (Nm)
+X	1	3.7334	5 + 8	0.8065
-X	2	-3.7556	6 + 7	-0.7976
+Y	3	5.102	7 + 8	2.3045
-Y	4	-5.0918	1 + 2	-0.9255
+Z	5	3.5844	7	3.4441
-Z	6	-3.5744	8	-3.4525

Thruster 1 and 2 Bending Operation

Since the propulsion subsystem was fully integrated and had been fully tested, much care was taken during the bend procedure not to damage existing hardware and to fully inspect, re-test, and re-verify any hardware that was affected.

Before any hardware was modified, Kennedy Space Center and Cape Canaveral Air Station Range Safety officials were consulted in order to get their approval on the post-bending test and verification plan. Once this plan was approved, a detailed procedure was written that included all aspects of the bending and testing effort. Since the propulsion subsystem was fully tested and integrated within the MAP spacecraft, the bending of the roll thruster tubing was performed *in situ*. The tubes which needed to be bent were in very close proximity to the spacecraft lower deck, tubing support brackets, and the thrusters themselves. The desired bend location was in the plane of the lower deck, with less than 1 inch of clearance between the tube and the deck edge. The extremely tight clearances and the requirement for a flight quality bend meant that standard tube bending equipment could not be used, so a custom bending tool was designed and fabricated.

The bend tool was custom designed around three major requirements. First, the available volume on the spacecraft was very small, because the desired bend location was inside a hole in the spacecraft structure near an existing 90° bend. Second, the bend needed to be formed with the proper bend radius without kinking or damaging the tubing. Third, the bend needed to be made in the correct plane and to the required angle of 10±0.5°. Figure 6 shows design drawings for the custom bend tool. This bending tool was tested on tubing from the flight lot to determine its accuracy and effect on the strength of the bent tube. All sample bends were dye penetrant and burst tested. All burst locations occurred in straight sections of tubing, not in the bent regions, at burst pressures greater than 34400 psi.

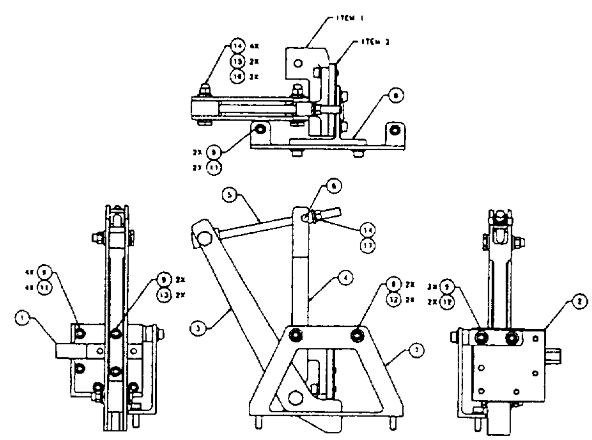

Figure 6: Custom Bend Tool

De-Integration

Figure 7 shows most of the layers surrounding each of the propellant lines that would need to be removed in the first phase of work in order to perform the bend operation. First, the multi-layered insulation (MLI) blankets from the thrusters and propellant feed lines near thrusters 1 and 2 were removed and discarded. Next, layers of Kapton tape, lead shield tape, lacing cord, and outer layers of aluminum tape were removed to expose the spiral line heaters. Inspections were performed after each layer was removed to look for damage. The spiral heaters were removed and their wires were labeled and cut as required. The inner layers of aluminum tape were removed and the propellant tubes were cleaned. The thrusters were unbolted from their brackets and the brackets were then unbolted from the spacecraft structure, removed, and weighed. Plans were in place to cut the brackets out but fortunately this was not necessary. At this point, the thrusters were only attached to the MAP spacecraft via their feed tubes and electrical harnesses.

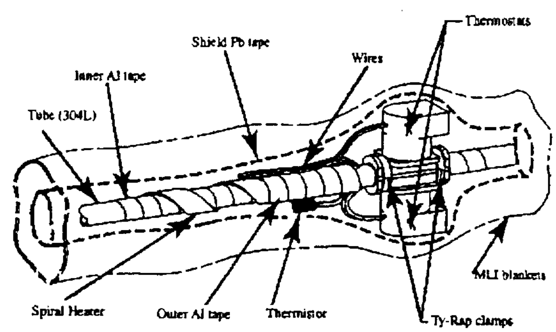

Figure 7: Thruster Tubing Hardware Layout

Bending

In the second phase, the bending tool was assembled in-place around the tube and thruster. Before the tube was bent, a measurement of the initial thruster orientation was taken to act as a starting reference. All orientation measurements were performed using optical theodolites, a reference cube attached to the spacecraft and, a flat mirror attached to the exit plane of the thruster nozzle. The bending tool was actuated by hand to execute the bend, which was measured frequently until the desired angle was reached.

The bend was performed in a similar manner to a common hand tube bender, although the 1 inch bend radius and sliding block of the bend tool supported the tube walls and precluded kinks. The tube bender mechanism consists of eight pieces which are bolted together. Some of the pieces are symmetrical so the tool can be assembled to perform bends in either direction. The tool was bolted to the thruster bracket mounting holes and then assembled in-place around the unbent tubes. A threaded rod allowed the tool operator to turn a nut to give a large mechanical advantage in forcing the sliding block about the radius.

The flight bends were performed while mirrors were installed on the thruster nozzles. Optical theodolites were used to measure the orientation of the nozzles before the bend and at several points during the bend until the desired angular change was met. Since the tool was reversible to accommodate thruster 1 or 2, four engineers were asked to verify that the thruster was going to be bent in the correct direction before the bending commenced. Thruster 1 was bent in four steps; the desired angular change from its starting orientation was 9.074±0.5° and its actual change was 9.605° (slightly out of the desired tolerance, but acceptable). Thruster 2 was bent in 5 steps; the desired angular change was 10.0±0.5° and its actual change was 9.557°.

The new thruster brackets which incorporated a 10° thruster orientation were installed via a clamshell arrangement and the fasteners were installed and torqued. The thruster orientations were re-verified with the alignment mirrors. No additional adjustments were needed. Figure 8 and Figure 9 show thruster photographs before and after the bend (the pictures were taken from slightly different angles, but the bend is clearly shown.)

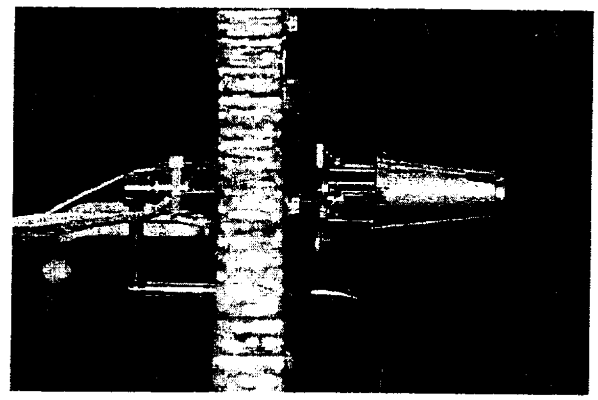

Figure 8: Thruster Before Bending

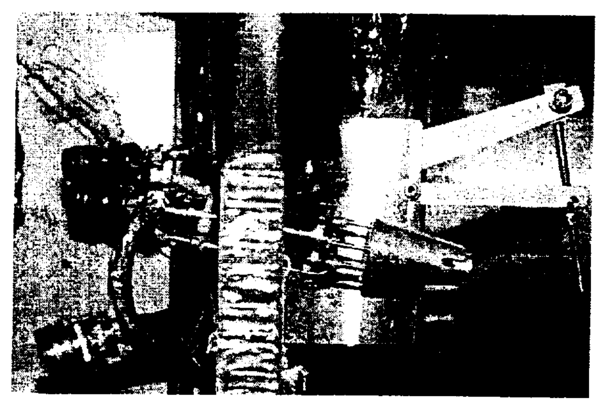

Figure 9: Thruster and Bend Tool After Bending

Post-Bend Verification

While the tubes were bare, a dye penetrant test on the tube surface was performed. To further verify the integrity of the bent tubing, a pressure test was performed on the entire subsystem. The maximum operating pressure of 350 psig was held for 5 minutes. Finally, during the pressure test, leak detection fluid was applied on the bent areas to look for gross leaks. No leaks were observed.

Re-Integration

Once the pressure test was completed and the tank pressure had been vented, re-integration began;

inspections and photographs were performed after every step. First the inner layers of aluminum tape were applied. Then the spiral heaters were installed and inspected. The outer layers of aluminum tape were applied and the heater circuits were reconnected using single pin disconnects. The harness was then routed and secured with lacing cord before the lead shield tape, drain wires, and Kapton tape layers were applied. Heater circuit and thermostat tests were performed to verify that they were correctly re-integrated. Cold spray was used to activate and verify thermostat operation. Finally, MLI was fabricated around the thruster feed tubes and the blankets were grounded.

ACS Re-Design

In addition to physically bending the thruster tubing to achieve a 10° cant of thrusters 1 and 2, there were also software changes that needed to be made to restore the MAP propulsion system to full redundancy . While the MAP flight software architecture made extensive use of loadable software tables in order to give it a high degree of flexibility on-orbit, the logic that implemented which thrusters were used as backups in each axis was hard-coded. So while a flight software table could be loaded to indicate that a given primary thruster had failed, the backup thruster or thruster set used in its place could only be changed with a software patch.

MAP also made use of automatic code generation to implement the ACS control modes directly from its high fidelity simulation (HiFi).[6–7] This made the process of implementing the necessary software changes fairly straightforward. The changes were created and directly tested in the MAP HiFi. Revised flight software was automatically generated, integrated onto the flight software simulator and spacecraft, and fully tested before launch.

In addition to the necessary flight software changes made to support using a different thruster pair as a backup in the event of a thruster 4 failure, two other enhancements to the thruster control software were proposed and implemented. Because of uncertainties in what would be the actual values of spacecraft CM and thruster plume impingement seen on-orbit, these enhancements increased the ability of the thruster mode controller to deal with problems in flight.

Thruster Bend Software Implementation

The necessary change to the flight software, having it use thrusters 1 and 2 as a backup for thruster 4 for attitude control in the –Y axis, was simply implemented in the MAP HiFi. The `REM_Failure` block in the Delta V Mode controller of the simulation implemented the logic for reassigning thruster commands from nominal to backup thruster(s) in the event of a failure. The only change necessary was to assign the thruster 4 firing command to thrusters 1 and 2, instead of 5 and 6, with the new propulsion system configuration.

Delta V Mode Duty Cycle

As mentioned earlier, one of the benefits of the addition of thrusters 7 and 8, in addition to providing redundancy in the event of a single thruster failure, was to improve the efficiency of the critical orbit maneuvers to be performed at each perigee via use of four thrusters instead of two. The four thrusters 5–8 locations were originally set to balance their torques about the spacecraft center of mass, but with the CM migration towards the thruster 5 and 6 firing plane, this was no longer the case.

So as a result of the CM migration, a four thruster orbit maneuver would result in a significant duty cycle from thruster 4 in order to offset the thruster 5–8 Y axis torque imbalance. Because of the uncertainties in the CM and in the amount of thruster plume impingement torques that would be seen from thrusters 5 and 6, there was some concern that a four thruster X axis ΔV would saturate the ability of thruster 4 to balance the Y axis disturbance.

In order to alleviate this concern and still preserve the ability to at least somewhat improve the efficiency of perigee maneuvers, an enhancement was made to the Delta V Mode flight software to allow each thruster pair to be commanded to a given duty cycle. The main purpose of this change was to allow the duty cycle of thrusters 7 and 8 to be commanded in the event that a full four thruster burn would saturate thruster 4. In that case, for example, a "three thruster" perigee maneuver could be commanded using thrusters 5 and 6 and also thrusters 7 and 8 at a 50% duty cycle, thus getting as much efficiency out of the burn as possible while retaining adequate control stability margins.

Backup Thruster Mode Control Gains

One final flight software enhancement was made to improve the ability of the thruster mode control code to deal with on-orbit failures. Recall from Table 4 that most of the backup control thruster sets had torque authority significantly lower than the primary thrusters; at end of life, the torque authority was even less. Because of the control system design, in the event of a thruster 4 failure, for example, the software would be configured to use thrusters 1 and 2 in its place. So thruster 3 would be used for +Y axis control and thrusters 1 and 2 would be used in the –Y axis. The torque authority from thruster set 1 and 2 was only 18% of thruster 3's, but the same control gains would be used for that axis in each direction. While the proportional-derivative controller used would remain stable, the performance could suffer.

To mitigate this torque imbalance, backup gain multipliers were added to the loadable flight software tables. In the event of a thruster failure, these multipliers could be used to increase the control gain for the backup thruster set in order to balance the two torque directions.

Flight Performance

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. 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 Checks

Before any use of either Delta V or Delta H Mode, thruster one-shot pulse tests were performed to verify the correct polarity of the propulsion system and determine if there were any obvious and significant differences between the performance of the eight thrusters. The one-shot tests fired each thruster for 400 milliseconds, one at a time, using ground commands while in Sun Acquisition Mode. (For more information on MAP's control modes and attitude control system design, see references 8–10.) 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 10 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 73–82% of the expected values.

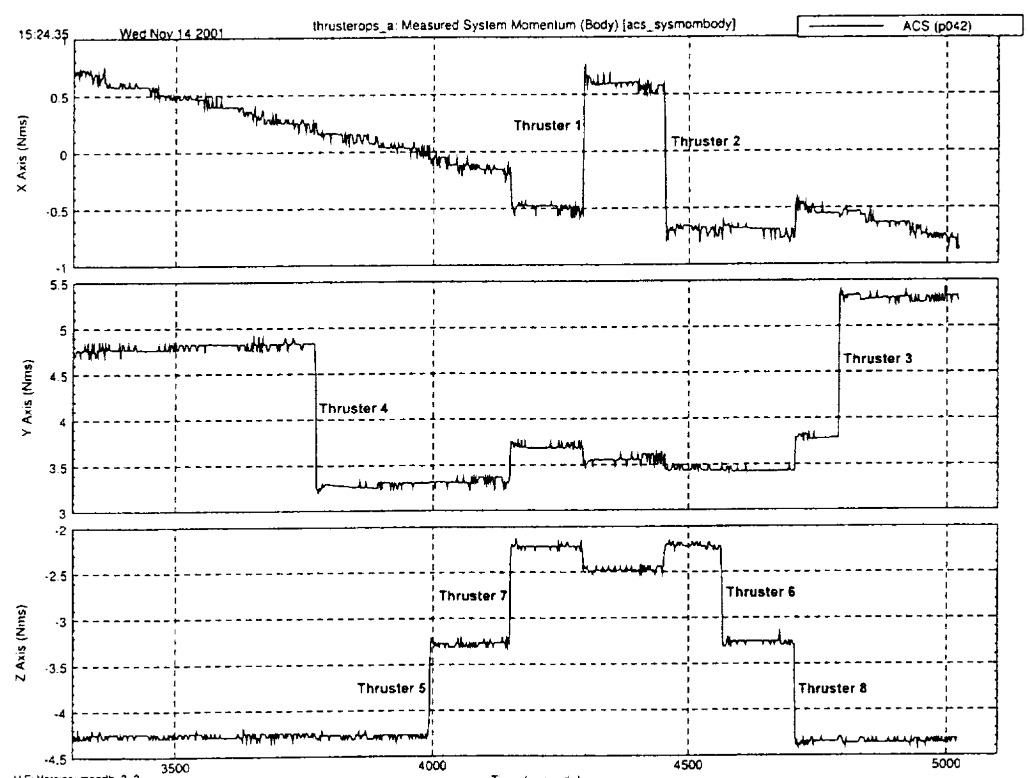

Figure 10: Thruster Pulse Check Momentum Effects

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 that the second round of thruster pulse checks would yield momentum changes closer to the expected value. When the second round of tests also produced lower than expected results, a different theory was suggested, that the 400 millisecond thruster firings were not long enough for the thrusters to reach a steady-state temperature, decreasing their effective thrust. In this case, the consistency and relative performance of the thrusters became the proof of correct thruster function.

Calibration Maneuvers

The nominal configuration for all of the perigee maneuvers was a four thruster +X axis burn, so the first calibration burn planned was a 102 second 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.

The +X axis calibration maneuver provided the first opportunity to determine how the actual spacecraft CM and thruster plume impingement torques would actually affect the thruster modes. 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 11 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 thruster plume impingement torques 50% of their expected magnitudes was found to allow accurate predictions of thruster mode performance. Figure 12 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 apogees and each proceeded nominally. After the last of these burns, the flight telemetry 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 5 shows the values found. It is interesting to note that thrusters 1 and 2, the X axis thrusters that were canted 10° by bending their tubing after they had been integrated onto the spacecraft, were perfectly balanced in the calibration burns.

Table 5: Relative ACS Thruster Scale Factors

Thruster	Relative Scale Factor
1	1.0000
2	1.0000
3	0.9619
4	0.9887
5	0.9789
6	1.0031
7	0.9999
8	0.9993

Orbit Maneuvers

Figure 13 and Figure 14 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 an "anomalous force" acting on the spacecraft near perigee,[11] the first 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.

From launch through May, 2002, MAP has executed 11 thruster maneuvers, as well as the initial momentum dump and thruster pulse checks. Seven of these maneuvers were executed during MAP's phasing loops about the Earth to put it in the proper position for its lunar swingby. Two mid-course correction maneuvers were executed after lunar swingby to fine tune its trajectory into an L_2 orbit. Maneuvers are planned every four months (the requirement was no more than once every three months); MAP's orbit performance and momentum buildup are such that it can easily go four months between maneuvers, perhaps more. A maximum period between maneuvers of four months is desired to maintain operations team proficiency. The first and second stationkeeping maneuvers were executed on January 14, 2002, and May 8, 2002. Table 6 summarizes all thruster operations.

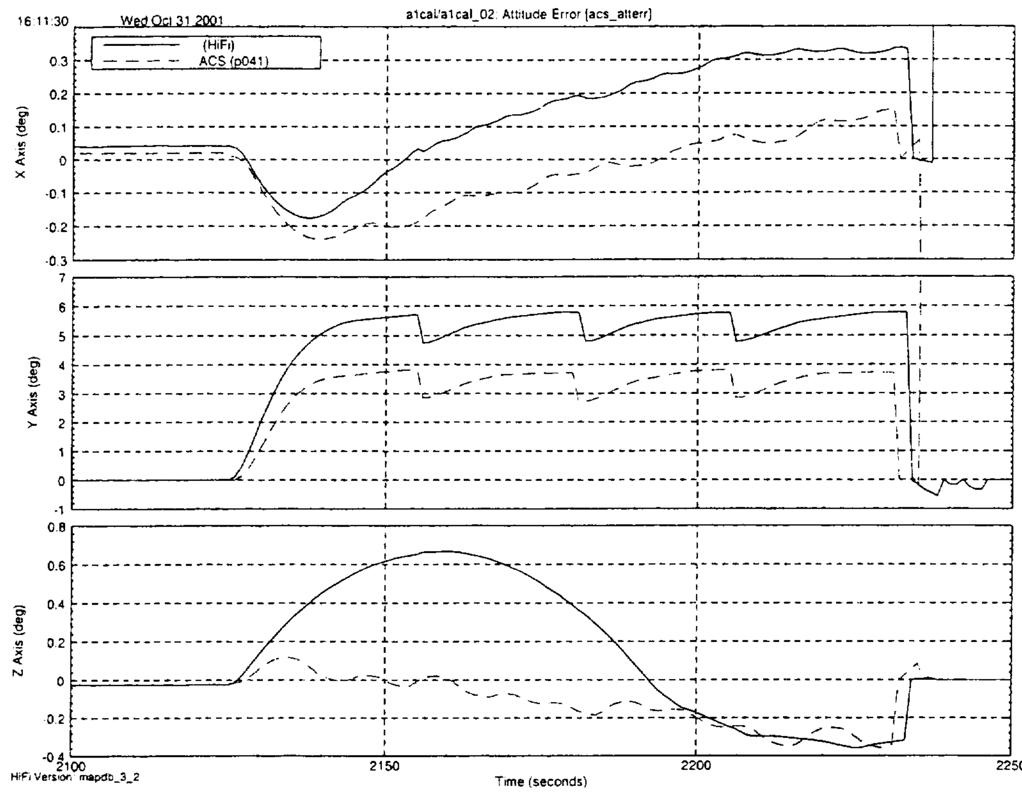

Figure 11: +X Calibration Maneuver Predicted and Actual Attitude Error (Pre-Calibration)

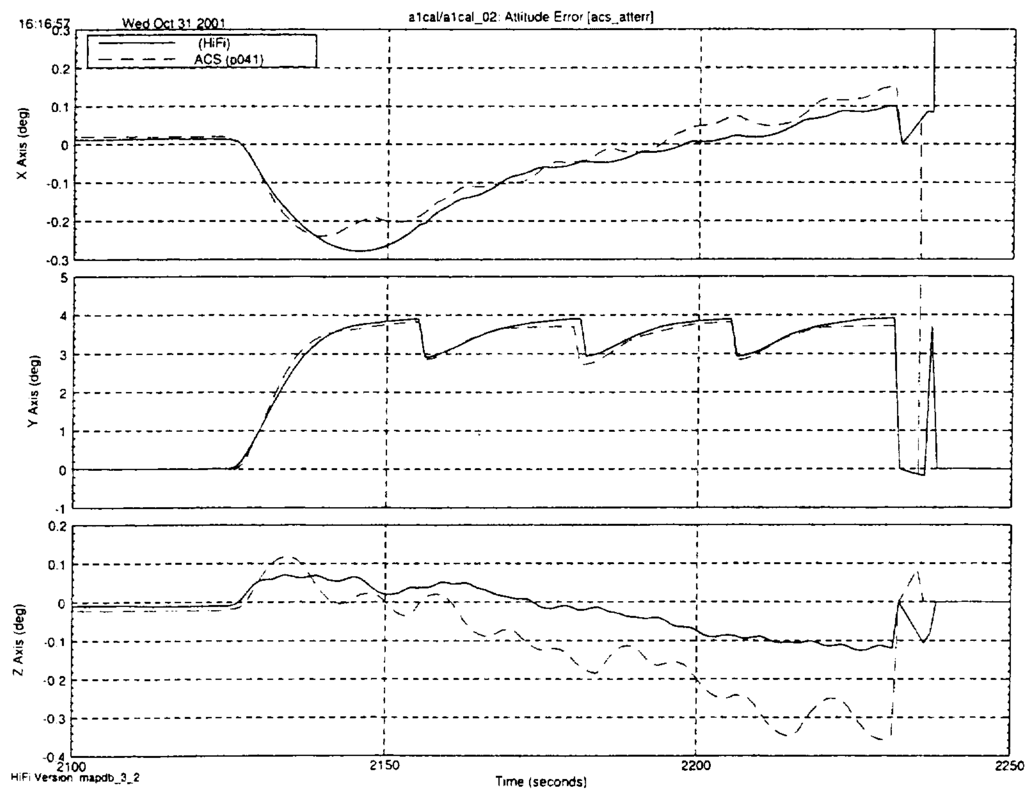

Figure 12: +X Calibration Maneuver Predicted and Actual Attitude Error (Post-Calibration)

Figure 13: Perigee Maneuver 1 Thruster Commands

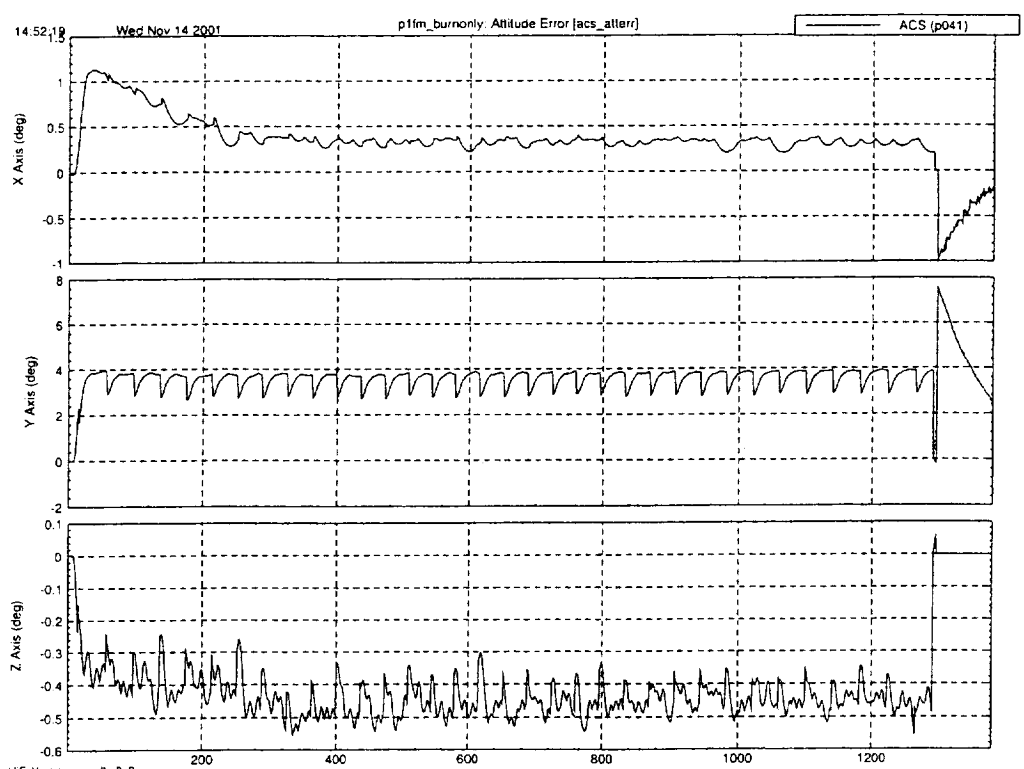

Figure 14: Perigee Maneuver 1 Attitude Error

Table 6: MAP Thruster Maneuver Summary

Maneuver	Date [GMT]	ΔV Direction	Duration (sec)	ΔV (m/s)
MAC ACE Thruster Pulse Checks	01-182	N/A	2×400 ms each thruster	~0.0
Initial ΔH	01-182	N/A	< 5	~0.0
LMAC ACE Thruster Pulse Checks	01-183	N/A	2×400 ms each thruster	~0.0
A1 calibration	01-185	+X	105.8	1.922
P1	01-189	+X	1275.4	20.194
A2 calibration	01-193	+Z	40.0	0.254
P2	01-198	+X	176.1	2.514
A3 calibration	01-202	–Z	43.4	0.296
P3	01-207	+X	542.9	7.410
P3C	01-208	+X	23.8	0.308
MCC1	01-218	+Z	17.8	0.103
MCC2	01-257	–Z	6.6	0.042
SK1	02-014	+Z	72.0	0.435
SK2	02-128	–Z	53.8	0.345

In Table 6, the date is specified as year and Julian day; e.g., 01-182 is Julian day 182, 2001, or July 1, 2001. For the thruster pulse checks, MAC ACE and LMAC ACE refer to the prime and redundant attitude control electronics (ACE) boxes on the spacecraft.

Conclusion

With a little over one year until launch, it was discovered that a center of mass migration caused MAP to lose functional redundancy in the event of a failure of one of its thrusters. Because the propulsion system was fully welded and integrated onto the spacecraft at the time and the flight software had finished its testing cycle, implementing a fix to restore redundancy was very difficult. Members of the propulsion team were able to come up with a plan and a custom tool to cant two of the thrusters *in situ*, while the ACS and flight software teams prepared and tested the necessary flight software changes to support the new propulsion system configuration.

MAP launched on June 30, 2001. While it has not been necessary to use any of the backup thruster modes of thruster mode enhancements described above, the propulsion system has performed all of its functions nominally. A calibration burn using the canted thrusters showed them to be the most balanced pair on the spacecraft. Because of a nominal flight and separation from its Delta II launch vehicle and nominal performance from the propulsion, attitude control, and other subsystems, MAP is in excellent shape to complete its two year mission and possibly an extended mission beyond that.

References

1. N. W. Bogges, *et. al.*, *Astrophysical Journal*, Vol. 397, p. 420, 1992.
2. S. Gulkis, P. M. Lubin, S. S. Meyer, and R. F. Silverberg, *Scientific American*, Vol. 262, No. 1, p. 132, 1990.
3. G. F. Smoot, *et. al.*, *Astrophysical Journal*, Vol. 396, p. L1, 1992.
4. C. L. Bennett, *et. al.*, "Four-Year COBE Cosmic Microwave Background Observations: Maps and Basic Results," *Astrophysical Journal*, Vol. 464, p. L1, 1996.
5. G. Davis, "The MAP Propulsion Subsystem," *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA-2002-4156, Indianapolis, IN, July, 2002..
6. D. K. Ward, *et. al.*, "Use of $MATRIX_X$ Integrated Toolkit on the Microwave Anisotropy Probe Attitude Control System," *AAS Guidance and Control Conference*, Breckenridge, CO, February, 1999.
7. J. R. O'Donnell, Jr., *et. al.*, "Development and Testing of Automatically-Generated ACS Flight Software for the MAP Spacecraft," *14th International Symposium on Space Flight Dynamics*, Iguassu Falls, Brazil, February, 1999.
8. F. L. Markley, *et. al.*, "The Microwave Anisotropy Probe (MAP) Mission," *2002 AIAA Guidance, Navigation and Control Conference*, AIAA Paper 2002-4578, Monterey, CA, 2002.
9. J. R. O'Donnell, Jr., *et. al.*, "MAP Attitude Control System and Analysis," *Flight Mechanics Symposium*, Goddard Space Flight Center, Greenbelt, MD, 1997.
10. A. J. Ericsson-Jackson, et. al., "MAP Stability, Design, and Analysis," *13th International Symposium on Space Flight Dynamics*, Goddard Space Flight Center, Greenbelt, MD, May, 1998.
11. S. Starin, *et. al.*, "An Anomalous Force on the MAP Spacecraft," *2002 AIAA Guidance, Navigation and Control Conference*, AIAA Paper 2002-4581, Monterey, CA, 2002.