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Restoring Redundancy to the Wilkinson Microwave Anisotropy Probe Propulsion System

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The Wilkinson Microwave Anisotropy Probe is a follow-on to the differential microwave radiometer instrument on the Cosmic Background Explorer. Attitude control system engineers discovered 16 months before launch that configuration changes after the critical design review 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. A tiger team was formed and identified potential solutions to this problem, such as adding thruster-plume shields to redirect thruster torque, adding or removing mass from the spacecraft, adding an additional thruster, moving thrusters, bending thruster nozzles or propellant tubing, or accepting the loss of redundancy. The project considered the impacts on mass, cost, fuel budget, and schedule for each solution and it was decided to bend the propellant tubing of the two roll-control thrusters to allow the pair to be used for backup control in the negative pitch axis. The problem and the potential solutions are discussed, and the hardware and software changes and performed verification are documented. Flight data are presented to show the on-orbit performance of the propulsion system and lessons learned are described.

Introduction

THE Wilkinson Microwave Anisotropy Probe (WMAP) spacecraft launched on June 30, 2001 as a follow-on to the Cosmic Background Explorer (COBE). COBE made precise measurements of the cosmic microwave background (CMB). The CMB is believed to be a remnant of the Big Bang, marking the birth of the universe.[1–4] WMAP was designed to measure the CMB anisotropy with much greater sensitivity and angular resolution than the differential microwave radiometer (DMR) instrument on COBE. Additional science return was accomplished by using a more advanced science instrument and eliminating many of the major error sources in the DMR by injecting the spacecraft into a Lissajous orbit around the sun–Earth L_2 Lagrange point. This orbit minimizes magnetic, thermal, and radiation disturbances from the Earth and sun. Figure 1 shows a sketch of the WMAP spacecraft.

WMAP 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. Figure 2 shows a sketch of WMAP's flight path to L_2. An onboard propulsion system on WMAP was necessary to perform the maneuvers required to reach L_2, conduct periodic stationkeeping maneuvers to maintain this orbit, and to unload momentum.

The original propulsion system design incorporated thruster pairs arranged in three planes aligned with the observatory's center of mass. [Figure 3 shows the approximate locations of thrusters 1–6; thrusters 5 and 6 were actually aligned with the center of mass (c.m.) at this point in the design.] This placement decoupled the torque axes for each thruster and enabled each pair to be used for nearly torque-free acceleration when fired together. Thrusters 1 and 2 were on the sunward ($+Z$) face of the observatory along the Y axis, providing a thrust in the $-Z$ direction and $\pm X$ torque for attitude control. Thrusters 3 and 4 were on the antisunward ($-Z$) face of the observatory along the X axis, providing a thrust in the $+Z$ direction and $\pm Y$ torque for attitude control. Thrusters 5 and 6 were on the $-X$ face of the observatory along the Y axis, providing a thrust in the $+X$ direction and $\pm Z$ 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, which is critical to maintaining the needed thermal stability during stationkeeping maneuvers at L_2. After WMAP's confirmation review in 1997, NASA decided 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 velocity-change (ΔV) maneuvers without exposing the instrument to the sun. Resource and design constraints limited the maximum number of thrusters to eight, and so two additional thrusters were added into the propulsion system design.

The team decided to mount the two new thrusters in a canted direction to provide functional redundancy for all three thruster pairs. To achieve this, thrusters 5 and 6 were moved in the $-Z$ direction with respect to the spacecraft c.m. and thrusters 7 and 8 were added on the $-X$ face of the observatory with a 15-deg cant from the X–Y plane to provide thrust vector in the $+X$ and $+Z$ directions, as shown in Fig. 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. 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 cutting the finite burn penalty (the penalty from applying a finite, rather than impulsive ΔV.)

The purpose of this paper is to describe the hardware and software changes that needed to be made to WMAP when it was discovered relatively late in the integration and test process that c.m. migration had rendered one of the backup thruster control modes ineffective. The changes are described along with the test and flight data that were used to verify that they had been done correctly. The paper concludes with a discussion of the lessons learned from the process.

Center-of-Mass Migration

In March 2000, the mechanical team released a new mass properties update 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 c.m. was also seen. At the

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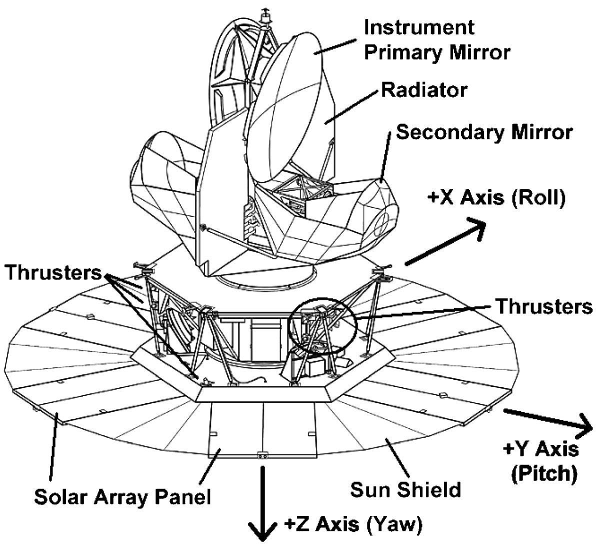

Fig. 1 MAP spacecraft layout.

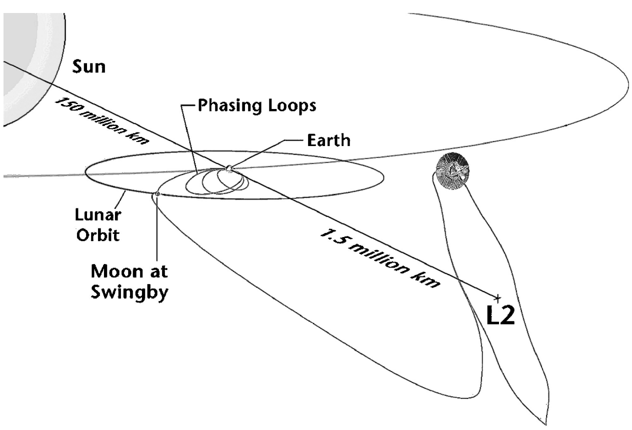

Fig. 2 MAP trajectory to L_2.

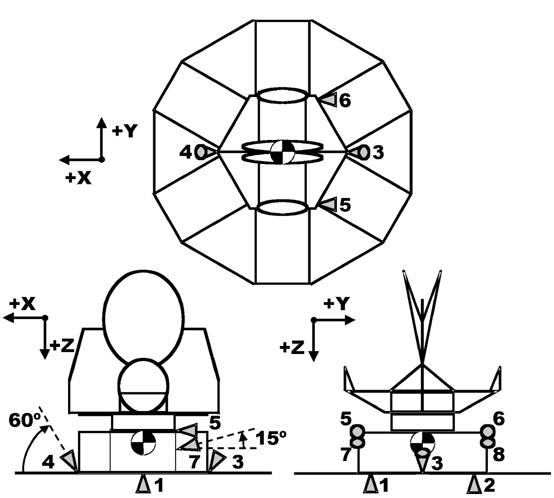

Fig. 3 Original thruster layout.

confirmation review, the beginning of life (BOL) c.m. was 63 cm from the separation plane. The new mass properties analysis showed this BOL value to have moved 9 cm in the $-Z$ direction, to 72 cm. At end of life (EOL), the new mass properties estimated a c.m. 76 cm from the separation plane.

Center-of-Mass 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

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

Table 2 $-Y$-axis torques

Thruster set	Y-axis torque, Nm
Original design	
Primary (4)	−5.13
Backup $(5+6)$	−1.0
Post-c.m. migration	
Primary	−5.52
Backup BOL	−0.11
Backup EOL	+0.25

a c.m. 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 the primary thruster, thruster 4, and the pair was a viable backup in that direction (Table 2).

A c.m. 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, with thruster plume impingement effects also factored in, thruster pair 5 and 6 could only provide a combined torque of 2% that of thruster 4 at BOL. At EOL, 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 for thruster 4.

Backup Thruster Solution Options

A tiger team was formed to consider a number of redesign options for WMAP. Given the strict mission requirement to reach L_2, the loss of thruster functionality was considered a mission-ending failure, and so the team agreed to consider all options before falling back to a nonredundant solution. These options fell into two categories: change the location of the c.m. or redirect the thrust of one or more thruster pairs. The first option was the logical solution: because 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 c.m. 1.5 cm, less than the 4.5 cm needed to ensure that thrusters 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, and so the team gave more serious consideration to redirecting the thrust.

WMAP 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 c.m. 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. The team considered the possibility of moving or changing the cant of thrusters 5 and 6 but eliminated this option for two reasons. First, the proposed change to both thruster brackets interfered with spacecraft structural members, making the modifications nearly impossible. More important, any redirection of the thrust direction for thrusters 5 and 6 to create a larger torque in the $-Y$ axis would also create a larger plume impingement torque in the $+Y$ axis. As shown in Fig. 4, the plume impingement torque increased faster than the torque from the redirection, eliminating any torque benefits gained by the increased moment arm relative to the c.m.

Instead, the team determined that rotating the thrust from thrusters 1 and 2 in the X–Z 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-deg redirection would not significantly affect the fuel budget, because thrusters 1 and 2 would only be used for ΔV during the shorter stationkeeping burns once WMAP reached L_2.

The team considered either a 5- or 10-deg redirection of thrusters 1 and 2. Table 3 shows how much additional c.m. 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 c.m. movement of only 2.2 cm or plume impingement torques just 26% higher than expected would saturate the thrusters if canted 5 deg, whereas the margins were significantly higher for the larger cant of 10 deg. The team chose to implement a 10-deg cant because its fuel cost was considered acceptable and it had much greater robustness to changes in mass properties or plume impingement effects.

The final question was how to accomplish the thrust redirection. Plume-deflection shields represented the simplest, but also the least deterministic, method among the options. Bending the thruster nozzles would have introduced significant reliability and performance risks. Instead, the team opted to bend the propellant tubing upstream of the thruster. Figure 5 shows the final thruster flight configuration.

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

Table 3 Center of mass and plume impingement margin for 5- or 10-deg cants, thrusters 1 and 2

Margin	5-deg Cant	10-deg Cant
Z-axis c.m. (cm)	2.2 cm	10.4 cm
Plume (% increase)	26%	115%

Thruster 1 and 2 Bending Operation

Since the propulsion subsystem was fully integrated and had been fully tested, the propulsion and mechanical teams exercised great care during the bend procedure not to damage existing hardware and to fully inspect, retest, and reverify any hardware that was affected. Before any hardware was modified, the propulsion lead consulted Kennedy Space Center and Cape Canaveral Air Station Range Safety officials to get their approval on the postbending test and verification plan and wrote a detailed procedure that included

Table 4 Postbend primary and backup ACS thrusters and BOL torques

			Backup set	
Torque axis	No.	Primary 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

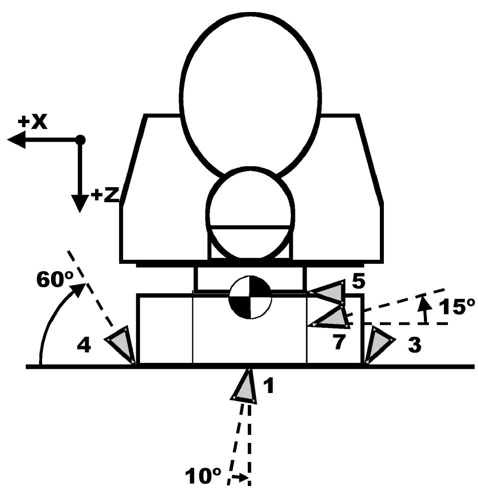

Fig. 5 Thruster layout with thruster 1/2 cant.

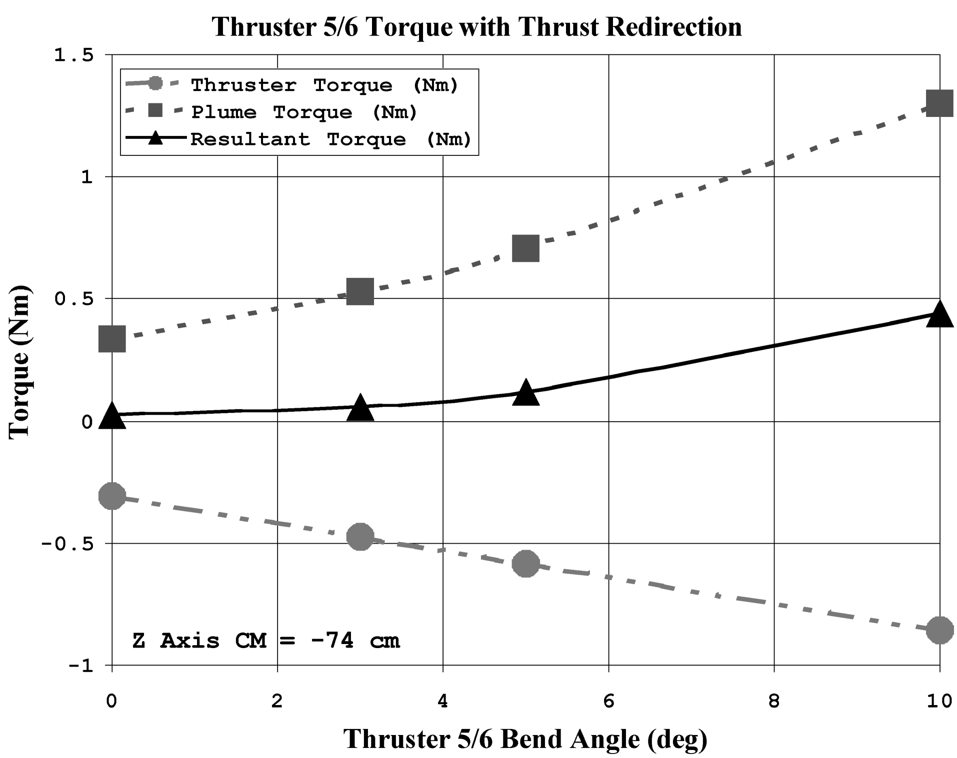

Fig. 4 Results of thruster 5/6 bend option.

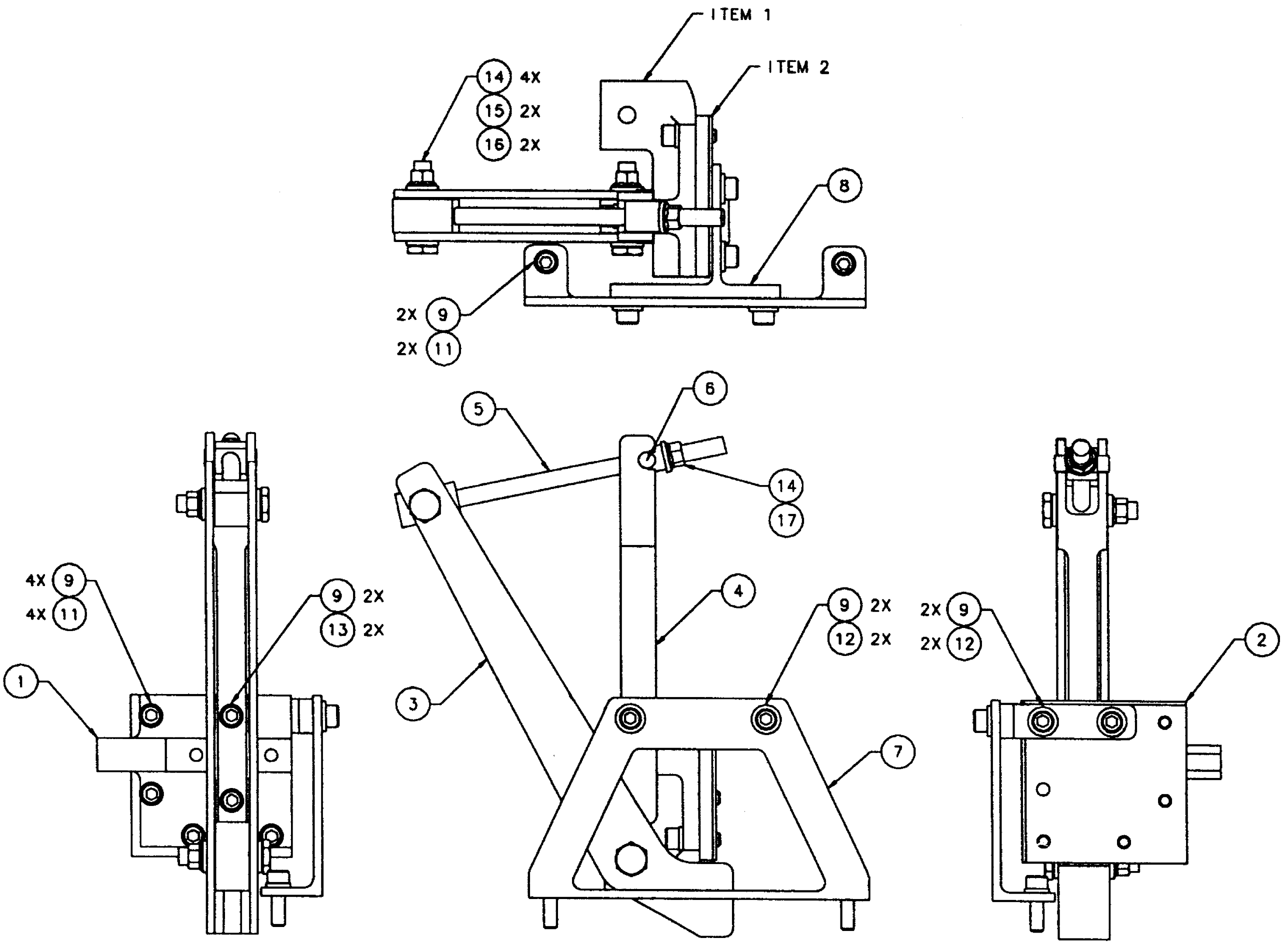

Fig. 6 Custom bend tool.

all aspects of the bending and testing effort. Because the propulsion subsystem was fully tested and integrated within the WMAP spacecraft, the bending of the roll thruster tubing was performed in situ. The tubes that 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 2.5 cm 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, and so a custom bending tool was designed and fabricated.

The bending tool's design evolved from 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-deg 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 deg. Figure 6 shows design drawings for the custom bending tool. This bend 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 237,000 kPa (34,400 psi).

Deintegration

Figure 7 shows most of the layers surrounding each of the propellant lines that needed to be removed in the first phase of work to perform the bend operation. First, the multilayered insulation (MLI) blankets from the thrusters and propellant feed lines near thrusters 1 and 2 were removed and discarded. Next, removing layers of Kapton® tape, lead shield tape, lacing cord, and outer layers of aluminum tape exposed the spiral line heaters. Inspections were performed after each layer was removed to look for damage. Technicians then removed the spiral heaters, labeling and cutting their wires as required. Removal of the inner layers of aluminum tape exposed the propellant tubes, which were then cleaned. The thrusters were unbolted from their brackets and the brackets were then unbolted from the spacecraft structure, removed, and weighed. The procedure had provisions for cutting the thruster brackets in order to remove them from the spacecraft, but fortunately this was not necessary. At this point, only the feed tubes and electrical harnesses attached the thrusters to the WMAP spacecraft.

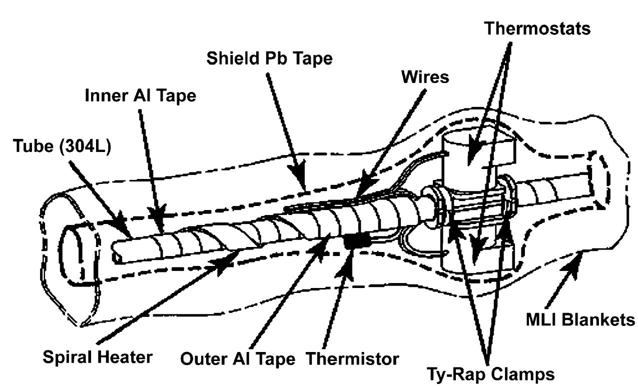

Fig. 7 Thruster tubing hardware layout.

Bending

In the second phase, technicians assembled the bend tool 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 technician actuated the bend tool to execute the bend; frequent measurements were taken until the desired angle was reached.

The custom bending tool performed the bend in a manner similar to that of a common hand tube bender, with the 2.5-cm bend radius and sliding block of the bend tool supporting the tube walls and precluding kinks. The tube bender mechanism consists of eight pieces bolted together. The tool could be assembled to perform bends in either direction because of the symmetry of some of its components. The technician bolted the tool to the thruster-bracket mounting holes and then assembled it 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.

Mirrors were installed on the thruster nozzles and optical theodolite measurements were taken while the flight bends were performed. The theodolites measured the orientation of the nozzles before the bend and at several points during the bend until the desired angular change was met. Because the tool was reversible to accommodate thruster 1 or 2, four engineers verified 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 deg and its actual change was 9.605 deg (slightly out of the desired tolerance, but acceptable). Thruster 2 was bent in five steps; the desired angular change was 10.0 ± 0.5 deg and its actual change was 9.557 deg.

The new thruster brackets incorporating the 10-deg thruster orientation were then installed. The thruster orientations were reverified with the alignment mirrors. No additional adjustments were needed. Figures 8 and 9 show thruster photographs before and after the bend. (The pictures were taken from slightly different angles, but the bend is clearly shown.)

Postbend Verification

While the propellant tubes were bare, the propulsion team conducted a dye penetrant test on the tube surface. To further verify the integrity of the bent tubing, they also performed a pressure test on the entire subsystem. The propulsion subsystem held the maximum operating pressure of 2413 kPa (350 psig) for 5 min. During the pressure test, leak detection fluid applied on the bent areas showed no gross leaks.

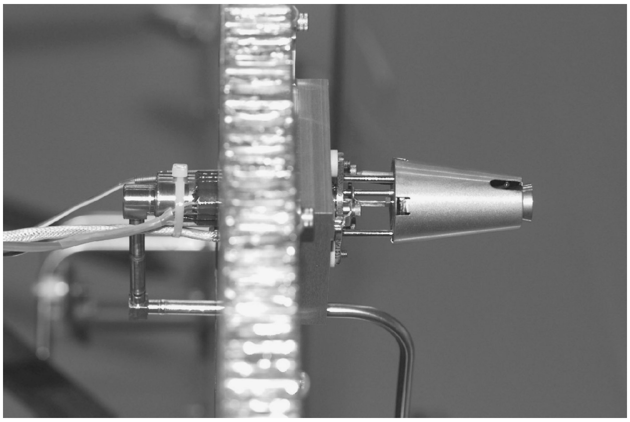

Fig. 8 Thruster before bending.

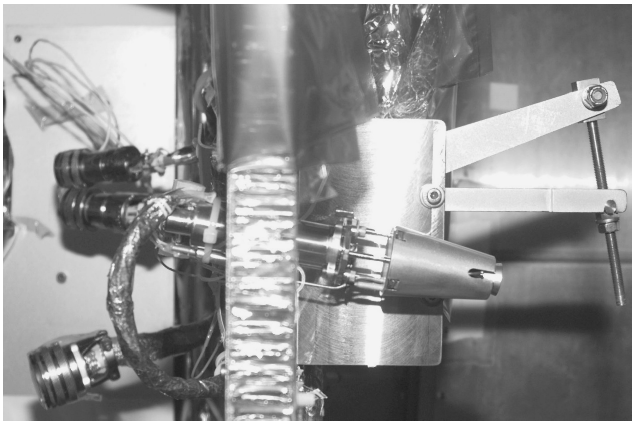

Fig. 9 Thruster and bend tool after bending.

Reintegration

After the propulsion team completed the pressure test and vented the tank pressure, they began reintegration, performing inspections and taking photographs after every step. They applied the inner layers of aluminum tape, installed and inspected the spiral heaters, applied the outer layers of aluminum tape, and connected the heater circuits 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. The team performed heater circuit and thermostat tests to verify that they were correctly reintegrated and used cold spray to activate and verify thermostat operation. Finally, MLI was fabricated around the thruster feed tubes and the blankets were grounded.

Attitude Control System Redesign

In addition to physically bending the thruster tubing to achieve a 10-deg cant of thrusters 1 and 2, ACS software needed to be changed to restore the WMAP propulsion system to full redundancy. Although loadable software tables were used extensively by the WMAP flight software architecture 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. Therefore, although 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.

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

Thruster-Bend Software Implementation

The necessary change to the FSW, using thrusters 1 and 2 as a backup for thruster 4 for attitude control in the ΔY axis, was implemented in the WMAP HiFi. A block in the Delta V mode controller (used to control spacecraft attitude during orbit maneuvers) 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 locations of thrusters 5–8 were originally set to balance their torques about the spacecraft c.m., but with the c.m. migration toward the thruster 5 and 6 firing plane, this was no longer the case.

As a result of the c.m. 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 c.m. and in the amount of thruster plume impingement torques that would be seen from thrusters 5 and 6, the team was concerned that a four-thruster ΔV would saturate the ability of thruster 4 to balance the Y-axis disturbance.

To alleviate this concern and still preserve the ability to at least somewhat improve the efficiency of perigee maneuvers, the ACS team enhanced the Delta V mode FSW to allow each thruster pair to be commanded to a given duty cycle. The change allowed 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

The team made one additional FSW enhancement 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, particularly at EOL. Although 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 FSW tables. In the event of a thruster failure, these multipliers could increase the control gain for the backup thruster set 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 WMAP mission, the primary focus throughout that time was on the orbit maneuvers and the thruster mode calibrations leading up to them. WMAP'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 WMAP's three perigee passes and calibration burns of the ACS Delta V mode used to perform these maneuvers were planned for each apogee, so that their disturbance to WMAP's orbit would be minimized.

Thruster Mode Pulse Checks

The spacecraft operations team performed thruster one-shot pulse tests to verify the correct polarity of the propulsion system and to determine whether there were any obvious and significant differences between the performance of the eight thrusters before any use of either Delta V or Delta H mode (used to dump momentum). The one-shot tests fired each thruster for 400 ms, one at a time, using ground commands while in sun acquisition mode. (For more information on WMAP's control modes and attitude control system design, see Refs. 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.

The ACS team determined a specific order for the thruster tests 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. 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: the 400-ms 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 polarity and function.

Calibration Maneuvers

The nominal configuration for all of the perigee maneuvers was a four-thruster $+X$-axis burn, and so the first calibration burn planned was a 102-s burn in this configuration. Assuming that this calibration burn and the first perigee maneuver proceeded nominally, the other two calibration burns would be done in the $+Z$ and $-Z$ directions. 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 spacecraft c.m. and thruster plume impingement torques would affect the thruster modes. By observing

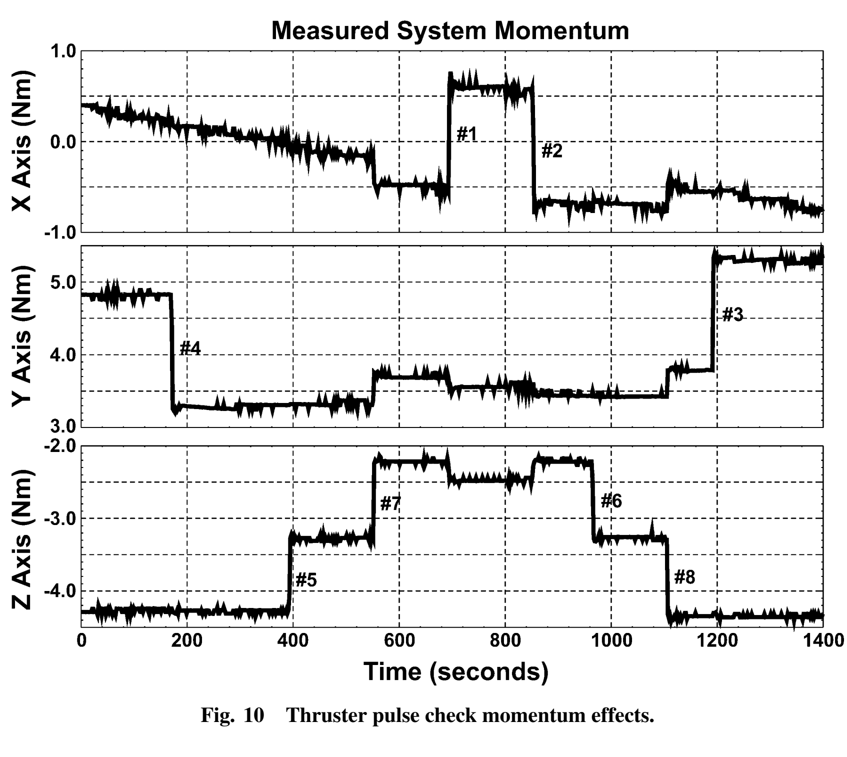

Fig. 10 Thruster pulse check momentum effects.

the Y-axis attitude error and the duty cycle of thruster 4, the ACS team could determine approximate values for the spacecraft c.m. and thruster plume impingement torque magnitude. The expected values of c.m. and thruster plume would give a 45% duty cycle for thruster 4 and a Y-axis attitude error of 6 deg.

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 deg. This was potentially good news—the lower duty cycle meant less fuel usage along with the smaller attitude error—as long as a viable explanation for the better performance could be found. After analysis, a c.m. 2.785 cm from its predicted value and thruster plume impingement torques 50% of their expected magnitudes were found to allow accurate predictions of thruster mode performance. The dashed lines in Fig. 11 show the actual vs predicted performance of the burn before and after calibration of the simulation parameters, with much better concurrence between flight and HiFi data afterward.

The other two calibration burns were performed at the second and third apogees and each proceeded nominally. The ACS team analyzed the flight telemetry from these three burns to determine the relative scale factors among the eight thrusters that would allow the 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 deg by bending their tubing after they had been integrated onto the spacecraft, were perfectly balanced in the calibration burns.

Orbit Maneuvers

Figures 12 and 13 show the thruster command profiles for the eight thrusters and attitude error flight data from the first perigee maneuver, a 20-min burn that was the longest performed. 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, from both ACS and trajectory points of view. The remaining orbit maneuvers at the second and third perigee and the final correction maneuver were also nominal and put WMAP on a good trajectory for its encounter with the moon and its path to L_2.

From launch through March 2003, WMAP has executed 14 thruster maneuvers, as well as the initial momentum dump and thruster pulse checks. Seven of these maneuvers were executed during WMAP's phasing loops about the Earth to put it in the proper position for its lunar swingby (apogee calibration burns A1, A2, and A3, perigee maneuvers P1, P2, and P3, and a perigee correction

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

Table 6 MAP thruster maneuver summary

Maneuver	Date[a] [GMT]	ΔV direction	Duration, s	ΔV, m/s
MAC ACE[b] thruster	01-182	N/A	2400 ms each thruster	~0.0
Pulse checks Initial ΔH	01-182	N/A	<5	~0.0
LMAC ACE[c] thruster pulse checks	01-183	N/A	2400 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
SK3	02-210	$-Z$	71.8	0.466
SK4	02-309	$+Z$	95.8	0.563
SK5	03-071	$-Z$	49.5	0.320

[a]Date is specified by year and Julian day; e.g., 01-182 is Julian day 182, 2001, or 1 July 2001.
[b]The MAC ACE is the primary attitude control electronics box.
[c]The LMAC ACE is the redundant attitude control electronics box.

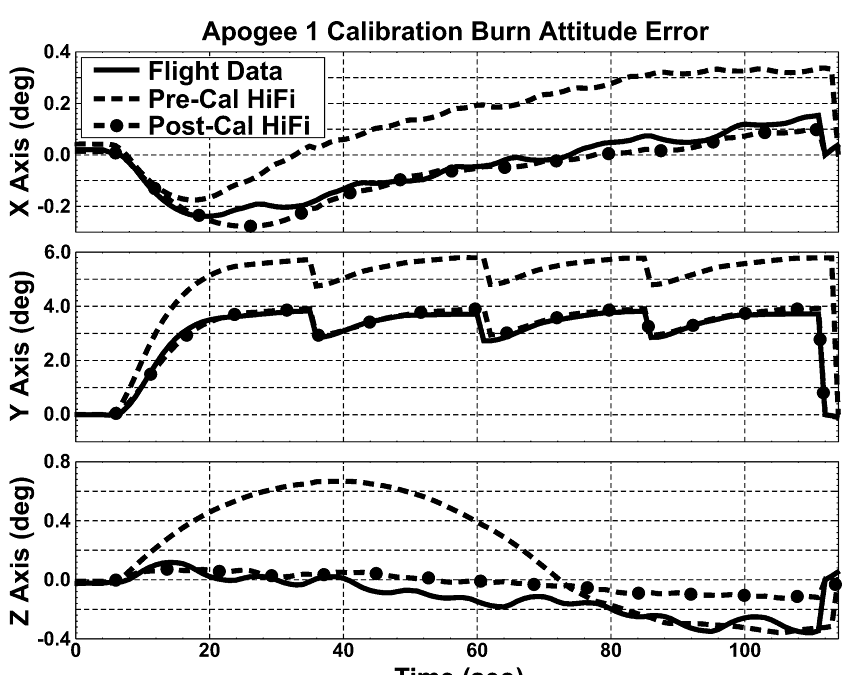

Fig. 11 +X cal maneuver attitude error.

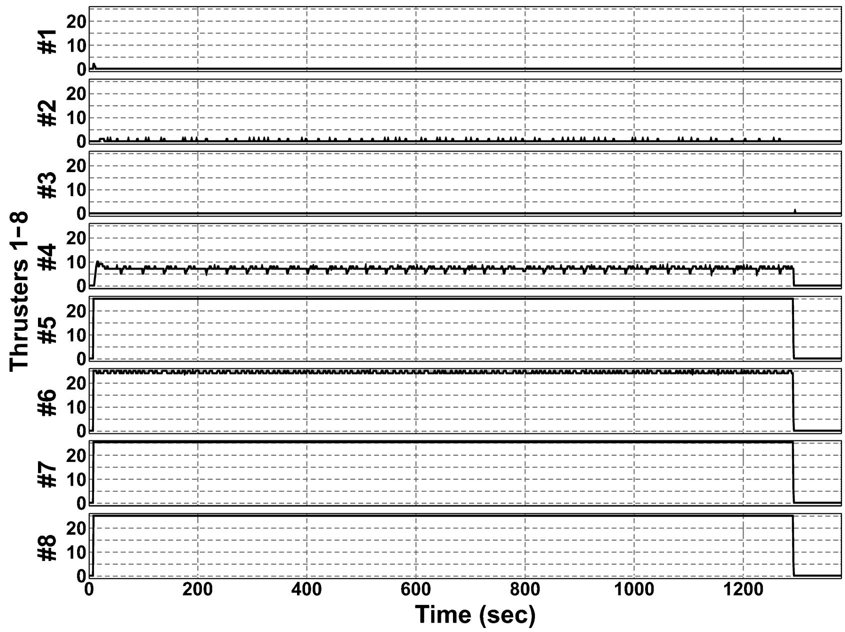

Fig. 12 Perigee maneuver 1 thruster commanded counts.

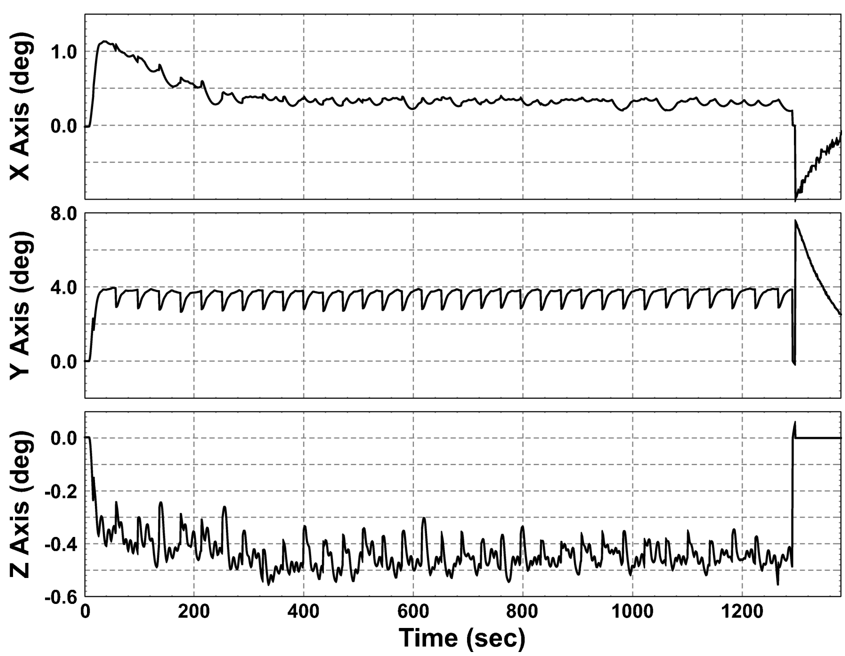

Fig. 13 Perigee maneuver 1 attitude error.

maneuver P3C). Two midcourse correction maneuvers (MCC1 and MCC2) 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); WMAP'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. Five stationkeeping maneuvers (SK1 through SK5) have been executed between January 2002 and March 2003. Table 6 summarizes all thruster operations.

Conclusions

With a little over one year until launch, it was discovered that a c.m. migration caused WMAP 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 FSW 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 FSW teams prepared and tested the necessary FSW changes to support the new propulsion system configuration.

WMAP launched on 30 June 2001. While it has not been necessary to use any or the backup thruster modes or thruster mode enhancements described earlier, 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, WMAP is in excellent shape to complete its two-year mission and an extended mission beyond that.

Although the process of realigning two of WMAP's thrusters to restore full functional redundancy to the propulsion system was a complete success, there are important lessons learned from the experience that should help keep such a situation from occurring in the future. Additionally, the very success of the bending operation yields some lessons of its own:

1) Mass properties should be treated as a configured resource to be tracked and changes should be clearly communicated to all parties as the project moves forward. The mechanical subsystem tracked the spacecraft mass, inertias, and c.m. for WMAP, but there was a period of time during which the ACS team did not stay up to date with the c.m. location. All relevant spacecraft mass properties should be configured and tracked at the systems engineering level to prevent this problem from happening.

2) The requirements for the layout and function of the propulsion system thrusters should be clearly written. The WMAP requirements for the propulsion system did not capture the functionality needed from the thrusters, and so the mechanical team did not realize that the movement of the c.m. was a problem. If the requirements for thruster layout had been done relative to the spacecraft c.m., or if a separate requirement on c.m. location had been levied, the issue would have been discovered much sooner (perhaps before it became an issue). This point is especially applicable to WMAP because its physical configuration meant that the c.m. migration was due almost entirely to payload weight growth, and science payloads are often significant weight risks.

3) Simplified thruster operations involving more thrusters might be cheaper and more reliable in the long run. The WMAP thruster design evolved from six-thruster single-string to eight-thruster fault-tolerant as a result of review action items. In hindsight, the cost of thrusters is small compared to other systems and complex analyses, and it might have been cheaper to use more thrusters with dedicated functions to simplify the control scheme. The WMAP design using eight thrusters to give three directions of ΔV, three axes of attitude control, and single-fault tolerance, while very economical, was also very complicated.

4) In hindsight, the behavior of the spacecraft propulsion system during the thruster pulse checks performed during the first few days of the mission should not have been surprising. The behavior of the thrusters given the potential of gas in the lines and the very short pulse durations is a well-understood phenomenon. A review of past missions with similar hardware and NASA's lessons-learned database should be mandated to prevent this sort of surprise.

5) Finally, it is important to remember that realigning (bending) the thrusters was very successful and was done to a very high accuracy. The fact that this operation was done so successfully demonstrates the important lesson that, with the proper amount of planning, effort to develop the procedure, and performance of the necessary analysis, very complicated operations can be formed under difficult circumstances with great success.

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