AN ANOMALOUS FORCE ON THE MAP SPACECRAFT

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Abstract

The Microwave Anisotropy Probe (MAP) orbits the second Earth-Sun libration point (L_2)—about 1.5 million kilometers outside Earth's orbit—mapping cosmic microwave background radiation. To achieve orbit near L_2 on a small fuel budget, the MAP spacecraft needed to swing past the Moon for a gravity assist. Timing the lunar swing-by required MAP to travel in three high-eccentricity phasing loops with critical maneuvers at a minimum of two, but nominally all three, of the perigee passes. On the approach to the first perigee maneuver, MAP telemetry showed a considerable change in system angular momentum that threatened to cause on-board Failure Detection and Correction (FDC) to abort the critical maneuver. Fortunately, the system momentum did not reach the FDC limit; however, the MAP team did develop a contingency strategy should a stronger anomaly occur before or during subsequent perigee maneuvers. Simultaneously, members of the MAP team developed and tested various hypotheses for the cause of the anomalous force. The final hypothesis was that water was outgassing from the thermal blanketing and freezing to the cold side of the solar shield. As radiation from Earth warmed the cold side of the spacecraft, the uneven sublimation of frozen water created a torque on the spacecraft.

Figure 1: MAP Observatory with Solar Shield Deployed

Introduction

This paper describes an anomalous force that acted on the MAP Observatory in a puzzling way. For background information, please refer to Bennett, Hinshaw, and Page[1] for MAP science, and Markley *et al*[2] for MAP engineering. The force acted each time MAP approached perigee in preparation for its crucial orbit-raising maneuvers, and it also appeared at the periselene—the lunar swingby to which those maneuvers directed the spacecraft.

Though in hindsight the presence of this anomalous force would not have ended the mission, the criticality of the mission operations occurring at its first appearance and the potential threat presented by such a mysterious and possibly unpredictable event combined to create one of the most challenging operations that faced the MAP team during the In-Orbit Checkout and Maneuvering phase of the mission.
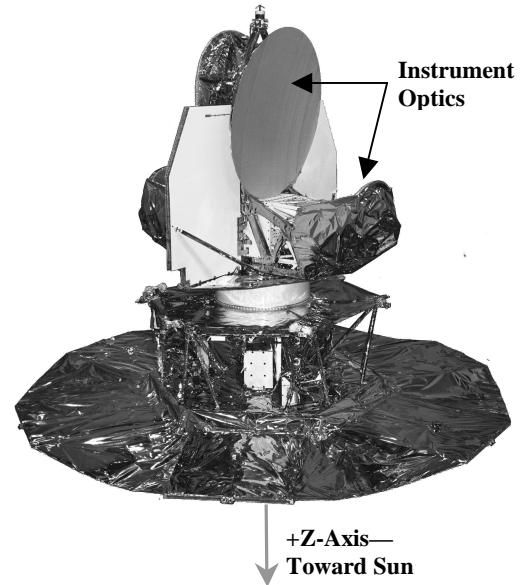

Figure 2: MAP Observatory—Sun Side

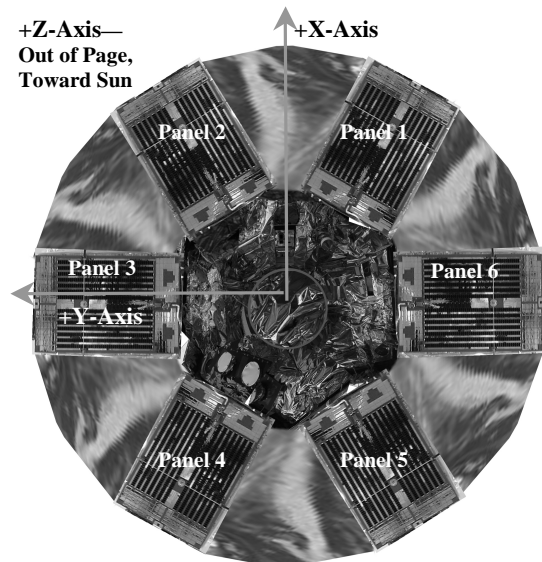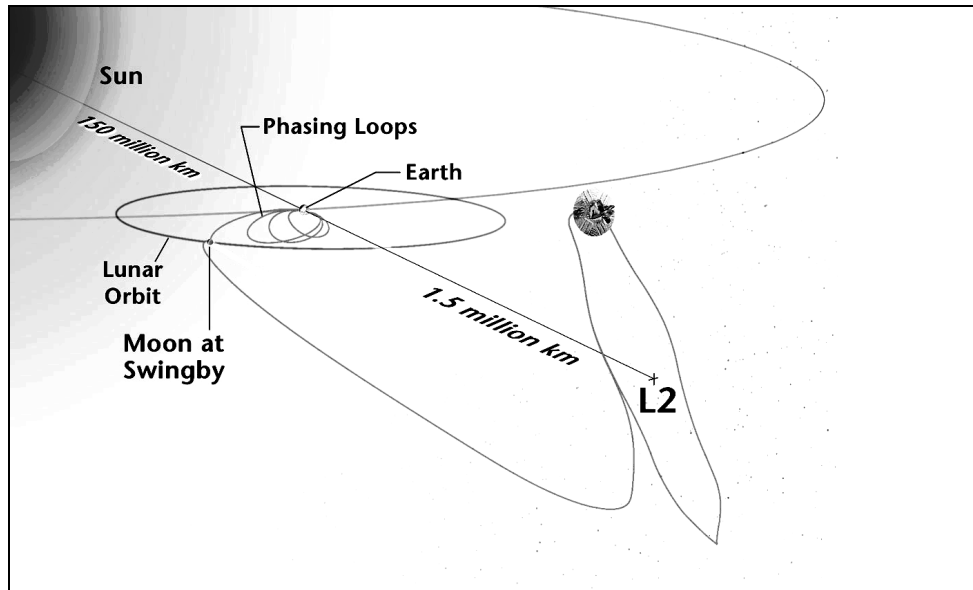American Institute of Aeronautics and Astronautics

Figure 3: Early Operations Trajectory Plan

The MAP Spacecraft

Configuration

The MAP Observatory is composed of three main portions—the instrument, the central truss, and the solar shield. Figure 1 shows the upright spacecraft, with the instrument, its optics, and its large thermal radiators on top of the hexagonal central truss. The passively cooled portions of the instrument operate at a physical temperature of about 60–100 Kelvin (K). Providing a relatively cold and extremely stable thermal environment is crucial to achieving the mission's science objectives.

To the central truss is attached the rest of the vital spacecraft components. At the bottom of the figure, and shown also in Figure 2, is the solar shield, which comprises the six solar array panels, thermal blankets stretched between those panels, and several components (*e.g.* Sun sensors) that need to be exposed to the Sun.

A key thermal design feature is that the backside of the solar shield is insulated from the Sun-facing side, improving the passive cooling of the instrument required for science observations. Also of particular interest in this paper, the coarse Sun sensors (CSS) are located in redundant pairs at the outer ends of the array panels. The CSSs on panels 1, 3, and 5 face toward the Sun at a 57° cant from the XY-plane,

and the CSSs on panels 2, 4, and 6 face away from the Sun with the same cant; the cold-side CSSs nominally receive no signal during science operations. Figure 2 shows the identifying numbers in relation to the spacecraft axes. Figure 3 shows the trajectory followed by MAP as it was guided toward L_2.

Nominal Perigee Maneuver Plan

Before each maneuver, MAP was in Observing Mode, in which it collects science data; the first command to prepare for a maneuver was to exit this mode. The spacecraft was then put into Inertial Mode for the pre-burn period. This mode established the desired attitude—which would be aligned with the correct velocity change (Delta V, or ΔV) direction at the burn start—in advance via commanded quaternion.

Each perigee pass used a slightly different attitude, but in all cases the spacecraft and its arrays were oriented about 45–50° from the Sun, and the instrument was directed approximately toward nadir at perigee. These factors combined to create an attitude profile that allowed the Sun to heat the instrument and Earth albedo to illuminate the cold side of the solar shield shortly before perigee. These were the only times after launch that these cold surfaces were illuminated

At the burn start, the spacecraft was commanded into Delta V Mode, which also used commanded

quaternions to follow the correct trajectory. Next, Delta V Mode autonomously exited into the angular momentum control mode (Delta H) at the completion of the burn. Finally, after the Delta H dumped momentum, a stored command put the spacecraft into its Sun Acquisition Mode.

Anomaly at First Perigee

About 40 minutes before the first perigee (often called P1), MAP telemetry showed a small but significant increase in system angular momentum. The momentum grew for approximately 17 minutes, with the total (root-sum-squared) system momentum increasing from 0.5 Nms to 1.6 Nms (see Figure 4). To protect against a thruster malfunctioning during a maneuver, on-board failure detection and correction (FDC) was configured to abort a burn at 5 Nms of system momentum. At the observed rate of growth, it seemed the limit could have been reached, and FDC would have aborted the maneuver just before it started. After a few tense minutes, it became clear that the system momentum rate of growth was slowing for the moment. There was still some concern, however, that the increased momentum could cause an unacceptable transient when the maneuver started.

The system momentum peaked 20 minutes before perigee; it then decreased significantly, but not to its pre-anomaly level, over the next 15 minutes. Operations in Delta V Mode started about 5 minutes before perigee, as scheduled, and concluded without incident. Because the Delta V Mode also acts to reduce system momentum, it was difficult to obtain information regarding the momentum change after the thrusters began to fire. However, after Delta H Mode (the thruster-based angular momentum control mode) left the spacecraft at a safe system momentum of about 0.4 Nms, the system momentum decreased due to continuing external torque disturbances by an additional 0.1 Nms before settling to a constant value.
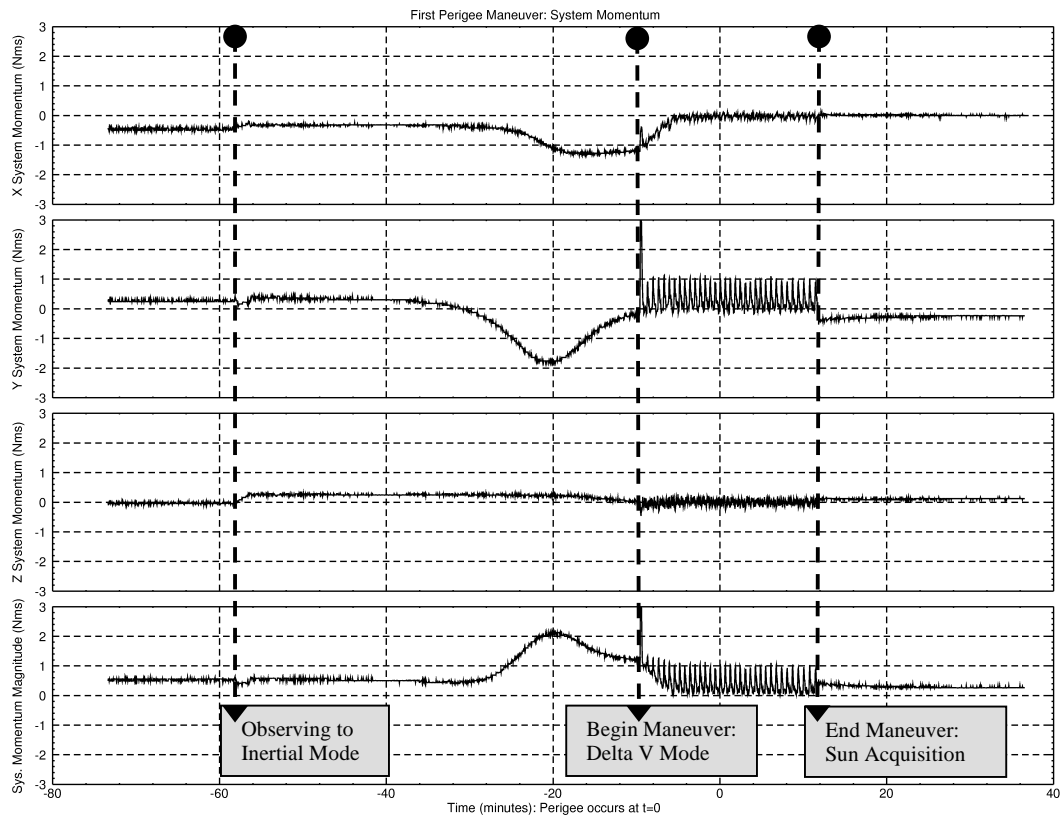

Figure 4: System momentum profile at the first perigee (P1) maneuver. The time axis displays number of minutes relative to the time of perigee passage.

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Analysis of Anomalous Force

In each case, a negative change in Y-axis momentum was observed first, suggesting a "nose-up" moment (note that this is opposite of aircraft convention, since the MAP +Z-axis pointed upward). This negative Y-axis torque was associated with an increase in the system momentum magnitude. The nose-up momentum increase was followed by both a negative roll moment (–X-torque) and a nose-down moment (+Y-torque). The Y-axis momentum returned nearly to its original value just before the burn, and the X-axis momentum had a small offset.

While a modified operations plan to guarantee good maneuver performance was being developed, the MAP team was also active in attempting to diagnose the problem to predict the future behavior of the force. The culmination of this effort was a model that accurately predicted the magnitudes of the system momentum changes seen at third perigee (P-final) and periselene. The reasoning used in the elimination of more mundane causes and the development of the accepted theory follow.

Sensor or Actuator Malfunction

During the anomaly, a quick look at other telemetry points suggested that the anomaly was the result of a true torque rather than a sensor or actuator malfunction. It was known that there was some error in the reaction wheel tachometer scaling factors by that time, but such errors would have affected momentum telemetry only if the attitude had been changing, causing the stored momentum to be traded between the wheels. However, the Inertial Reference Units and Digital Sun Sensors were in agreement that the attitude was not changing. The reaction wheels were behaving properly by absorbing the change in system momentum and maintaining the desired attitude profile.

It was postulated that the spinning reaction wheels might have been tipped by thermal deflection of the deck. This was not credible, though, since the wheels were spinning too slowly to act as Control Moment Gyros.

Another idea was that, due to a problem with the reaction wheel electronics, false speeds could have been indicated, thus creating a virtual source of momentum. It was extremely unlikely, however, that the signature seen could have had this cause. The wheel axes were so aligned that only a very particular and complex combination of failures in all three wheels could have resulted in false X- and Y-axis momentum readings with very small Z-axis changes.

Typical Disturbance Torque Sources

Shortly after the first perigee (P1) maneuver, team members began to offer hypotheses for the anomalous force. The first hypothesis was gravity gradient torque, because the torque occurred close to Earth and the time-varying momentum profile could correspond to the movement of the nadir vector with respect to the spacecraft body axes. The maximum gravity gradient torque was calculated assuming a 45° angle with nadir and using the known mass properties of the Observatory. Three other near-Earth disturbance torques—atmospheric drag, solar radiation pressure, and magnetic field—were calculated at that time (See Larson & Wertz[3] for equations to calculate typical disturbance torques). Table 1 shows the maximum magnitude for each of the disturbance torques. The atmospheric calculation uses an average value for atmospheric density, and it assumes a moment arm of 3 meters, which approximates the height of the entire Observatory. The same moment arm was used for the solar pressure torque, along with a maximal reflectivity of unity. Finally, the magnetic torque figure uses the predicted maximum residual dipole for MAP of 0.8 amp-turn-meter[2].

This simple, worst-case magnitude analysis was sufficient to eliminate all four possibilities. The solar radiation torque had the greatest maximum magnitude of the four; despite the estimation of a very large moment arm for the torque, it was still a factor of 6 less than the observed maximum torque of 0.004 Nm at P1. In addition, the solar radiation pressure could not have caused a time-varying torque because the attitude with respect to the Sun was held strictly constant until the thrusters began to fire. Analysts were forced to turn to more exotic hypotheses to explain the phenomenon.

Actual Disturbance	4.0E–03 Nm
Gravity Gradient	6.0E–05 Nm
Atmospheric Drag	1.2E–08 Nm
Solar Radiation Pressure	6.8E–04 Nm
Magnetic Field	1.6E–05 Nm

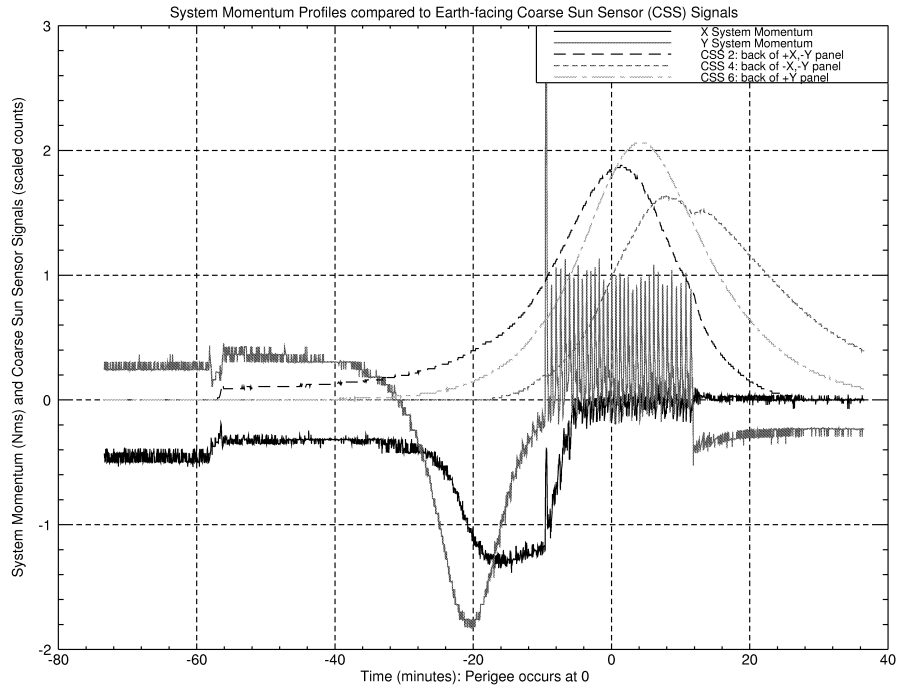Table 1: Maximum Magnitudes for Common Disturbance Torques

Figure 5: Comparison of first perigee (P1) system momentum and coarse Sun sensor (CSS) profiles. The profiles of the CSSs shown here are located on the dark side of the spacecraft and were stimulated by Earth albedo only.
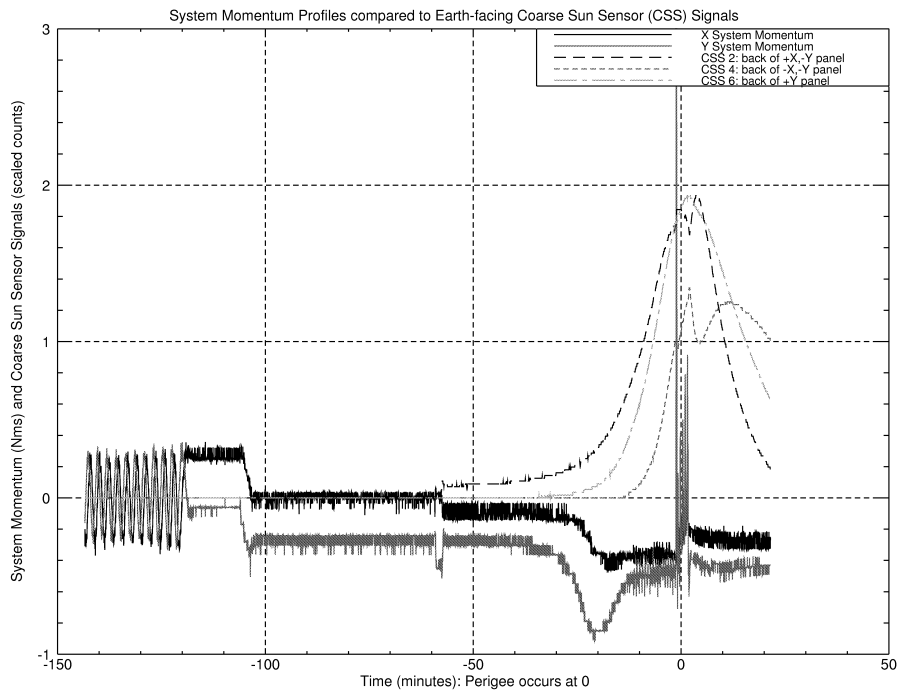

Figure 6: Second perigee (P2) system momentum and CSS profiles. Apparent momentum variations before t = −100 minutes were due to reaction wheel scale factor errors; such errors were ruled out as a factor in the anomaly.

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Propellant Leak

The possibility of thruster leakage was considered. If any one thruster had been leaking, the resulting change in momentum would have been in one of the eight particular, known thruster torque directions, and would have resulted in a specific combination of X-, Y- and Z-axis changes to momentum. Though the first few minutes of the anomaly allowed the possibility of a leak in thruster 4, which only provides negative pitching moment, the later changes in X-axis momentum discounted that hypothesis.

Thermal Bending

Differential heating of the solar array panels and their attached blankets could have bent these components, resulting in a compensating rotation of the spacecraft hub. This explanation was the first that seemed consistent with the time profile of the torques. However, calculations ruled out this possibility as well; any momentum imparted to the spacecraft body by warping solar arrays and blankets would have required equal and opposite momentum in the arrays and blankets. The 2-Nms peak momentum observed implied a sustained angular rate—1–3°/second for several seconds, based on the moments of inertia of the arrays and the blankets—that would have exceeded any motion that could have actually occurred in the arrays. These rates indicated that the array tips would have been deflected ~0.05 meter/second for several minutes. On MAP, this would have resulted in the arrays closing entirely, which certainly did not occur.

Illumination of Anti-Sun Side of Solar Shield

Figures 5 and 6 show CSS profiles scaled and super-imposed over the X- and Y-axis momentum profiles for the first and second perigees (P1 and P2). 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. The radiation pressure associated with this illumination, or with infrared (IR) blackbody radiation, would have been far too weak to torque the spacecraft noticeably. This seemed to be another dead end.

The recorded torques could have been produced, however, if the IR radiation was heating and sublimating ejecta from the spacecraft that had frozen to the back of the solar shield. As the other candidate theories, which at first seemed more likely, were disproved, the freezing and then boiling of outgassed matter was analyzed more carefully.

Outgassing

As mentioned before, the attitude profile leading up to the perigee maneuvers was unique in that the cold surfaces of the instrument and the solar shield were illuminated. It occurred to some team members that the instrument could be outgassing—first from the sunlit side, and then from the other side as it was heated by the Sun. However, this would have produced first a positive pitching moment and then a negative moment, which was the opposite of the torque profile observed.

Soon after, it was noticed that the back of the solar arrays could see a similar heating profile, and that that combination could produce the correct torque profile. This theory was developed more thoroughly as the team gained more evidence to support it; the full development of the theory will be discussed in a later section. Meanwhile, in the absence of a predictive theory, adjustments were made to the maneuver operations plan to be able to respond to further anomalies.

Operational Considerations

Since it was not known whether the anomalous behavior could recur or possibly worsen at subsequent perigee passes, preparations were made for the disabling of Telemetry and Statistics Monitors (TSM) dealing with system momentum and the possible manual aborting of the next burn. Because the peak system momentum change decreased at each subsequent periapse, these special preparations had no effect on the P2 or P-final maneuvers.

There were two concerns raised by the presence of this unanticipated force as the spacecraft approached perigee. First was a concern that the spacecraft attitude control might not perform within acceptable limits in the presence of the force. Second, because of the critical nature of the perigee-pass Delta V maneuvers, there was a concern that the effects of the anomalous force would cause the spacecraft FDC logic to autonomously abort the burn. At best, a burn delay would have resulted in a large, additional expenditure of fuel. At worst, due to the precise timing demanded by the lunar swing-by, there might not have been enough fuel to reach L_2, so the mission could have been terminated.

Attitude Control System Performance

From the onset of the anomalous force and its resultant torque on the spacecraft, the attitude control system was able to remove the disturbance with no obvious effect on pointing performance. This is because the anomalous force created a disturbance torque on the spacecraft of only 0.004 Nm, much less than the 0.215-Nm torque authority of each reaction wheel. So the anomalous force would not have affected the attitude control system performance directly, but it could have affected ACS performance indirectly through the system momentum buildup in the reaction wheels.

For the wheel-based control modes, system momentum buildup from the anomalous force was not likely to pose an ACS performance problem. Most of the various control modes could accommodate much higher momentum levels than those caused by the anomalies. However, the MAP perigee environment had high charged-particle densities that increased the risk of temporary outage of ACS hardware. The most basic Safehold mode for MAP is based on CSS measurements, and this mode was rated for a maximum momentum of 10 Nms.

In the two thruster-based control modes, performance concerns were more about initial transients into the mode than how well the control mode would perform at steady state, because both Delta V and Delta H Modes were effective in reducing system momentum. Any initial system momentum added by the anomalous force and still present at the beginning of the maneuver would have been removed by the action of the thruster mode during the maneuver. However, if the higher initial system momentum had caused the entry transient into Delta V Mode to be unacceptably high, onboard FDC would have aborted the burn.

FDC Configuration Changes

For the critical perigee-pass maneuvers, the FDC logic on the spacecraft, as implemented with ACS FDC points, telemetry statistics monitors (TSM), and relative time sequences (RTS) of commands, was put into its Critical Burn configuration. This configuration used the bare minimum of TSMs and RTSs to keep the spacecraft safe in the event of a failure. Consideration of the entire FDC configuration revealed that the greatest danger from the anomalous force was that it could cause even the minimum safe FDC configuration to abort the burn.

Leading up to and during the Delta V maneuver, there were three TSMs enabled that might have aborted a maneuver due to system momentum buildup. The first two—the Yellow and Red High System Momentum TSMs—were designed to detect system momentum buildup itself. The Yellow High System Momentum TSM was designed to detect a system momentum magnitude over 5 Nms. If tripped, the TSM would execute an RTS that would abort a maneuver and put the spacecraft into Sun Acquisition Mode. The Red High System Momentum TSM was similar, except that it looked for a higher system momentum magnitude of 13 Nms, and it also would close the propulsion system isolation valves. In addition to these two TSMs, there was a Delta V Performance TSM that would also abort a burn if the attitude or rate error in the burn was too high; such an error could have been caused by a momentum-induced transient response.

As the system momentum magnitude increased during the first encounter with the anomalous force, it was the Yellow High System Momentum and Delta V Performance TSMs that were of primary concern. If the system momentum magnitude had reached 5 Nms the maneuver would have aborted. Even though that limit was not reached, the initial transient might still have been worse and could have tripped the Delta V Performance TSM. When the momentum peaked at approximately 2.5 Nms, it was expected that the maneuver would perform nominally.

Operations at Second Perigee Pass

At the time of the second perigee pass, several reasonable theories for the cause of the anomalous force had been discredited, but no certain answer was yet forthcoming. Therefore, preparations were made to ensure that if the anomaly recurred with greater force, it would not needlessly abort the second or third maneuver.

During the time between the first and second perigee maneuvers, simulations were run on FlatSat, the high-fidelity dynamic simulator for MAP, to examine the effects of momentum buildup on the initial attitude and rate error transient into Delta V Mode. It was found there that the system momentum buildup would not cause an increased transient performance error, so the Delta V Performance TSM was not a problem. The Yellow High System Momentum TSM remained most likely to abort a maneuver if the anomalous force caused a greater system

momentum buildup. The following strategy was adopted to mitigate this risk.

As part of the sequence of commands used to implement the perigee maneuver, additional commands were included. The Yellow High System Momentum TSM was disabled before the expected onset time of the anomalous force for two reasons: (1) to allow a greater level of system momentum buildup prior to the maneuver, and (2) to survive the initial transient into Delta V mode and allow Delta V to decrease system momentum. The Red High System Momentum TSM was still left in place to provide safety for the spacecraft. Five seconds after the maneuver began, after the initial transient into Delta V Mode, the Yellow High System Momentum TSM was autonomously re-enabled.

In addition to the TSM changes above, contingency procedures were prepared to perform a contingency momentum dump using Delta H Mode before the maneuver, if necessary. Also, plans were made to resume the maneuver quickly if prematurely aborted. The Mission Operations Team closely monitored the system momentum prior to the maneuver to be ready to enact the contingencies in the event of a problem.

Development and Modeling of the Water Sublimation Theory

Collection of Frozen Material

After the maneuvers and subsequent Sun Acquisition, portions of the cold side of the Observatory rapidly cooled by radiating to space. Within about one day after exposure, by design, many surfaces on or with significant view to the MAP instrument cooled below the temperatures at which outgassing byproducts could easily boil off in high vacuum. Materials that came into contact with these cold surfaces had a significant capture probability. At the same time, the sunlit side of the solar shield was very warm and could continue to outgas, as could the blanketing for elements that produced their own heat.

As a result, the cold surfaces served as a cryogenic collector, or getter, for the outgassed material from the warm portions of the Observatory. It was observed that the solar shield fills approximately one third of the spacecraft central truss field-of-view, allowing outgassed matter to be ejected and condense on the shield. In addition to spacecraft blanketing on the exterior hub, the blanket venting paths for the

instrument and inner hub liner blankets are directed at the cold side of the array panels through a pair of low-conductance vent apertures.

A review of the possible outgassing byproducts from the blankets indicated that the dominant component ought to be water. The humidity and temperature of sensitive components were monitored prior to launch to insure the safety of the Observatory. Given the observed, pre-launch environmental profile, the effective surface area of blankets, the on-orbit thermal profile, and the venting path and getter geometry, the best estimate of water mass available to settle on the back of the solar shield is in the range of 0.2–1.4 kg.

It was theorized that, once deposited, the frozen water needed to be warmed above about 130 K to have sufficient energy to boil off in high vacuum. Earth IR exposure was thought to be sufficient to sublimate the products on the back of the solar shield during maneuver operations. This premise is supported by thermal data recorded by the instrument package during the perigee maneuver. The key question was whether the temperature of the outer layers of the solar array panel was cold enough to efficiently capture the outgassing products; the answer provided by the MAP Thermal Subsystem Team at the time was affirmative.

The order of magnitude of the average velocity[4] for the boil-off material, under the assumption that its dominant component is water, was estimated as

$$V_{kinetic} = \sqrt{\frac{2k_bT}{m_{nuc}N_{nuc}}} = 370\,m/s\,,$$

where $k_b = 1.38\mathrm{x}10^{-23}$ joules/K, $T \sim 150$K, $m_{nuc} = 1.7\mathrm{x}10^{-27}$ kg, and $N_{nuc} = 18$ for H_2O. For the P1 momentum anomaly, a peak magnitude of about 2 Nms was observed. Assuming a lever arm from the center of mass of 1.5m, the anomalous force corresponded to an ejected differential mass, *dm*, of about

$$dm = \frac{2\,Nms}{2(1.5\,m)(370\,m/s)} = 2\,grams.$$

Therefore, a collected-and-sublimated mass of about 2 grams of water could have produced the torques seen at P1. This amount is small compared to the ~1-kilogram estimate for the total outgassing mass for the Observatory. Only a fraction of the total outgassing mass could be expected to freeze to the cold solar shield, but

this calculation does show that the effect is not excluded by our knowledge of the parameters of the system.

The data are essentially consistent with uniform build up of material. However, if the back of the solar array blanket were uniformly heated, the deposited material would only slightly perturb the forward momentum of the Observatory, since torque response is a result of differential thrust experienced by spacecraft. The final piece of the puzzle was that the release of material on one portion of back of solar array panel was delayed in time by the instrument and central hub shadowing some panels from Earth IR. This hypothesis was supported by telemetry from the CSSs on the cold side of the solar shield—CSSs 2, 4, and 6.

Relationship between Attitude and Torque

The spacecraft Z-axis was inclined roughly 45° with respect to the Earth nadir during its approach, and the orbital velocity vector lay approximately between the +X-axis and the +Z-axis. CSS 2 was located on the leading edge of the spacecraft (+X-axis: see Figure 2 above), and indicated when that edge was exposed to albedo, and approximately, to IR as well. However, CSSs 4 and 6 were not illuminated at the same time; rather, the midpoint CSS 6, on the –Y-axis, was lit second, and the CSS 4, on the trailing edge of the shield, was lit third. Figures 5 and 6 show how the time histories of the illumination of cold-side CSSs lined up with the changes in torque direction.

Putting the pieces together provides a coherent story of what happened during each perigee passage. When the +X-axis side of the shield was lit, the water sublimated and imparted a force to that side, resulting in a negative (nose-up) pitching moment. Because of orbit geometry, the nadir vector had a small –Y-component in the body frame. The result was that more of the +Y-side of the shield was shaded for longer, there was less sublimation on that side, and the balance of force provided a negative rolling moment. The time that this force was felt coincided with the lighting of the midpoint cold-side CSS 6. Finally, just before the maneuver, the nadir vector moved more into alignment with the –Z-axis (cold side) and the trailing side of the shield became exposed to Earth radiation; as the trailing side was lit, CSS 4 was illuminated, and the sublimation of frozen material created a positive pitching moment approximately equal to the earlier negative moment.

Predictive Modeling

An inverse dependence of mass deposition with time, $dm/m = -dt/\tau$, was expected as the system relaxed by outgassing to its final state. Since each IR heating event was of a similar illumination geometry and thermal profile, it was reasonable to assume that the peak momentum buildup would be proportional to the integral of the mass deposited since the previous event. Recalling that the material coming into contact with the blankets was frozen, we integrated probability to find the total amount of material available to provide torque at each IR heating encounter. The integral is given by the expression:

$$\frac{m(n)}{m_o} = e^{\frac{-t(n+1)}{\tau}} - e^{\frac{-t(n)}{\tau}},$$

where m_o is the total mass of material available for outgassing, τ is the outgassing time constant, and n is an index to denote each discrete heating event that clears the surfaces of deposited material.

In Table 2 and Figure 7 below, the observed momentum buildup and the buildup predicted by this simple model are compared. The time constant of $\tau \sim 9$ days was appropriate for the geometry and composition of the spacecraft for this portion of the anticipated outgassing profile. This is consistent with data obtained in thermal vacuum testing and previous flight experience.

Conclusions

Between the second and third perigee passes, a clear picture of how water outgassed from the thermal blanketing could be causing the anomalies had emerged. The theory was applied to knowledge of the spacecraft design and pre-launch environment to develop a predictive model. That model indicated that the force would no longer present a threat to the spacecraft; still, the team was ready to respond in case the model was in error. At the third perigee, the momentum levels observed corresponded well with the model (See Figure 8 for a comparison of the three perigee events). In addition, the model accurately predicted the occurrence of some small changes in system momentum at periselene—an event no one had otherwise foreseen.

By design, the thermal control coatings on the passively cooled portions of the structure radiatively cool much faster than the outgassing

time scales. For the MAP mission, the time interval between accumulation and subsequent reheating and ejection of the outgassing products was compatible with the overall attitude control capability. The maneuvers were, in the end, untroubled by the anomalies, and MAP is currently operating nominally in orbit near L_2.

Important lessons can be gained from this flight experience. Given actual constraints on ability to control the pre-launch environment for the spacecraft, the effect discussed above should be considered in mission design and planning for a cooled system. If ignored, systems with large, passively cooled surfaces and significant potential for outgassing could experience a loss of torque storage or software design margins. In the design phase, this effect can be mitigated by limiting the view of cryogenic surfaces to likely outgassing vent paths and exploration of mission profiles that allow the system to bake out in flight prior to the passive cooling phase. Alternatively, mission designers could build in periodic dumping by means of IR exposure to limiting the buildup of frozen material.

References

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Event	Day [J]	Time [days]	Momentum Magnitude [Nms]	Actual Torque	Model Torque
				[% of P1 values]	
Launch	181	0			
Earth P1	189	8	2	100%	100%
Earth P2	198	17	0.7	35%	42%
Earth P3	207	26	0.3	15%	14%
Periselene	211	30	0.1	5%	3%

Table 2: Comparison of actual observed torques with predicted torques from the water capture-and-sublimation model.
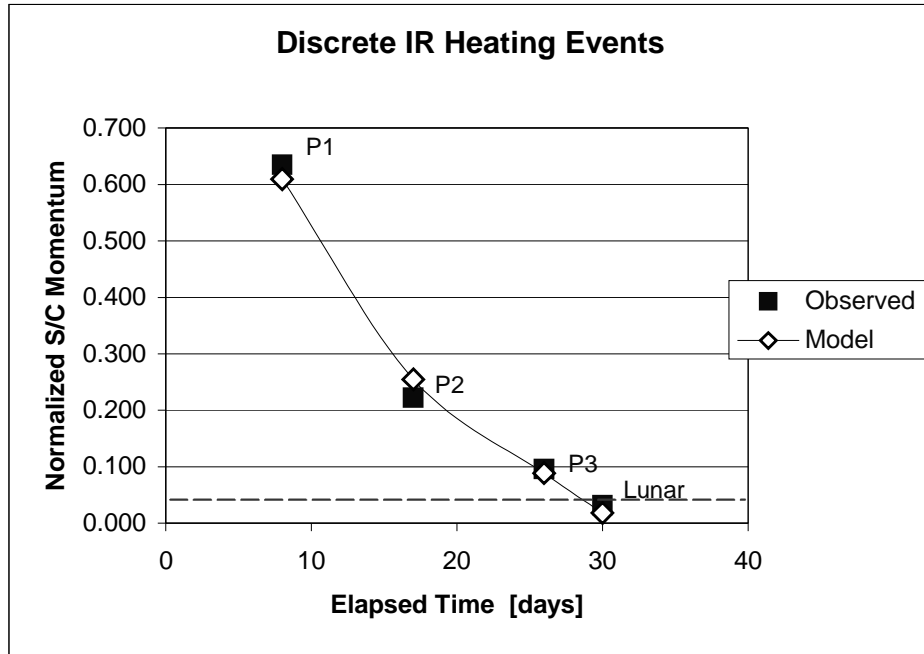
Discrete IR Heating Events

Figure 7: Comparison of actual torques with torques predicted by the water capture-and-sublimation model. Dashed line gives the potential strength of another event at L_2.

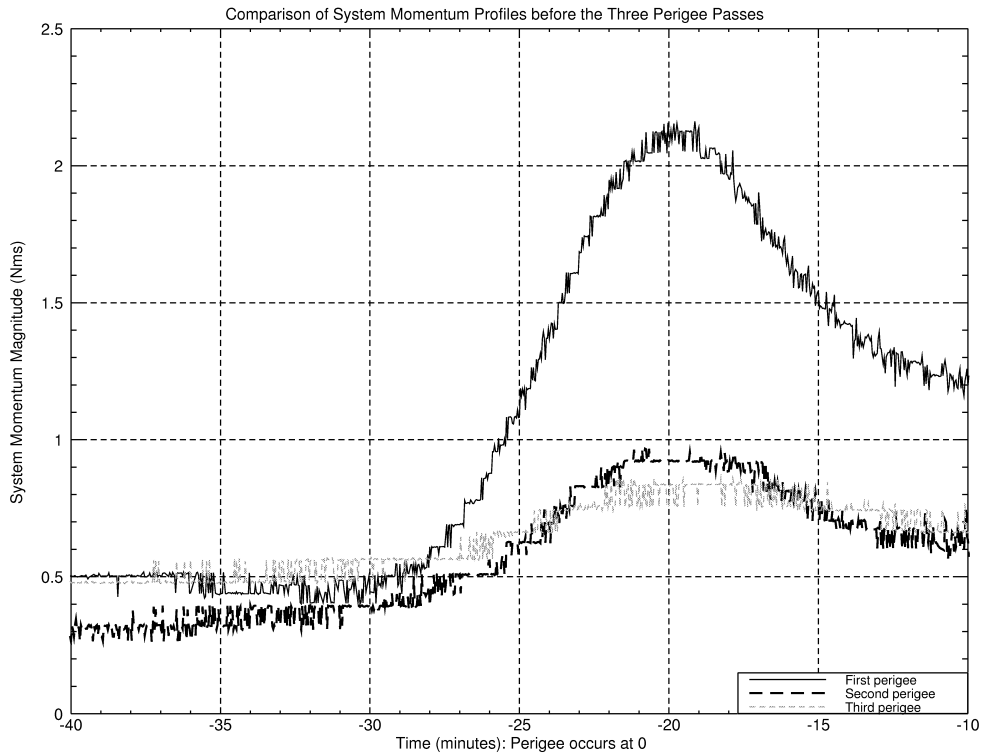Comparison of System Momentum Profiles before the Three Perigee Passes

Figure 8: System momentum magnitude profiles just before the three perigee maneuvers.

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