AN OVERVIEW OF TRAJECTORY DESIGN OPERATIONS FOR THE MICROWAVE ANISOTROPY PROBE MISSION

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Abstract

The purpose of this paper is to document the results of the pre-launch trajectory design and the real-time operations for the Microwave Anisotropy Probe (MAP) mission, launched on June 30, 2001. Once MAP was successfully inserted into a highly elliptical phasing orbit, three perigee maneuvers and a final perigee correction maneuver were performed to tailor a lunar encounter on July 30, 2001. MAP achieved its final Lissajous orbit (0.5° by 10.5°) about the Sun-Earth/Moon L2 libration point via this lunar encounter. This paper will show the maneuvers that were designed to arrive at the mission orbit. A further discussion of how the MAP trajectory analysts altered the pre-launch phasing loop maneuvers as well as the lunar encounter to meet all mission constraints, including the constraint of zero lunar shadows is also included.

Introduction

MAP is a Medium Class Explorers (MIDEX) mission produced in partnership between Goddard Space Flight Center (GSFC) and Princeton University. The primary goal of the MAP observatory is to measure temperature fluctuations (known as anisotropy) of the cosmic microwave background radiation over the entire sky between 22 and 90 GHz and to produce a highly sensitive, spatial resolution (approximately 3°) map. These data will be used to shed light on several key questions associated with the Big Bang theory and to expand the information provided by the National Aeronautics and Space Administration's (NASA) Cosmic Background Explorer (COBE) mission flown in the early 1990s. The MAP satellite will produce a much more detailed picture of the early universe than the COBE satellite. The MAP mission is exceptional from a trajectory perspective because it is the first mission to orbit the Sun-Earth L2 Lagrange point. The GSFC Flight Dynamics Analysis Branch (FDAB) within the Guidance, Navigation, and Control Center (GNCC), together with their contractors from *a.i. solutions, Inc.*, staffed a Trajectory Design Team that provided mission analysis, maneuver planning, and maneuver calibration in support of MAP.

MAP was launched from the Cape Canaveral Air Force Station Complex 17 aboard a Delta II 7425-10 expendable launch vehicle on June 30, 2001 at exactly 19:46:46.183 UTC. The spacecraft received a nominal direct insertion by the Delta launch vehicle into a highly elliptical orbit (185 km perigee) with a 28.7° inclination. A target launch energy (C_3) of -2.6 km^2/s^2 was chosen to minimize the impact of a large launch vehicle overburn[1]. In the following weeks, MAP executed a sequence of phasing loop perigee maneuvers and performed a lunar gravity assist in order to achieve its mission orbit about the Sun-Earth/Moon L2 Lagrange point, about 1.5 million km from Earth in the anti-Sun direction. MAP used the lunar gravity assist strategy since it reduced the fuel required to achieve the desired Lissajous orbit. The L2 Lissajous orbit was selected by the MAP program to minimize environmental disturbances and maximize observing efficiency. MAP has started its observation schedule and will continue to collect data for its nominal mission length of two years.

The MAP spacecraft (Figure 1) carries a single instrument, consisting of passively cooled, differential microwave radiometers with dual Gregorian 1.4 x 1.6 m primary reflectors. The wet spacecraft mass is 831 kg, including approximately 72 kg of usable propellant. The monopropellant hydrazine system consists of a single tank connected to eight 1-lbf thrusters which are employed for attitude and orbit control. MAP is a three-axis-stabilized spacecraft in ΔV mode, but spins while in observing mode. In its mission orbit, the MAP spin axis (the Z body axis) is maintained to point 22.5° of the spacecraft-Sun line while executing a compound spin. This compound spin consists of a "fast" spin of 0.5 revolutions per minute about the Z-body axis coupled with a slow one revolution per hour precession of the Z body axis about the Sun-line (Figure 2). The spin strategy will allow MAP to complete a full sky map after six months of operations at L2. NASA's Deep Space Network (DSN) was responsible for tracking MAP as well as providing the link for telemetry and command. The Tracking and Data Relay Satellite System (TDRSS) was used during launch and early orbit operations to assist in telemetry gaps during the phasing loop perigee passes.

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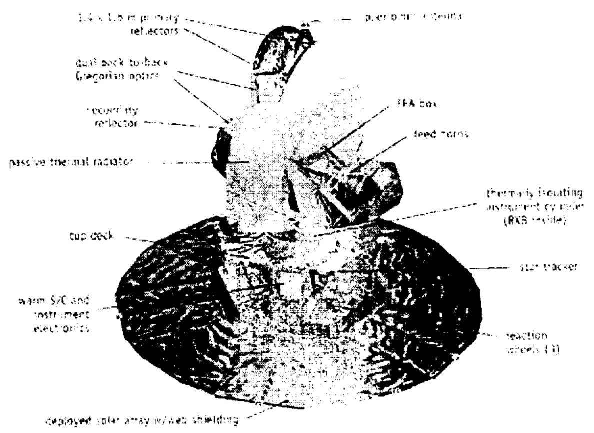

Figure 1: MAP Spacecraft

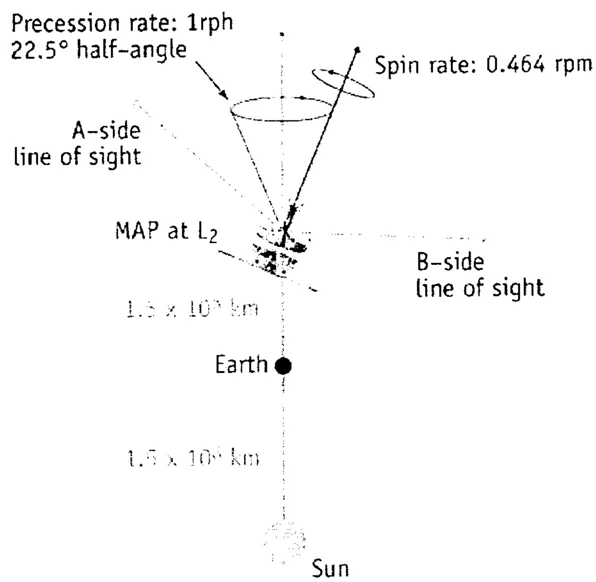

Figure 2: MAP Compound Spin at L2

MAP Trajectory Design

Designing a trajectory to meet the MAP mission goals while conforming to the performance parameters (e.g. propellant) of the spacecraft was a challenging enterprise. Early on in the mission design process, a lunar gravity assist with phasing loops was chosen as the method to achieve MAP's Lissajous orbit about L2. The lunar gravity assist method was chosen given the size of MAP's propellant tank and the lift capability of the Delta-II 7425. MAP's propellant tank was filled to capacity at 72.6 kg and was thereby limited in its ΔV capability. The phasing loop method of achieving the lunar gravity assist was chosen as a means to minimize the effect of launch vehicle errors on the success of the mission. Also, the phasing loop strategy allows time between launch and the lunar encounter, thus providing a longer launch window since the phasing loop periods can be adjusted by maneuvers to arrive at the chosen epoch and lunar phase angle with respect to the Sun-Earth line. It was determined that scenarios utilizing either 3 or 5 phasing loops (plus the final half-loop to meet the Moon) worked best for the trajectory design. Two loops were deemed too risky because of the fewer opportunities for error correction in the event of contingency. On the other hand, scenarios involving four loops were discarded because the launch vehicle errors subjected the trajectory to stronger lunar perturbations, requiring more ΔV for correction[2]. For any of the trajectories examined, a minimum perigee altitude of 500 km was observed to comply with attitude control limits. A schematic of a 3-loop case is shown in Figure 3. Most pre-launch maneuver scenarios were planned with deterministic perigee maneuvers at the first perigee (P1) and final perigee (Pf, where Pf is P3 or P5 in a 3-loop or a 5-loop case, respectively). Placeholders were kept for a final perigee correction maneuver (PfCM) (18 hours after Pf) and a mid-course correction (MCC) maneuver seven days after the lunar encounter. Nominally, both the PfCM and the MCC were zero and would only be executed as needed. Apogee maneuvers (at A1, A2, A3, A4, or A5) would be performed, as necessary, in order to comply with the minimum perigee requirement of 500 km. Small engineering maneuvers were performed in an attempt to characterize the different propulsion modes.

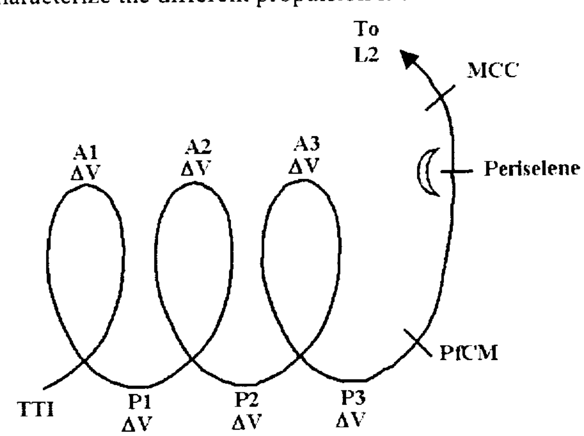

Figure 3: Schematic of MAP 3-Loop Scenario

The major trajectory design requirement for the MAP mission was to deliver MAP into a Lissajous orbit about the Sun-Earth/Moon L2 Lagrange point and maintain that orbit for at least two years. The size of the Lissajous orbit was defined by angle limitations off of the Sun-Earth line and was dictated by two factors. The minimum size (0.5°) was limited by the desire to keep MAP free from Earth shadows while orbiting L2. There was no need for expensive stationkeeping at L2 and, as such, the Lissajous orbit would be allowed to evolve through its natural pattern in a 14-year cycle. Therefore, every attempt was made to deliver MAP into an "opening" Lissajous orbit so as to delay the eventual passage through these small angles. The maximum size of 10.5° was required because of half-angle limits on MAP's X-band antenna while operating at L2.

Because the ΔV capability was restricted due to the filled propellant tank, a limit was placed on the ΔV to be made available during the phasing loop portion of the mission. After the removal of maneuver executions "taxes" (e.g. attitude control losses, impulsive-to-finite maneuver losses, cant angle losses, etc.), an impulsive ΔV budget of 70 m/s was allocated to the maneuvers required in the phasing loops. As an additional constraint to the mission design, the final perigee maneuver (Pf) was limited to 30 m/s. This was done in order to limit the size of PfCM as a result of execution errors at Pf. Therefore, by default; a cap of 15 m/s was set on the size of PfCM.

Further work was performed to meet the mission goal of minimizing lunar shadows during the cruise phase (from lunar encounter to Lissajous orbit insertion) and the mission phase at L2. Using an analytic model, it was determined that the lunar shadow duration and depth (% penumbral shadow) varied depending on whether the Moon was "opposite" (opposite the Earth from L2) or adjacent (between Earth and L2) – see Figure 4. Analysis revealed that adjacent lunar shadows typically had a maximum duration of 6 hours with a maximum depth of 13% while the opposite lunar shadows had a maximum duration of 8 hours with a maximum depth of 4.5%[3]. While these depths of shadow are relatively small, any changes to MAP's thermal stability were to be avoided. As MAP is passively cooled, any changes in the spacecraft's thermal characteristics would require a significant time (weeks) to return to normal. Through the design of the daily launch opportunities, it was observed that lunar shadows encountered during the cruise phase could be eliminated with small changes to the lunar encounter parameters, in particular, B•R (see Reference 4 for a thorough discussion of the encounter parameters). It was discovered that eliminating the lunar shadows while in the Lissajous orbit was more complicated. Changes in the lunar encounter parameters could be used to eliminate some shadows, but then others could appear further downstream. Therefore, it was decided to budget a small amount of ΔV for lunar shadow avoidance while at L2. Every attempt would be made to eliminate the lunar shadows using the lunar encounter, but, in the event that this was not possible, 20 m/s was allocated to avoid 2 shadow events per year (for the 2-year nominal mission). Analysis showed that a maneuver of approximately 5 m/s, normal to the ecliptic plane, was sufficient to eliminate a single shadow event[3].

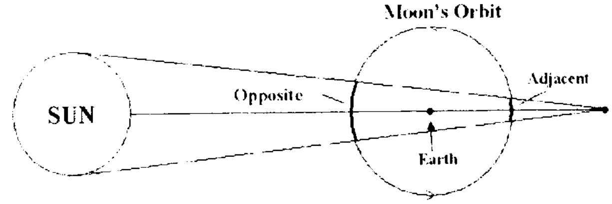

Figure 4: L2 Lunar Shadow Classification

Once all of these constraints were examined, the Trajectory Team proceeded to determine the days within the month for which a viable trajectory met all of these requirements. Three trajectories per day were verified against the constraints: a daily nominal, and the $\pm 3\sigma$ launch dispersion cases. This "end-of-box" method was determined to be sufficient to bound the analysis after a small Monte-Carlo analysis task was performed on the launch vehicle errors[5]. Days on which all three cases met constraints were considered valid launch dates, and corresponding injection parameters were supplied to the launch vehicle provider (Boeing). The next step was to expand the launch window about the daily nominal trajectory[6]. The was accomplished through the re-distribution of the perigee maneuver ΔV. As the launch time shifted, the phasing loop perigee maneuvers were used to target back to a suitable lunar encounter. At each step in the launch window expansion, checks were performed to ensure that these trajectories could also compensate for the $\pm 3\sigma$ launch vehicle dispersions. Daily launch windows varied from 4 to 20 minutes, depending on the launch day. In the end, approximately 10 days per month (in two blocks of consecutive days) were found to satisfy all of the MAP trajectory requirements. This typically included 6, 3-loop days and 4, 5-loop days, where the 3-loop and 5-loop blocks were separated by, roughly, 10 days. Figure 5 shows the possible MAP launch dates (showing the required phasing loop ΔV) given all of the mission constraints.

Previous work in the discipline of libration point orbit design is presented in the sources listed in the Bibliography at the end of the paper.

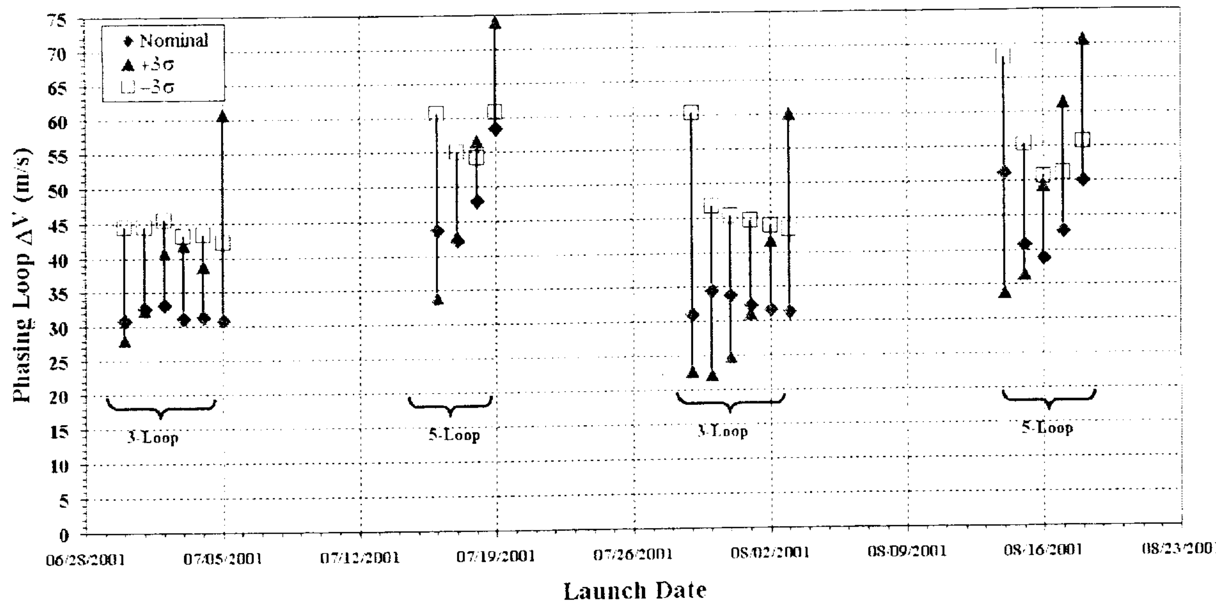

Figure 5: MAP Launch Opportunities for June, July, & August

During pre-launch activities, the Maneuver Operations Team identified the need for several engineering maneuvers to test the propulsion system. These engineering maneuvers were to test the different thruster configurations that would be used during the actual phasing loop and stationkeeping burns. These configurations are listed in Table 1 and the thruster locations are shown in Figure 6. It is important to note that all of MAP's eight thrusters were included in the maneuver control logic and were available to fire as necessary for stability.

The +X maneuvers were used for the major phasing loop maneuvers: the perigee maneuvers (to target the lunar encounter) and the apogee maneuvers (to comply with MAP's 500 km perigee requirement). All MAP maneuvers using the +X thrusters were performed using a command quaternion table (CQT) to point the spacecraft. The CQT was used to allow the +X thruster firings to follow the velocity vector during the maneuvers. MAP's low-thrust of 4-lbs (using thrusters 5, 6, 7, & 8) during the +X maneuvers necessitated this implementation. The CQT contained predicted attitude quaternions from 30 minutes prior to two hours after the maneuver, at 1° increments. These maneuvers were executed in the "Velocity-Sun" frame where the +X axis is aligned with the velocity vector and the +Z body axis is in the direction of the Sun, in the plane made by the velocity vector and the MAP-Sun vector. This orientation ensured that the Sun would be visible in MAP's digital sun sensor (DSS) assembly. The DSS was used as a backup rate source during the maneuvers in the event of a gyro failure. Prior to the maneuver, the spacecraft pitched 7.5° about the +Y body axis so that the net +X maneuver thrust was aligned with the velocity vector (thrusters 7 & 8 are aligned 15° off of the +X body axis).

Maneuvers using the ±Z thruster configurations were performed in an inertial attitude. At L2, the orientation required pointing the spacecraft Z body axis 19° off of the Sun-line. Careful selection of the precession angle about the Sun-line allowed for optimization of the maneuver.

After each maneuver was executed, tracking data was collected in support of thruster calibration. The calibration work involved the calculation of a thrust scale factor (TSF) for that particular maneuver. An initial value of 1.0 was used as the TSF for each maneuver configuration. This value was changed after each configuration was utilized. The calibrated TSF after a maneuver incorporates a combination of propulsion system performance and any orbit uncertainties included in the post-maneuver orbit determination. No attempt was made to calibrate an individual thruster. The TSF value computed corresponding to a particular maneuver was used in planning subsequent maneuvers of similar duration. Separate TSF's were used for each of the three thrust configurations (+X, +Z, and -Z).

Table 1: **MAP Thrust Configurations**

Thrust Direction	Thrusters	Primary Use
+X	5,6,7, and 8	Phasing loop maneuvers
+Z	3 and 4	L2 Stationkeeping
-Z	1 and 2	L2 Stationkeeping

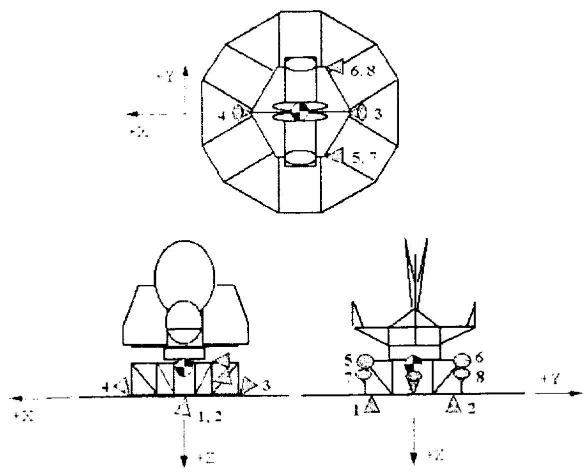

Figure 6: **MAP Thruster Diagram**

MAP Launch and Early Orbit Operations

This section of the paper discusses the operations activities that span the time from launch until the second stationkeeping maneuver (SK2). These activities include the modification of the trajectory to remove lunar shadows, the planning of all maneuvers (both perigee maneuvers and engineering burns), as well as the calibration of the maneuvers.

Launch

The MAP launch date of June 30, 2001 was the first day of the July 3-loop launch period. The actual lift-off time was 19:46:46.183 UTC – less than a quarter of a second after the pre-launch planned launch time. Although the launch was nearly nominal, the Second Stage Engine Cut-Off (SECO)-1 burn occurred 6 seconds later than expected as the second stage automatically extended its burn time to ensure the vehicle reached the proper parking orbit. All the early orbit acquisition data was based on the actual SECO-1 data due to a problem with receipt of usable Delta II inertial guidance data from the third stage. However, the MAP Navigation Team personnel were able to get a preliminary OD solution based on TDRS and DSN tracking data by 22:33 UTC. The Trajectory Team then used the 6- and 12-hour orbit determination solutions to update the MAP trajectory and to verify that the Delta insertion was near nominal.

The pre-launch parameters for the phasing loop maneuvers and for the lunar encounter are shown in Table 2. At the top of the table, the perigee events are shown with their associated maneuver magnitudes. For this launch date/time, the total phasing loop ΔV required was 29.47 m/s. At the bottom of Table 2, the lunar encounter parameters are shown at periselene (the closest approach to the Moon). No apogee maneuvers were required for the nominal launch case.

Table 2: **Pre-Launch Predicted Maneuvers and Lunar Encounter Parameters**

Maneuver	Date (UTC)	ΔV (m/s)
P1	07/08/2001 02:08	20.73
P2	07/17/2001 04:15	0.00
P3	07/26/2001 07:27	8.74
P3CM	07/27/2001 01:27	0.00
	Total	29.47
Periselene		
Date (UTC)	07/30/2001 17:04	
Radius (km)	6418	
B•T (km)	12632	
B•R (km)	-1642	

Using the post launch orbit determination solutions, the Trajectory Team re-targeted the pre-launch nominal planned trajectory for June 30th using the actual launch time. Fortunately, this trajectory was subject to beneficial lunar perturbations and all three perigees (P1, P2, and P3) were well above the minimum 500 km requirement. Therefore, there was no need for a "perigee raising" maneuvers to be performed at any of the phasing loop apogees. Further examination of this updated trajectory proved the pre-launch prediction that there was a lunar eclipse event in the cruise phase of the mission. Furthermore, two lunar eclipse events were also seen to occur while at L2 - one during the first half-revolution about L2, and a second during the first half-rev of the third year of the mission. All trajectories at L2 were predicted through four years from insertion in order to satisfy the goal for a two-year extended mission. All of these shadows were of the "opposite" type (as described above) and had durations of 4 – 5 hours with depths of 2% - 4 % (Table 3). While most spacecraft would be able to "fly through" this type of eclipse event, it was decided to examine how the trajectory could be modified to meet that goal of limiting lunar eclipse events due to MAP's thermal stability requirements.

Table 3: Predicted MAP Shadow Events Immediately After Launch

Eclipse Event Date	Location	Duration (hr)	Max. Depth of Eclipse
10/17/2001	Cruise	5	4.0%
01/13/2002	1st Half-Rev, Y1	4	2.5%
01/20/2002	1st Half-Rev, Y3	4	3.2%

As mentioned above, the phasing loop maneuvers were used to alter or "shape" the lunar gravity assist until the desired goal of eliminating the shadows at L2 was achieved. Hopefully, the shadows could be removed without inducing new shadows at different points in the L2 orbit. This method was chosen as a result of the experience gained from designing the MAP launch opportunities. The MAP trajectory analysts initiated a parametric search by varying the phasing loop ΔV magnitudes to alter the periselene B•R value. It had been seen that achieving different values of B•R could change the phase of the Lissajous orbit. In changing the phase, the timing between the positions of the spacecraft and of the Moon with respect to the Sun could be changed sufficiently to remove the eclipse events. Careful analysis showed that shaping the gravity assist such that B•R = -2100 km (the original value was −1642 km) could eliminate the eclipses. In order to accomplish this, small changes to the perigee ΔV maneuvers were needed. The B•R value of −2100 km was chosen such that there was a buffer of ±100 km before shadows appeared. This buffer provided some margin on the actual lunar encounter achieved during the mission. The perigee maneuvers and the periselene parameters for the "no-shadow" trajectory are shown in Table 4.

Table 4: Maneuver and Lunar Encounter Parameters for No-Shadow Trajectory

Maneuver	Date (UTC)	ΔV (m/s)
P1	07/08/2001 02:08	21.14
P2	07/17/2001 05:26	0.00
P3	07/26/2001 09:46	8.58
P3CM	07/27/2001 03:46	0.00
	Total	29.72
	Periselene	
Date (UTC)	07/30/2001 16:40	
Radius (km)	6807	
B•T (km)	-2100	
B•R (km)	13018	

A comparison of both Table 2 and Table 4 show that shaping the gravity assist has increased the P1 ΔV and decreased the P3 ΔV with a net increase in the total perigee ΔV of only 25 cm/s. The epoch times for both P2 and P3 have changed by no more than a two hours while the time of periselene has remained nearly constant – only a 24-minute change. Hence, the Sun-Earth-Moon geometry for the gravity assist was maintained while the angle at which MAP approaches the Moon (B-plane parameters) and the close approach radius (the periselene radius increased by nearly 400 km) was altered. More importantly, these modifications to the maneuver strategy have eliminated all lunar shadows from the cruise phase to L2 and from the entire trajectory for four years around L2. This ability to redistribute the ΔV at the perigee maneuvers shows the power of using phasing loops to help achieve MAP's mission goals.

+X Engineering Maneuver

Prior to launch, it was decided that each of the engineering burns (to test out the three thruster configurations) should be long enough for both the propulsion system and the attitude control system to reach steady state. Each thruster configuration would be tested prior to its first use for a critical maneuver and that tests would occur at a point in the orbit that maximized observability from the tracking stations. At the same time, the maneuvers would be designed to minimize adverse effects on the orbit. Using these criteria, the +X thrusters were planned for testing on Day 2, prior to A1. Due to a small contingency and because a perigee raising maneuver was not required at A1, it was decided to perform the +X engineering maneuver at A1 (Day 3 instead of the Day 2 plan). This plan allowed some flexibility in accommodating some spacecraft health and safety procedures during Day 2 of the mission. Since this engineering burn was also designed to test the procedures to be applied at perigee, some small modifications needed to be made to apply these procedures at A1. The burn was planned along the velocity vector and since the spacecraft moves more slowly at apogee than at perigee, the attitude would not experience a major variation, resulting in a relatively constant commanded spacecraft quaternion. Thus, in order to mimic the attitude changes at perigee, the trajectory design team generated a set of quaternions consisting of three 1°- transitions at 25-second intervals for the ACS. This approach successfully allowed the testing at apogee of the command quaternion capability to be experienced at perigee.

The planned 2.019 m/s, 102-second maneuver went very smoothly, with rate and attitude transients about 60% of predicted and an attitude hangoff of only 3.7°– compared to the predicted 5.5°. The attitude hangoff is the steady-state control error experienced during the maneuver. After collecting 24 hours of post-burn tracking data, the Navigation Team provided the Trajectory Team with an updated orbit state, which they used to calibrate the burn and estimate a TSF of 0.950. This maneuver had been planned with a TSF of 1.0 since this was the first time this thruster configuration was used during the mission. The actual ΔV and duration for the +X engineering burn were 1.92 m/s and 106.32 seconds, respectively. The total duration of this maneuver was increased because thruster 4, which has a component of it's thrust vector opposite to the main +X thrusters, was required to pulse in order to maintain pitch control about the body Y-axis. This control necessitated increased firing of the +X thrusters in order to provide the correct ΔV. The attitude control software compensates for this during all maneuvers by increasing the executed burn duration accordingly.

P1 Maneuver

After assessing the "cold" +X engineering burn, the P1 maneuver magnitude changed to 22.230 m/s (with a duration of 1229 seconds), easily the largest maneuver planned for MAP. Therefore, the majority of the P1 planning work involved contingency analysis of what would happen if the maneuver were delayed, aborted, or missed altogether[7], in addition to deciding what TSF to use. Because the duration of the calibration maneuver at A1 was relatively short, it was unclear if the thrusters would perform in a similar way for a much longer maneuver. Thus, a TSF of 1.0 was chosen for planning the first perigee maneuver.

The P1 maneuver used the +X thrusters (5,6,7, and 8) and occurred as planned on July 8th at approximately 04:43:40 UTC. The maneuver lasted approximately 1274.44 seconds and had a computed ΔV magnitude of 20.194 m/s. Again, the increase in duration from the plan was due to on-board compensation by the ACS impulse controller. During the burn, an attitude hangoff of about 3.8° (lower than expected) was noticed. This was probably caused by the fact that both the plume torque and center-of-mass computed values were lower than the preflight computed values. Reconstruction results indicated, as predicted, that the burn was slightly cold. Using the +15 hour orbit determination solution, the Trajectory Team calibrated the P1 maneuver and obtained a TSF of 0.956. This TSF is very comparable to the TSF achieved during the A1-cal burn, indicating that the propulsion system performance was very repeatable over a wide range of burn durations.

±Z Engineering Burns

Locations for testing the ±Z thrust configurations were also determined prior to launch. However, the plans were altered right after launch because it was determined that there was too much to be accomplished during the first three days of the mission. At the P1 maneuver debriefing, the MAP team decided to perform the ±Z maneuvers as simulated stationkeeping maneuvers at A2 and A3 instead of the locations originally chosen. There was a concern that the trajectory was very sensitive to small changes in ΔV, and it was deemed unwise to risk imparting energy that might disturb the trajectory unnecessarily. The purpose of the engineering burns was to make sure that thrusters 3&4 and 1&2 configurations perform as expected. Since the +Z and -Z thruster configurations were not needed prior to the first SK maneuver, performing the burns at A2 and A3, respectively, allowed plenty of time to calibrate the thruster configuration sets before they were needed.

Based on the achieved performance of the ACS controller, it was determined that a 40-second burn duration was sufficient to confirm steady-state performance of the system and the change was made relative to the +X engineering burn. The +Z engineering burn was performed at the nominal stationkeeping attitude (Z-axis 19° of the S/C-to-Sun line) to determine the thermal effects that would occur during a stationkeeping maneuver at L2. This was the first burn to be executed without a CQT and using a single fixed attitude. The planned magnitude of this maneuver was approximately 0.27 m/s and was planned with a thrust scale factor of 1.0, since it was the first time this configuration was used during the mission. After sufficient tracking data had been collected, a TSF of 0.936 was computed

The -Z engineering burn was also planned with a duration of 40 seconds and it was executed at A3. Despite the cant of thrusters 1 and 2 (10° off of the Z-axis), the -Z thrusters performed very much like the others, with pointing errors in the X- and Z-axes of less than 1° and an expected 3° hangoff in the Y-axis[8]. Once again, a TSF of 1.0 was used for planning this engineering burn, since it was the first time this configuration was used during the mission. It was expected that the Y-axis errors would be larger than at A2 because of the cant of the thrusters; however, the maneuver execution was very similar to that of the +Z engineering burn. After sufficient tracking data had been collected, a TSF of 0.967 was computed.

P2 Maneuver

Since the P1 maneuver was a little "cold", it was decided to insert another maneuver into the planned trajectory at the second perigee (P2) instead of waiting until the final perigee (P3) to make up for the ΔV. The mindset for this strategy was to help mitigate the risk in case there was a non-nominal burn at the third and final perigee. The planned magnitude for the P2 burn was 2.5 m/s and had a duration of 169.6 seconds. To prepare for this maneuver, the ACS team took data from previously executed burns and estimated the plume impingement and center of gravity migration needed to match simulated data to the on-orbit data. The estimates were fed back to the simulators to improve the team's planning accuracy for the P2 maneuver and the final perigee maneuver, P3, and, thus, minimize the PfCM. The results indicated that each of our pre-burn planning tools consistently predicted the thruster duty cycles and pointing errors during the maneuver planning process. The P2 maneuver was planned using a TSF of 0.94 and occurred nominally on July 17th at approximately 03:36 UTC. The maneuver had a magnitude of 2.51 m/s and it lasted approximately 177.25 seconds. Using a 16-hour orbit determination solution, the Trajectory Team calibrated the burn and determined a TSF of 0.950. Once again, this value was very comparable to the TSF achieved for the +X calibration burn.

P3 and PfCM Maneuvers

The next burn was the final perigee maneuver (P3), designed to provide a final velocity boost so that the spacecraft would achieve the desired time and location for the lunar encounter. The P3 burn magnitude was planned to be 7.35 m/s with a duration of approximately 522.8 seconds. The main focus of the planning of this critical burn was what to do in the case of a P3 contingency, since any errors would have to be corrected within 36-hours. Since the lunar encounter was only about three days after P3, any maneuver errors could result in a very expensive correction maneuvers. Thus, the P3/PfCM pair became very critical for mission success. The final perigee maneuver was planned with a TSF of 0.95 and was executed as planned on July 26th at approximately 10:29:50 UTC. The maneuver was nominal, with a magnitude of 7.41 m/s and a duration of approximately 546.16 seconds. After a preliminary assessment of the maneuver, it was determined that a small PfCM would be needed to guarantee an accurate encounter with the Moon. The Trajectory Team calibrated the P3 maneuver using a 6-hour post-maneuver orbit solution and calculated a TSF of 0.951. Several hours after the maneuver, a new orbit solution was generated and we were able to confirm the preliminary results. Thus, it was determined that MAP required a PfCM of only 0.273 m/s, which translates to a duration of less than 25 seconds. Better still, the required correction maneuver would be a retrograde burn, meaning that the spacecraft could remain within the desired 45° Sun-line- cone and not have to burn in a direction off the velocity vector. This resulted in less exposure of the shaded area of the observatory to the Sun, which minimized the risk of hardware degradation due to thermal shock[8].

The PfCM was planned not only to correct for small P3 errors, but also to minimize any further corrections between the swingby and the L2 Lagrange point. This small maneuver will ensure an accurate encounter with the Moon. The maneuver was planned strictly along the velocity direction, eliminating the need for any burn in the normal direction. Had there been a larger correction needed, it might have necessitated yawing MAP out of the orbit plane to provide a ΔV component in the normal direction. However, since the correction was small, a burn only in the velocity direction was required. There are some advantages with this strategy. First, this orientation makes the maneuver planning much more straightforward because the attitude constraints are much easier to meet. Second, the maneuver was more efficient since there was no out-of-plane ΔV incurred. As a result, this burn would result in a slightly different B•R value of -2112 as opposed to the current value of -2100. This is well within the margin on B•R before another lunar shadow would appear. PfCM was executed, as planned, 18-hours after the P3 maneuver. The actual magnitude of the maneuver was 30.8 cm/s and it lasted approximately 24 seconds. A preliminary reconstruction of the maneuver indicated that the burn was nominal and that MAP was on its way to L2. The TSF for this burn was determined to be 0.936.

Phasing Loop Maneuver Summary

The final results for the phasing loop maneuvers and the periselene parameters are shown in Table 5. Overall, the perigee times have changed on a scale of a couple of hours. The total ΔV expended in the phasing loops has increased slightly, mostly due to the addition of the engineering burns. Comparing Table 4 and Table 5 we see an increase in ΔV of only 2.5 m/s, discounting the $\pm Z$ engineering burns. These two burns are not being considered because they were executed primarily perpendicular to the velocity direction and therefore did not increase the orbit energy. Furthermore, because of their opposite orientations, they tended to cancel each other. On the other hand, the +X engineering was executed directly along the velocity vector at A1. This maneuver did add energy to the orbit but the effect was small due to its inefficient execution at apogee. The lunar encounter time changed by only three minutes and the periselene radius and B-plane parameters were also very close too, exhibiting changes in the "tens" of kilometers. Regardless, the total ΔV expended in the phasing loops, 32.89 m/s, was much lower than the pre-launch limit 70 m/s. The remaining ΔV saved during the phasing loops is now available for operations out at L2.

<u>Table 5:</u> Final Map Maneuver Magnitude and Periselene Parameters

Maneuver	Date (UTC)	ΔV (m/s)
A1 (+X Cal)	07/04/2001 13:22	1.92
P1	07/08/2001 02:08	20.19
A2 (+Z Eng)	07/12/2001 16:11	0.25
P2	07/17/2001 05:26	2.51
A3 (-Z Eng)	07/21/2001 18:54	0.30
P3	07/26/2001 09:46	7.41
P3CM	07/27/2001 03:46	0.31
	Total	32.89

Periselene	
Date (UTC)	07/30/2001 16:37
Radius (km)	7017
B•T (km)	13332
B•R (km)	-2112

Post-Lunar Encounter

The lunar encounter occurred as planned on July 30th at approximately 16:37 UTC. The actual B-plane parameters were B•T = 13332 km, and B•R = -2112, bringing the spacecraft to approximately 5280 km from the lunar surface. The accuracy of the encounter ensured that the spacecraft trajectory could be easily maintained with small ΔV corrections and meet all the Lissajous orbit requirements, including no Earth or lunar shadows.

While the gravity assist happened as planned, a small Mid Course Correction maneuver (MCCM1) was added to the baseline trajectory. A slight correction was required since small errors incurred prior to the lunar swingby were now magnified (during the gravity assist) and could grow to an unreasonable amount if the correction were done later. The maneuver was planned using the +Z thrusters (3 & 4), much like a station-keeping maneuver. Analysis was performed to determine the best attitude orientation for the maneuver and showed that burning directly along the anti-velocity vector was preferable to maintaining the 19° off point from the Sun-line – the typical stationkeeping attitude. This maneuver was planned with a thrust scale factor of 0.936, a magnitude of 0.104 m/s and a duration of, approximately, 18 seconds. The MCCM1 occurred as planned on August 6th at 16:37 UTC. It lasted exactly 18 seconds and had a magnitude of 0.103 m/s. The Trajectory Team waited one week in order to get a good and stable post maneuver state for calibrating the MCCM1 maneuver. The thrust scale factor was determined to be 0.928.

A second Mid-Course Correction maneuver (MCCM2) was added to make up for a small MCCM1 underburn and get back to our nominal Lissajous. The plan was to execute this maneuver prior to the first Jupiter calibration scheduled to take place from the end of September through mid-November. The planned maneuver had a magnitude of 0.043 m/s and a duration of approximately 6.44 seconds. If we waited until after the first Jupiter calibration to perform the maneuver, the magnitude would have grown to 2.5 m/sec. A maneuver of that magnitude would be easy to perform; but it would have interrupted the scientists' intended thermal balancing period. Weighing the trades, the project decided to complete the burn two weeks before the first Jupiter calibration on Sept 14th at approximately 16:37 UTC. Impulsive planning of the burn indicated that it would be along the -Z-axis, similar to the engineering burn performed at A3. The desired attitude placed the spacecraft Z-axis 19° from the Sun-line, with the Z-axis moving further away from the Sun-line as the maneuver was executed, due to the attitude hang-off. Furthermore, previous analysis showed that thrusting as much as possible along the SEM-L2 frame +X-axis was the optimal direction for the thrust. Thus, the Trajectory Team analyzed different attitudes and determined the optimum orientation to perform the maneuver. The maneuver occurred as planned on September 14th at approximately 16:37 UTC. Its magnitude was 0.042 m/s and it lasted approximately 6.6 seconds. Initial reconstruction using the pre-maneuver OD solution verified the results; however, we waited two weeks in order to get a good and stable post-maneuver orbit state for calibrating the maneuver. Calibration yielded a TSF of 0.953.

The first stationkeeping maneuver (SK1) was performed on January 16th, 2002 at 16:50 UTC. This maneuver fired the +Z thrusters (3 & 4) for 72.96 seconds, achieving a ΔV of 42.9 cm/s. As with all stationkeeping maneuvers, the maneuver was performed at an attitude where the body Z-axis remains within 19° of the MAP-Sun line. A TSF of 0.936 was used for planning and 0.2 kg of fuel was consumed. Despite calibrating MCCM1 with a TSF of 0.928, it was decided to plan SK1 using a TSF of 0.935 after discussion with MAP subsystem personnel. After two weeks of tracking data was collected, the SK1 maneuver (42.9 cm/s) was calibrated with a TSF of 0.950. The magnitude of SK1 is much less than the pre-launch allocation of 1 m/s per stationkeeping maneuver. The successful execution of this maneuver ensured that there would be no interruption during the second instrument calibration event with Jupiter scheduled for February through April of 2002.

The second stationkeeping maneuver (SK2) was executed on May 8, 2002 using the -Z thrusters (1 & 2). Pre-maneuver planning assumed a TSF of 0.97 and estimated a maneuver magnitude of 38.8 cm/s, a duration of 49.5 seconds, and a fuel loss of 0.13 kg. The maneuver was executed nominally with post-maneuver calibration yielding a preliminary TSF of 0.98. The next stationkeeping maneuver (SK3) is currently planned for August 2002.

Summary and Current Status

MAP has successfully completed its lunar encounter and is now in its lissajous orbit about L2 (Figure 7). A summary of all MAP maneuvers can be seen in Table 6. Fortunately, MAP did not experience any major contingencies and only consumed 14.7 kg of propellant – only 20% of the total propellant. As can be seen from the results presented in this paper, the actual flight ΔV numbers compared extremely well with the pre-launch predicted values. MAP has sufficient propellant to stationkeep for a 2-year extended mission and beyond. Unfortunately, MAP's Lissajous orbit evolution will allow the trajectory to cross into the Earth's penumbra after 6 years. Such a shadow (length of almost 3 days with a depth of 43%) would be catastrophic given the size of MAP's battery, which was only sized to handle energy storage needs on the launch pad. An out-of-plane maneuver at L2 could allow MAP to jump over such a shadow, however, such a strategy has not been examined at this time.

To date, the MAP mission has been a complete success. At the time this paper was written, MAP collected enough data to complete a full-sky map of the cosmic microwave background radiation. After much data analysis, the first full-sky map should be released near the beginning of 2003.

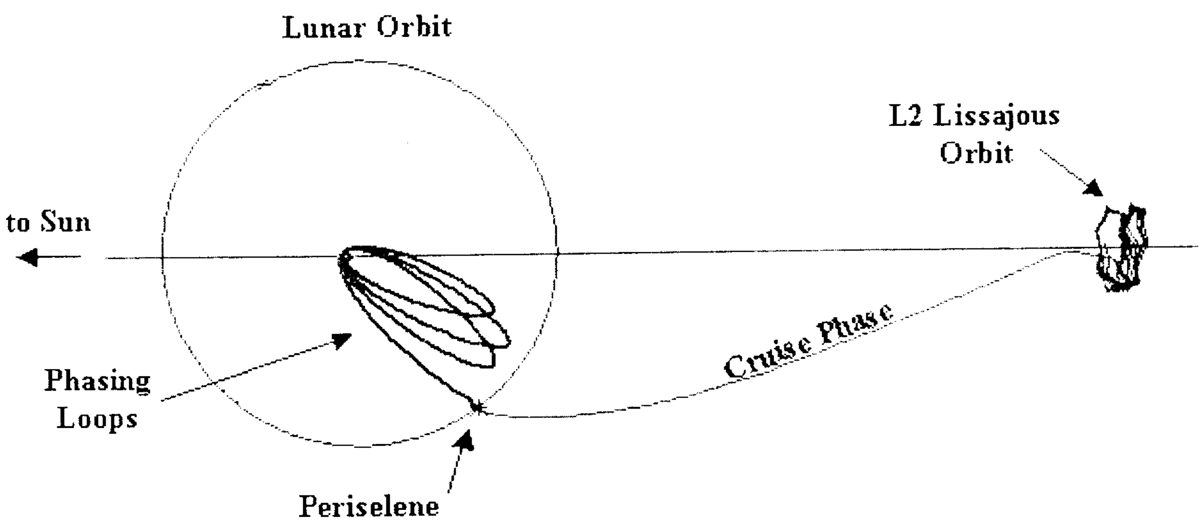

Figure 7: MAP Trajectory to L2 (in Solar Rotating Coordinate Frame)

Table 6: Summary of MAP Maneuvers

Maneuver	Date	Planned TSF	Achieved TSF	Delta-V (m/s)	Fuel Usage (kg)	Duration (sec)	Thrusters Used
A1	07/04/2001	1.000	0.950	1.92	0.84	106.32	+X
P1	07/08/2001	1.000	0.956	20.19	8.76	1274.44	+X
A2	07/12/2001	1.000	0.936	0.25	0.12	40.64	+Z
P2	07/17/2001	0.940	0.950	2.51	1.11	177.25	+X
A3	07/21/2001	1.000	0.967	0.30	0.14	43.44	-Z
P3	07/26/2001	0.950	0.951	7.41	3.23	546.16	+X
PfCM	07/27/2001	0.950	0.936	0.31	0.14	23.92	+X
MCC1	08/06/2001	0.936	0.928	0.10	0.05	18.00	+Z
MCC2	09/14/2001	0.920	0.953	0.04	0.02	6.60	-Z
SK1	01/16/2002	0.935	0.950	0.43	0.20	72.80	+Z
SK2	05/08/2002	0.970	0.982	0.34	0.16	53.80	-Z
			Total	**33.80**	**14.77 of 72kg**		

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