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STATIONKEEPING APPROACH FOR THE MICROWAVE ANISOTROPY PROBE (MAP)*

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The Microwave Anisotropy Probe was successfully launched on June 30, 2001 and placed into a Lissajous orbit about the L2 Sun-Earth-Moon libration point. However, the L2 libration point is unstable which necessitates occasional stationkeeping maneuvers in order to maintain the spacecraft's Lissajous orbit. Analyses were performed in order to develop a feasible L2 stationkeeping strategy for the MAP mission. The resulting strategy meets the allotted fuel budget, allowing for enough fuel to handle additional fuel taxes, while meeting the attitude requirements for the maneuvers. Results from the first two stationkeeping maneuvers are included.

INTRODUCTION

The Microwave Anisotropy Probe (MAP) was successfully launched on June 30, 2001 into a series of phasing loops, which terminated with a lunar gravity assist (LGA). The effect of the LGA was to transition MAP into a Lissajous orbit about the L2 Sun-Earth/Moon-barycenter libration point about 1.5 million kilometers from the Earth in the anti-Sun direction at the beginning of October 2001. This type of orbit was selected for the mission in order to minimize environmental disturbances and maximize observing efficiency.[1] The particular Lissajous orbit selected for MAP enables the Sun-Earth-Vehicle (SEV) angle requirements to be met for an extended mission lifetime; a two-year requirement in the Lissajous orbit plus two additional years beyond that with no Earth shadows. The Lissajous orbit was designed such that the SEV angle, which is the angle between the Sun-Earth line and the Earth-to-spacecraft vector, will remain greater than approximately 0.5 degrees and less than 10 degrees. The lower bound is for Earth shadow avoidance and the upper bound is to maintain communications link margins. However, the L2 libration point is unstable and MAP would tend to "fall out" of its orbit, thus violating these requirements, if no measures were taken to periodically stabilize its trajectory. The desired stability is achieved through the use of periodic stationkeeping maneuvers, which maintain the spacecraft's quasi-periodic motion by essentially balancing the trajectory's energy. Analyses were

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performed in order to develop a feasible L2 stationkeeping strategy for the MAP mission. The aim of this analysis was to determine the fuel allocation that MAP must carry to cover the stationkeeping phase of its mission. Due to MAP's limited fuel capacity and the large delta-V requirements of the phasing-loops, an accurate allocation was vital.

The problem of how to perform stationkeeping maneuvers around the L1 and L2 Lagrange points has been studied extensively.[2,3,4,5] From this theoretical work it is clear that maneuvers constrained to be along a coordinate axis of the rotating libration point (RLP) coordinate system, are most fuel-efficient if they coincide with the X-axis. The RLP frame[6] will hereafter be referred to as the Sun-Earth-Moon L2 coordinate frame (SEM L2) in keeping with the usage on MAP. Geometrically, the X-axis is very nearly along the Earth-Sun line. In fact, it has been shown that performing maneuvers along the SEM L2 X-axis is almost as efficient as unconstrained optimized maneuvers with components along each of the three axes.[5] Thus, based on these works, the SEM L2 X-axis was deemed the ideal direction for stationkeeping maneuvers.

However, obtaining estimates of the fuel usage from the same works presented a greater difficulty. Each of the analyses performed above was based on the restricted-three-body problem and did not take into account the presence of the Moon and the perturbations due to solar radiation pressure. Moreover, these theoretical studies have predicted a wide range of delta-V budgets for stationkeeping control, some as low as 0.25 m/sec or less[2]. In practice, most operational propulsion systems have execution uncertainties in the cm/sec range, which invalidates the optimistic estimates, not to mention the operational constraints that usually restrict the maneuver direction.

A historical survey of actual flights to the Lagrange points was then performed. There have been three spacecraft that have been placed into orbits about libration points, in each case about the L1 point. They are the International Sun-Earth Explorer (ISEE-3), the Solar Heliospheric Observer (SOHO), and the Advanced Composition Explorer (ACE). SOHO and ACE are still in their respective orbits. Results of stationkeeping maneuvers from all three missions have been carefully documented.[7] The results are varied. ISEE-3 averaged 2 m/sec per maneuver and 82 days in between each maneuver. SOHO results varied over the first eight stationkeeping maneuvers by almost two orders of magnitude. ACE results were somewhat more consistent but still varied by almost an order of magnitude. This is not surprising considering the differences in hardware, mission constraints, and various operational problems of each spacecraft. Additionally, ISEE-3, SOHO, and ACE all had a much greater fuel budget than that of MAP, which meant that fuel allocation and estimation on MAP could not employ the margins that were used on the other missions. This variance in the stationkeeping maneuver results coupled with the differences in predicted results from theoretical analyses, led to a determination that previous flight results were too inconsistent to be applied to the MAP mission.

In addition, MAP is subjected to certain unique attitude and operational requirements that must be modeled in order to accurately determine the fuel allocation. First, MAP is limited in its ability to perform maneuvers in an arbitrary direction. Specifically, the +Z-axis of the spacecraft must remain 19 degrees from the spacecraft-Sun line during each maneuver to accommodate thermal requirements (including a 5-degree attitude control margin). Furthermore, thermal considerations made it desirable to use MAP thrusters no more often than once every three months to periodically dump angular momentum from the reaction wheels, at which time the stationkeeping maneuvers would also be performed. The residual delta-V of these "delta-h maneuvers", which were performed last, combined with the execution error in performing the stationkeeping maneuvers, contribute two additional error sources that must be included with the orbit determination (OD) error when determining the fuel allocation.

As a result of all of the considerations discussed above, the decision was made to use a Monte Carlo analysis to determine the stationkeeping fuel allocation.[8] The first step was to choose an initial state that, when propagated, remained in bounded motion about L2 for at least 2 revolutions (1 year). This was defined to be the "nominal" state that resulted from a "perfect" stationkeeping maneuver, in other words, one in which the propulsion system executes an orbit adjust with no error and in which the pre-maneuver position and velocity knowledge are without uncertainty. Each Monte Carlo trial began by perturbing the nominal state by Gaussian-distributed noise in both position and velocity. This noise models the effects of the OD error, maneuver execution error and any other delta-V residuals from the previous maneuver (e.g. resulting from delta-h maneuvers). The resulting "perturbed" state is now a realization of the final state after a "real" stationkeeping maneuver. A point was chosen downstream for the subsequent maneuver, which was then targeted to rebalance the Lissajous trajectory (the actual targeting strategy used is consistent with the "loose" stationkeeping strategy discussed by Dunham and Roberts.[7]) The level of noise was varied parametrically and statistics were collected on the correction delta-V required at the downstream stationkeeping maneuver. Performed in this way, the Monte Carlo analysis allowed us to specify a desired fuel allocation and then to determine the maximum tolerable uncertainties for each stationkeeping maneuver. From this total uncertainty, the tolerable error from each error source could then be budgeted. In addition, this approach allowed a more careful assessment of the impact of each error source and resulted in an established philosophy on how to mitigate their effects. This led to a confidence that the resulting budget allowed for enough fuel to perform the maneuver and handle any associated uncertainties, such as OD error and the residual delta-V imparted by prior momentum management or stationkeeping maneuvers.

For MAP the desired stationkeeping delta-V budget was 8m/sec. This assumes four maneuvers per year, each of 1m/sec, over the 2-year mission lifetime. As discussed above, this 8m/sec budget must cover all error sources – orbit determination error, maneuver execution error, and the error associated with the Attitude Control System (ACS) which performs the delta-h maneuver. Since the fuel "taxes", namely the finite burn and ACS penalties, associated with each maneuver change as the spacecraft matures, this analysis was confined to determining impulsive estimates of the delta-V. In general, the effect of these taxes is to lower the budgeted delta-V from a purely impulsive estimate to something lower. This affect can be backed out after the impulsive values have been determined without having to repeat the analysis.

The analysis was done in two phases. In the first phase, any operational constraints were ignored and the stationkeeping maneuvers were performed either along the SEM L2 X- or Y-axis. This allowed the establishment of the bound of the required delta-V and also provided a check on the assumption that the SEM L2 X-axis is the ideal direction. Phase two consisted of determining suitable spacecraft attitude orientations and associated stationkeeping maneuver fuel costs that allow mission constraints to be met. Both phases were carried out at various points along the Lissajous orbit to assure that the correction delta-V's were essentially independent of the maneuver location.

PHASE I ANALYSIS

The scope of the first part of the analysis focused on determining the cost of performing stationkeeping maneuvers along the SEM L2 X- and Y-axes.[8] Maneuvers along each of these two axes were chosen to bound the delta-V costs and to verify that the X-direction was indeed the most efficient control axis. A Monte Carlo analysis was performed to determine the mean and 3-sigma values of delta-V costs associated with a simulated stationkeeping maneuver. Each component of the initial Lissajous state was perturbed using a Gaussian distribution. This initial state was then propagated 90 days forward where a stationkeeping maneuver was applied that targeted to achieve a zero component of velocity along the SEM L2 X-axis at the subsequent XZ-plane crossing (Figure 1). Each run consisted of one hundred trials and this process was repeated for various levels of position and velocity uncertainty. The uncertainties were randomly assigned along each of the position and velocity components. The Monte Carlo runs were done for each of the two scenarios discussed above (thrust direction along the SEM L2 X- and Y-axis).

Tables 1 and 2 show the results of the Monte Carlo analysis. The numbers along the top and side of the tables indicate the amount of position and velocity uncertainty used respectively. These two values define the size of the uncertainty "sphere", so named because all of the perturbed states lie

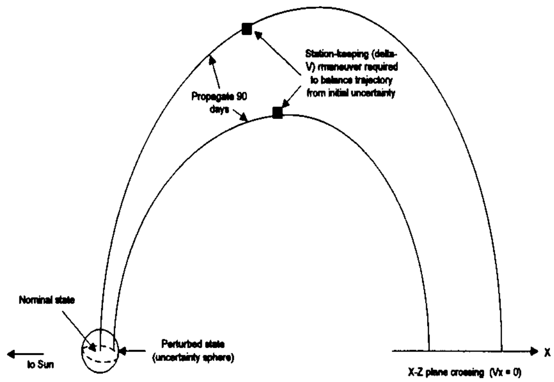

Figure 1. Diagram showing functionality of Monte Carlo analysis.

within the given uncertainties. These values include any uncertainties associated with OD as well as residual affects from the previous maneuver. Most of the latter is attributed to thruster uncertainty. The data values in each column refer to the size of the resulting stationkeeping maneuver required to achieve the targeting goal. Results of maneuvers along the SEM L2 Y-axis are shown in Table 1. The position uncertainty had little effect on the results but velocity uncertainty had a significant effect.

	3σ Position Uncertainty		
3σ Velocity Uncertainty	5 km	3 km	1 km
1 cm/s	**0.56 m/s**	**0.52 m/s**	**0.53 m/s**
2 cm/s	**1.09 m/s**	**1.09 m/s**	**1.09 m/s**
3 cm/s	**1.63 m/s**	**1.68 m/s**	**1.62 m/s**

Table 1: Results for burning along the SEM L2 Y-axis.

Table 2 contains the SEM L2 X-axis results. Once again, the position uncertainty had little effect on the results compared with the velocity uncertainty.

	3σ Position Uncertainty		
3σ Velocity Uncertainty	5 km	3 km	1 km
1 cm/s	**0.26 m/s**	**0.26 m/s**	**0.25 m/s**
2 cm/s	**0.46 m/s**	**0.47 m/s**	**0.43 m/s**
3 cm/s	**0.76 m/s**	**0.74 m/s**	**0.70 m/s**

Table 2: Results for burning along the SEM L2 X-axis.

However, comparing the two tables shows that the 3-sigma totals for the stationkeeping maneuvers along the SEM L2 X-axis were two to three times more efficient, in terms of delta-V cost, than maneuvers along the SEM L2 Y-axis. One can observe from Table 1 that the greatest uncertainty that would allow the stationkeeping budget to be met would be a velocity uncertainty of less than 2 cm/sec, keeping in mind that the total budget (fuel taxes included) must be 1 m/sec. For example, for position and velocity uncertainty of 5km and 2cm/sec respectively for a Y-axis maneuver, the required delta-V for the stationkeeping maneuver is over one meter per second (1.09 m/sec). However, the cost of a maneuver along the X-axis with the same amount of uncertainty was only 46 cm/sec 3-sigma. Obviously, the X-axis strategy becomes more attractive in that it provides a larger error budget that can be used to absorb greater uncertainties resulting from the error sources. The next question to be answered was; how closely along the SEM L2 X-axis can the thrust be achieved, given the operational science and attitude requirements?

The possibility of performing the stationkeeping maneuvers as a linear combination of maneuvers along the X- and Y-axis (i.e. some orientation in the X-Y plane) to take advantage of the X-axis direction fuel savings was analyzed in phase two of this study. X-Y plane maneuvers are limited by the spacecraft attitude; therefore we needed to assess which orientations yielded the greatest benefit to the fuel budget.

PHASE II PROCEDURES

Phase two consisted of several steps.[8] First, there had to be an understanding of what limitations were placed on the spacecraft attitude, due to science and power requirements. Given these restrictions on the attitude, the attitude that was the most desirable, in terms of aligning the thrust vector as closely to the X-axis in the X-Y plane as possible, had to be determined. Another restriction is that the resulting orientation had to allow for the spacecraft Z-axis to precess away from the Sun-line during the burn for thermal reasons.

MISSION ATTITUDE

The first step was to determine what orientations were permissible in terms of meeting all mission requirements and constraints. Several meetings with ACS Engineers were held to determine what attitudes were acceptable for maneuvering. The ACS Engineers specified the spacecraft attitude in a reference frame called the RSR (Rotating Sun Referenced) frame.[9] The RSR frame is defined as having its Z-axis point along the spacecraft-to-Sun line. The X-axis is the cross product of the RSR Z-axis and the inertial Z-axis. The RSR Y-axis completes the triad. This frame is important in understanding how the thrust vectors will be oriented with respect to the SEM L2 frame. Once in the Lissajous, MAP must maintain an observing mode in which the spacecraft body Z-axis is off-pointed from the Sun by between 19 and 22.5-degrees. In addition, the spacecraft is both coning about the Sun line and spinning about its Z-axis. When it is time to perform a maneuver, the spacecraft is de-spun and the body Z-axis is reoriented to the desired off-point from the Sun-line. The spacecraft can then be slewed to the requested attitude for maneuvering but must maintain the off-point from the Sun-line. In other words, the spacecraft X- and Y-axis can be oriented at any angle about the Z-axis, but the Z-axis must always maintain the desired angle from the spacecraft-to-Sun vector.

EFFECTIVE THRUST VECTOR

The next step was to determine the most beneficial orientation possible for performing stationkeeping maneuvers, given the constraints on the attitude. Preliminary analysis, discussed earlier in this paper, determined that being able to thrust directly along the SEM L2 X-axis was much more fuel-efficient than along the SEM L2 Y-axis. The goal was to determine possible attitude orientations that would yield the most thrust in the SEM L2 X-axis direction. The spacecraft attitude is defined by a 3-1-3 Euler angle rotation sequence from its nominal position (body axes aligned with RSR axes). The first rotation is through an angle of ϕ about the body Z-axis. The second rotation is about the body X-axis by an angle of θ, and the final rotation is about the body Z-axis by an angle of φ. Mission constraints dictate that θ must always be between 19 and 22.5-degrees for the maneuver phase. The remaining two angles, ϕ and φ, are not restricted in any way.

Given the thruster orientations, one of the main goals of the second phase of this study was to determine what values of ϕ and φ would yield the maximum amount of thrust along the SEM L2 X-axis. MATLAB m-files were written to perform the transformations and calculate the resulting angles while scanning through values of ϕ and φ from 0 to 360 degrees. The thruster orientations had to be taken into account because the delta-V will be performed along the effective thrust vectors. A parametric study was done to show the relationship between each of the thrust vectors and the SEM L2 X- and Y-axes. The given thrust vectors in the body frame were rotated into the RSR frame and then into the SEM L2 frame. Angles were calculated between each of the thrust vectors and the SEM L2 X- and Y-axes for various attitude orientations. The results were verified independently. The Euler angle rotations that yielded the most efficient orientation were then further analyzed to assure that, during the maneuver, the spacecraft Z-axis would precess away from the Sun.

While the axes of the RSR and the more familiar SEM L2 frames do not align exactly, their differences, as far as L2 stationkeeping is concerned, are small enough to be ignored. With this approximation, the two frames differ only in a permutation of the axis labels. Figure 2 shows the orientation between the RSR and SEM L2 coordinate frames as well as the effective thrust direction.

DESIRED ATTITUDE ORIENTATION

Several conclusions can be drawn from analyzing the results. First, maneuvers should never be performed using thrusters 5, 6, 7 or 8. The results show that the effective thrust vector is never less than 55 degrees from the SEM L2 X-axis for thrusters 7 and 8 and never less than 70 degrees for thrusters 5 and 6 [complete results of the analysis are presented by Rohrbaugh and Schiff].[8] Stationkeeping maneuvers should be done with thrusters 1 and 2 for maneuvering towards the Sun (along the +Z-axis in the RSR frame) and thrusters 3 and 4 for maneuvers along the anti-Sun line (the -Z-axis in the RSR frame). These thruster sets will yield the best possible resulting thrust in the SEM L2 X-axis direction. This is apparent from Figure 3, which illustrates the location and orientation of MAP's thrusters.

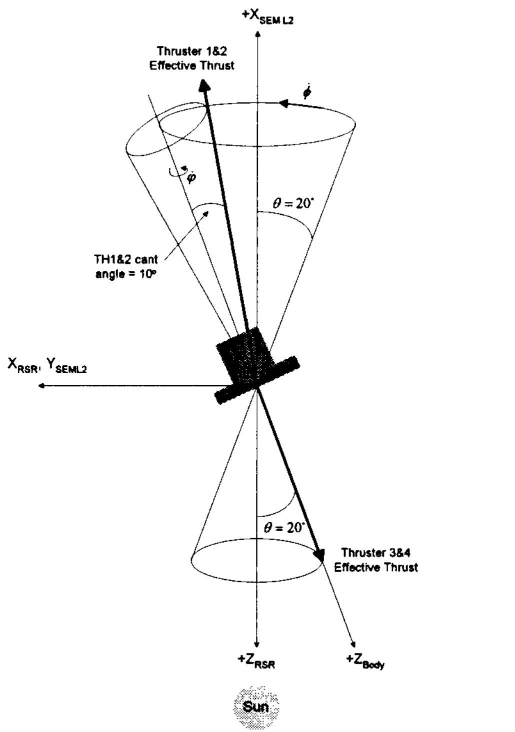

Figure 2. This diagram shows the relationship between the RSR, SEM L2, and s/c Body frames. It also shows how the Euler angles are defined and shows the orientation of the effective thrust vectors

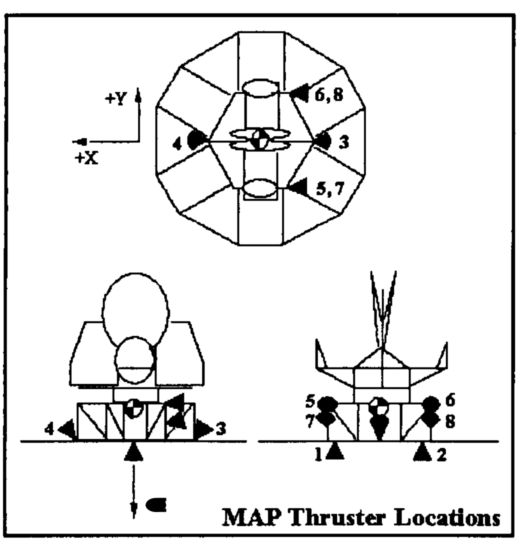

Figure 3: MAP Thruster locations and orientations.

The most beneficial attitude orientations result in an effective thrust vector that is just 9 degrees off the SEM L2 +X-axis in the X-Y plane (-Z RSR direction) and 19 degrees from the -X-axis (+Z RSR direction) for a 19-degree desired off-point. Table 3 summarizes these results. Figure 2 is a good illustration of how the effective thrust vectors are aligned and how the Euler angles are defined.

SEM L2 +X Direction (-Z RSR)			
ϕ	θ	φ	Thrust angle
Any	19	90	9

SEM L2 -X Direction (+Z RSR)			
ϕ	θ	φ	Thrust angle
Any	19	Any angle	19

Table 3. Selected attitude orientations for performing stationkeeping maneuvers. Angles listed are the Euler angles of the 3-1-3 rotation sequence. Thrust angle is the angle from the ±X-axis (SEM L2) to the effective thrust vector. All angles are in degrees.

PHASE II MONTE CARLO

The stationkeeping fuel budget is 1 m/sec of delta-V for each stationkeeping maneuver. Operationally, finite burns are used for the maneuvers, and since there is a 5% finite burn penalty associated with impulsive maneuvers, the fuel budget is adjusted to reflect this. Therefore, the amount of fuel available for each stationkeeping maneuver is effectively 95 cm/sec for the purposes of this study.

A Monte Carlo analysis consisting of eighteen different cases was run using various values of position and velocity uncertainty. A subset of these runs was made using initial Lissajous states whose epochs corresponded to three different locations along the Lissajous orbit; the nominal case, 45 days after the nominal case, and 90 days after the nominal case. This was done to examine the effects of the stationkeeping maneuvers at various points along the Lissajous orbit. Each Monte Carlo run consisted of one hundred trials. For the first set of trials, the values for velocity uncertainty were chosen to correspond to the bounds calculated in Phase I of this analysis: 3.0-, 3.5-, and 4.0-cm/sec. The position uncertainty was held constant at 5km since the previous phase determined its contribution to be insignificant. We also ran a second set of trials where the velocity uncertainty was held constant while the position uncertainty was varied to verify that neither the position uncertainty nor the location of the maneuver had any significant effect on the results.

RESULTS

The objective of the Monte Carlo analysis was to determine the maximum uncertainty that would allow for stationkeeping maneuvers to be performed within the given budgeted delta-V, keeping in mind that this uncertainty would have to absorb all errors associated with the maneuver. Tables 4 and 5 summarize the results. Both tables list the ±3-sigma total fuel costs (the mean delta-V plus 3 times the standard deviation) for the simulated stationkeeping maneuver for a given position and velocity uncertainty as well as the location of the initial state on the Lissajous orbit. Table 4 results were run using a fixed value of 5km for the position uncertainty while varying the velocity uncertainty. The velocity component is the major contributor to the delta-V required for the burns. Keeping in mind that the fuel budget for each stationkeeping maneuver for this study is 95 cm/sec, the values must be below this to be considered acceptable. Referring to Table 4, a velocity uncertainty of up to 3.5 cm/sec can be tolerated and still meet the fuel budget (delta-V values for the 4 cm/sec case exceed the 95 cm/sec budget). Data is also presented for the other two Lissajous states. These results reveal that the location along the Lissajous orbit, at which the maneuvers are executed, does not significantly affect the delta-V costs.

Velocity Uncertainty	Nominal state	45 days later	90 days later
3.0 cm/sec	74 cm/sec	75 cm/sec	79 cm/sec
3.5 cm/sec	90 cm/sec	81 cm/sec	88 cm/sec
4.0 cm/sec	106 cm/sec	94 cm/sec	105 cm/sec

Table 4: Velocity uncertainty varied, position uncertainty held constant at 5 km.

Table 5 results were run with a velocity uncertainty of 3.5 cm/sec while varying the position uncertainty. This portion of the analysis reveals the fact that velocity is indeed the major contributor to the fuel cost and that changing the position uncertainty has little effect on the results. A velocity uncertainty of 3.5 cm/sec is used because it is the maximum tolerable error.

Position Uncertainty	Nominal state	45 days later	90 days later
2.0 km	79 cm/sec	81 cm/sec	89 cm/sec
3.5 km	87 cm/sec	81 cm/sec	78 cm/sec
5.0 km	90 cm/sec	81 cm/sec	88 cm/sec

Table 5: Position uncertainty varied, velocity uncertainty held constant at 3.5 cm/sec.

SUMMARY OF PHASE II WORK

The attitude orientation the MAP spacecraft should be in to maximize fuel efficiency while performing stationkeeping maneuvers consistent with the attitude constraints has been resolved based on this analysis. In addition, the thruster set that should be used for the stationkeeping maneuvers was determined. Using this information in a Monte Carlo analysis, the maximum velocity uncertainty MAP can tolerate and still meet the mission requirements was established. It is important to note that perturbations due to all error sources, not just OD uncertainty, were modeled.

Results indicate that the largest tolerable error budget is 3.5 cm/sec. This 3.5 cm/sec must cover three error sources; OD uncertainty, residual delta-H errors, and residual delta-V errors (thruster uncertainty). ACS engineers provided us with data to calculate the delta-H errors. Using values for a thrust of 2 N, a mass of 795 kg, and an ISP of 221 seconds at the beginning of the Lissajous phase, an upper bound on the error of **2.0 cm/sec** will result during delta-H maneuvers. The residual delta-V error can be calculated by assuming a 5% thruster uncertainty, and applying this to a typical stationkeeping maneuver of 45 cm/sec (average mean plus average STD from all three states from Table 3). The error attributable to residual delta-V will, therefore, typically be **2.25 cm/sec**. The last error source is that attributable to OD uncertainty. An independent study recently completed by GSFC flight dynamics analysis personnel verified that the OD uncertainty would be known to within **1 cm/sec**, provided that the tracking requirements agreed upon and documented in the Detailed Mission Requirements (DMR) document are met.[10]

Since there is some variance in each of these errors, we can calculate the expected error for a typical stationkeeping maneuver as the root sum square (RSS) of the errors from the three sources:

$$E = \sqrt{\Delta H_{error}^2 + \Delta V_{error}^2 + OD_{error}^2}$$

For this case, the expected error is 3.17 cm/sec and does not exceed the 3.5 cm/sec error budget available for stationkeeping maneuvers. Had the expected error exceeded the error budget, one alternative would have been to use a stationkeeping strategy that uses a tighter control technique, similar to that used for ISEE-3. However, this will not be necessary, as the current strategy indicates. Based on the information provided on the three error sources discussed above, a delta-V budget of 95 cm/sec (1 m/sec per maneuver for finite burns) should be enough to cover errors associated with a typical stationkeeping maneuver.

OPERATIONAL APPROACH

Once the lunar swingby occurred, MAP performed two Mid Course Correction Maneuvers (MCCMs) in order to successfully transition into its Lissajous orbit. The second MCCM allowed MAP to remain "stable" in the Lissajous for several months before the first required stationkeeping maneuver. Shortly after the second MCCM, the trajectory team began its stationkeeping procedures. Preliminary planning for each maneuver begins several months in advance. The direction and approximate magnitude of the burn are calculated to determine the timeframe for the next stationkeeping burn. The maneuver plan is fine-tuned with each subsequent OD solution. A set of maneuver products are delivered one week prior to the maneuver and then verified using hi fidelity simulators. After the burn is completed, it is reconstructed using actual thruster data from telemetry and a predicted post-burn orbit state. Once the orbit state is updated with post-burn tracking data, which takes about two weeks, the maneuver is calibrated. The results are used to help determine any trends that can be used in planning subsequent stationkeeping maneuvers.

OPERATIONAL RESULTS

To date, two stationkeeping maneuvers have been performed. The first stationkeeping maneuver (SK1) occurred on January 16, 2002. The maneuver start time was 16:50:55 UTC and the burn was 72.92 seconds in duration. The amount of delta-V was 43.5 cm/sec and the direction of the burn was along the +Z spacecraft axis (19 degrees off the Sun-Earth line). The 3-1-3 Euler rotation sequence for the burn in the RSR frame was 0 degrees, 19 degrees, and 90 degrees. This placed the spacecraft Z-axis 19 degrees off the Sun-line. Since thrusters 3 and 4 were used for this maneuver, there was no precession of the spacecraft Z-axis because the net thrust from thrusters 3 and 4 is directly along the +Z-axis of MAP. MAP was despun and then slewed to this attitude approximately ten minutes prior to the maneuver start time. During the maneuver, the ACS maintained the attitude by firing thrusters 1 and 5. This has the effect of lengthening the burn duration slightly. For SK1, the original planned burn was 72 seconds exactly, so the additional .92 seconds is a result of the control system maintaining the attitude orientation of the spacecraft. The results are plotted and are shown in Figure 3 below.

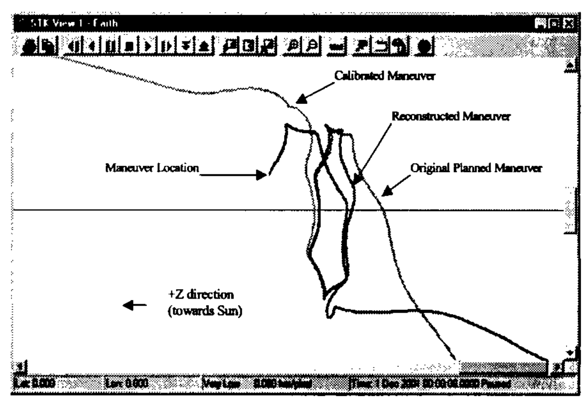

Figure 3: X-Y projection of the Lissajous orbit in Sun-Earth-Moon rotating frame. The three trajectories shown represent the planned, reconstructed, and calibrated SK1 maneuver.

The SK1 maneuver turned out to be slightly "hot". In other words, there was a slight over-burn, as can be seen from the "Calibrated Manuever" curve in Figure 3. Too much energy was added along the Z-axis (to the left in the diagram) and caused the trajectory to "fall back" towards the Sun. The calibrated thrust scale factor (TSF) verifies this fact. The planned TSF for SK1 was 0.935 and the calibrated TSF was 0.95 which indicates the maneuver was more efficient than planned. This information will be useful in planning subsequent stationkeeping maneuvers. The maneuver, however, was accurate enough to allow MAP to stay in its Lissajous orbit for another 6 months and still be stabilized for just under 1m/sec.

The second stationkeeping maneuver (SK2) was executed on May 8, 2002. The maneuver start time was 16:03:27 UTC. The burn duration for SK2 was 54.12 and the delta-V was 34.8 cm/sec and the direction of the burn was along the -Z spacecraft axis (19 degrees off the Sun-Earth line). The 3-1-3 Euler rotation sequence for this burn in the RSR frame was 60 degrees, 19 degrees, and 90 degrees. Thrusters 1 and 2 were used for this burn, which caused an attitude hang-off of 2.9 degrees due to the torque resulting from the cant of the thrusters. Attitude control was maintained during the maneuver, predominantly by thruster 3. The original planned maneuver was 49.5 seconds in duration but did not model attitude control. The actual burn was 4-1/2 seconds longer to compensate for the attitude control. Notice that the additional duration for attitude control was far greater for SK2 than for SK1, due to the fact that SK1 used thrusters that were aligned directly along the Z-axis, while the thruster set used for SK2 is canted by 10 degrees. Calibration results for SK2 were not yet available at the writing of this paper.

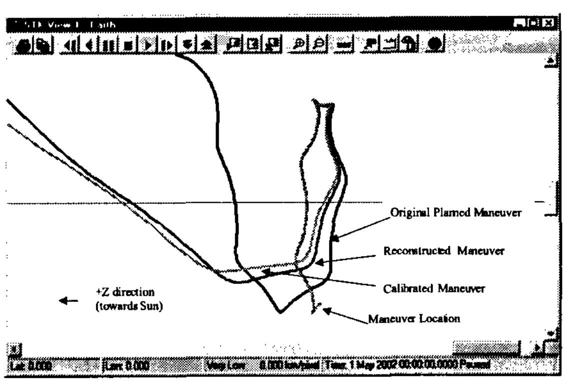

Figure 4: X-Y projection of the Lissajous orbit in Sun-Earth-Moon rotating frame. The three trajectories shown represent the planned, reconstructed, and calibrated SK2 maneuver.

CONCLUSION

The results of the stationkeeping support thus far are very encouraging. Although only two stationkeeping maneuvers have been planned and supported, the MAP trajectory team has been able to perform the maneuvers every four months, compared to the projected 3 months, for half the budgeted cost.

The calibration process involves adjusting the TSF using the recorded burn information from spacecraft telemetry to match pre-burn and post-burn orbit states. An important point to make is that the TSF calibrated during post-maneuver processing is an estimator of uncertainty in that it represents any uncertainties associated with the maneuver, not just those resulting from the propulsion system. Comparing the planned and calibrated TSF for each maneuver indicates that the resulting uncertainty was on the order of 1-sigma or less of the allowable error budget as determined in the Phase II analysis. This is to be expected since MAP is performing nominally. Pre-launch budgeting requires a 3-sigma estimation in order to generate conservative estimates so it is not surprising that the results so far indicate the delta-V resulting from stationkeeping maneuvers for the first year in the Lissajous will be about 1.5 m/sec compared to the budgeted 4 m/sec.

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