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A New Trajectory Concept for Exploring the Earth's Geomagnetic Tail

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An innovative trajectory technique for a magnetotail mapping mission is described. With this technique, it is possible to control the apsidal rotation of an elliptical Earth orbit and keep its apogee segment inside the tail region. The required apsidal rotation rate of approximately 1 deg/day is achieved by using the moon to carry out a prescribed sequence of gravity-assist maneuvers. Apogee distances are alternately raised and lowered by the lunar-swingby maneuvers. Several categories of the "sun-synchronous" swingby trajectories are identified. The strength and flexibility of the new trajectory concept is demonstrated by using real-world simulations. It is shown that a large variety of trajectory shapes can be used to explore the Earth's geomagnetic tail between 60 and 250 R_E.

Introduction

IN 1977 the Space Science Board of the National Academy of Sciences undertook a study to identify future objectives of research in space plasma physics. Their final report[1] gave a high priority to a comprehensive understanding of the cause and effect relationships between time-dependent magnetospheric processes in the near-Earth space environment. To satisfy this objective, NASA has formulated a four-spacecraft program called Origins of Plasmas in the Earth's Neighborhood (OPEN)[2] that is currently scheduled for implementation in the mid-1980's.

A primary goal of the OPEN program is to study the behavior of the distant geomagnetic tail on a nearly continuous basis. The main region of interest begins at the moon's orbit ($\sim 60\ R_E$)‡ and extends as far as the L_2 libration point (see Fig. 1). This is largely unexplored territory. As shown in Fig. 2, the Explorer-33 spacecraft has probed the magnetotail out to distances of about 80 R_E (Ref. 3), but the only measurements beyond this point have been obtained from single traverses by Pioneer 8 at 500 R_E and Pioneer 7 at 1000 R_E (Ref. 4).

From a flight-mechanics standpoint, the magnetotail mission represents an exciting challenge. Trajectory requirements call for a flight profile that stays inside the magnetotail about 90% of the time. Repeated longitudinal scans between 60 and 250 R_E are also required. On occasion, the trajectory should cut across the tail boundaries. It should also be possible to alter the planned profile while the mission is in progress to respond to changing scientific objectives.

Designing a trajectory profile that satisfies these specifications is not an easy task. A 1968 study[5] defined a trajectory that provided intermittent tail coverage out to distances of 500 R_E, but required a solar-electric propulsion unit to accomplish the feat. Another study, performed at the Jet Propulsion Laboratory (JPL) in 1975 (JPL EM-393-279), tried to apply Jupiter Orbiter gravity-assist techniques[6] to the magnetotail trajectory problem. Although the JPL investigation showed that lunar gravity-assist maneuvers are able to produce large changes in orbital size and inclination, it could not find a trajectory sequence that remained in the magnetotail.

In this paper, the possibility of using lunar gravity-assist maneuvers to piece together an appropriate magnetotail trajectory is re-examined. It is demonstrated that by using a new and versatile lunar-swingby concept, a high-quality result can be obtained.

Magnetotail Trajectories

The fundamental difficulty in keeping a spacecraft trajectory inside the magnetotail is brought out in Fig. 2. Because the apsidal line of an elliptical Earth orbit is essentially fixed in inertial space, this line appears to rotate about 1 deg/day in the reference frame of Fig. 2. Therefore, the apogee segment of the Earth orbit rapidly sweeps through the magnetotail, which is almost stationary in this reference frame. Of course, propulsive maneuvers could be used to counter the apsidal rotation and maintain the apogee segment in the tail region, but the ΔV cost for these maneuvers would be about 400 m/s per month!

Libration-Point Orbits

One way to avoid the unwanted apsidal rotation, without incurring an excessive ΔV penalty, would be to place the magnetotail spacecraft in a periodic orbit around the sun-Earth L_2 libration point.[7,8] An entire family of these orbits exist, and they all have orbital periods of about six months. The L_2 orbits are inherently unstable, but stationkeeping costs for orbital maintenance would be less than 15 m/s per year. Three possible orbits are shown in Fig. 3. It is easy to see that although libration-point orbits are advantageous for long-term monitoring at larger distances, they do not give enough longitudinal coverage.

Egorov Solution

The apsidal rotation can also be regulated by utilizing lunar gravity-assist maneuvers. In a general investigation of lunar-swingby trajectories,[9] Egorov showed how the moon's gravity could be used to oppose the natural rotation of the apsidal line. Figure 4 contains a plot of Egorov's solution for

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‡One Earth radius (R_E) = 6378 km.

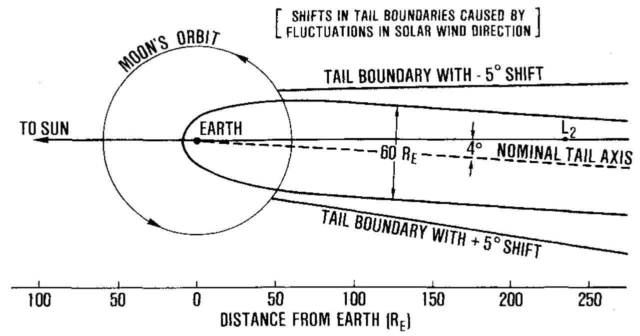

Fig. 1 Geomagnetic tail in ecliptic plane.

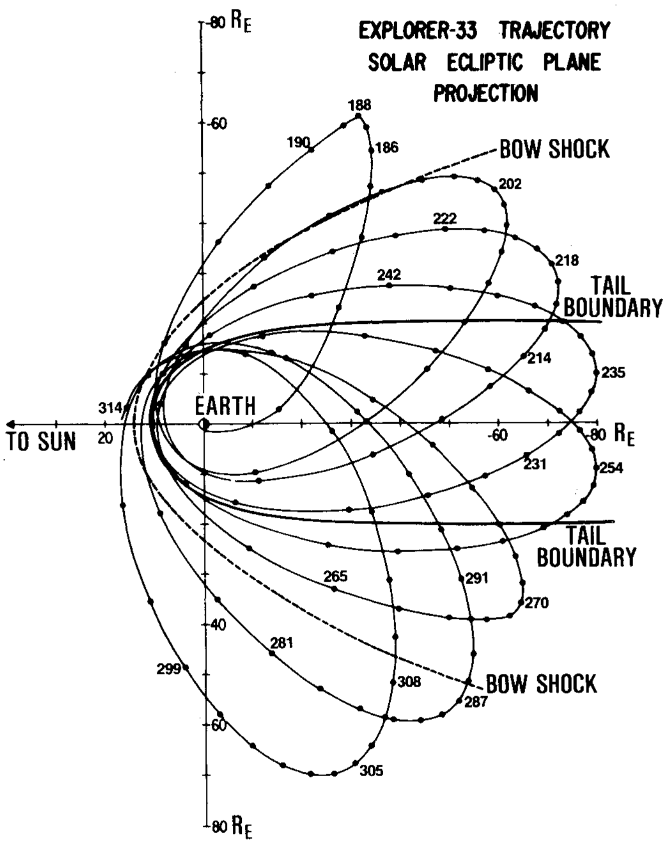

Fig. 2 Explorer 33 trajectory from launch on July 1, 1966 (decimal day 181) to November 10, 1966 (decimal day 314).[3]

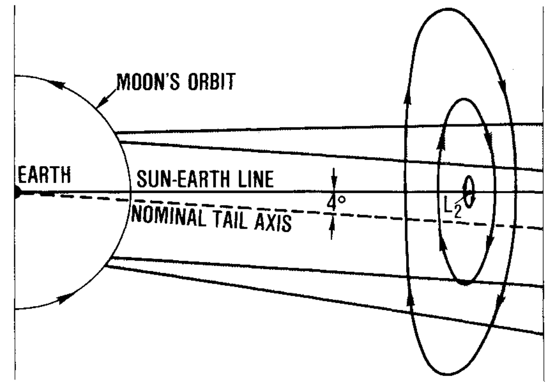

Fig. 3 Periodic orbits around the sun-Earth L_2 libration point.

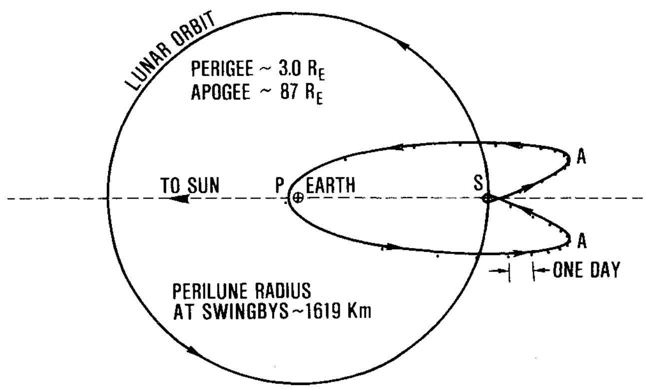

Fig. 4 Sun-synchronous periodic orbit using single lunar swingby (Egorov class).

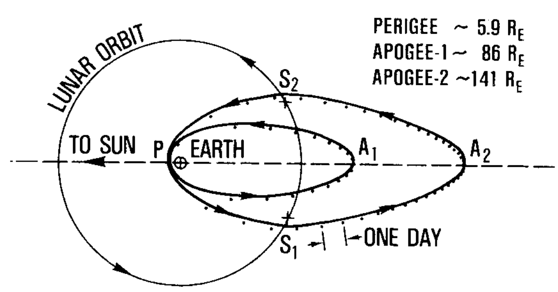

Fig. 5 Sun-synchronous periodic orbit using double lunar swingby, [1,1,1] class.

a sun-synchronous rotation rate (i.e., ~1 deg/day). The apogee of this periodic orbit is only 87 R_E, but the entire trajectory is located within the magnetosphere. Unfortunately, the looping swingby of the moon at S has a perilune radius that is 119 km below the lunar surface. Large ΔV maneuvers, having a cost of almost 100 m/s per month, are needed to attain a positive perilune altitude of 200 km.

Double Lunar-Swingby Concept

None of the methods outlined in the preceding section are able to provide an acceptable magnetotail trajectory. However, a new study of possible lunar-swingby trajectories has yielded a greatly improved result. Details of the new trajectory concept are present in this section. To focus the discussion on the main features of this plane, a simplified patched-conic dynamical model has been employed. In the simplified model, the moon's orbit is circular and all of the trajectories are coplanar.

The basic procedure is diagrammed in Fig. 5. Assume that a spacecraft is initially located near the apogee of the smaller orbit at A_1. After its next perigee passage, the natural orbital precession with respect to the sun-Earth line will position the spacecraft for a trailing-edge swingby of the moon at S_1. The swingby maneuver at S_1 will then rotate the line of apsides back to the sun-Earth line and will also raise the apogee to A_2. A leading-edge lunar swingby at S_2, after the moon has completed one full orbit plus the S_1S_2 segment, will return the spacecraft to its original orbit.

An interesting property of this type of sun-synchronous periodic orbit is exhibited in Fig. 6, where the orbit is plotted with respect to a fixed Earth-moon line. Notice that the combination of periodic lunar swingbys and sun synchronization gives rise to a special class of orbits that could be termed "doubly periodic." Neighboring members of the orbit family shown in Fig. 6 will have an apsidal rotation that is slower or faster than the sun-synchronous rate. Parameters for these orbits are given in Fig. 7.

Several kinds of sun-synchronous periodic orbits can be produced with the double lunar-swingby technique. For instance, the higher apogee (A_2) can be increased by allowing the moon to complete additional orbits while the spacecraft is

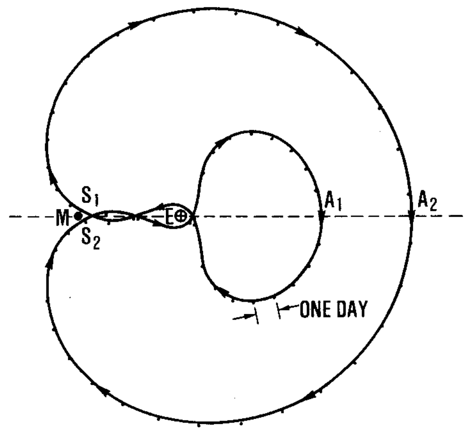

Fig. 6 [1,1,1] class periodic orbit in the Earth-moon reference frame.

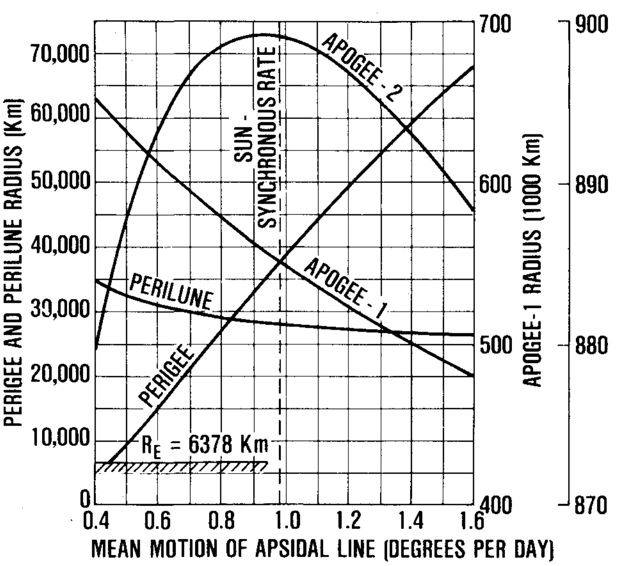

Fig. 7 Parameters for sub and super sun-synchronous orbits of the [1,1,1] class.

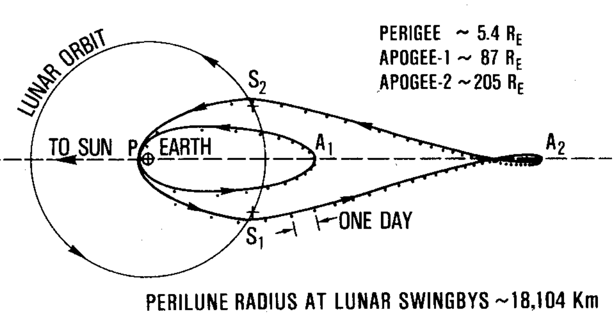

Fig. 8 Sun-synchronous periodic orbit using double lunar swingby, [1,1,2] class.

located in the outer trajectory segment ($S_1A_2S_2$). A modified trajectory with a two-month outer segment is plotted in Fig. 8, and an example with a three-month outer segment is shown in Fig. 9. The pretzel-like shapes of these periodic orbits have led to the descriptive terminology "orbit twisting and turning."

The time spent in the inner trajectory segment can also be extended. Figure 10 shows a case where the time interval between lunar swingbys for the inner segment is almost two months. Note that the inner trajectory segment has three complete orbital loops.

The sun-synchronous periodic orbits illustrated in Figs. 5 and 8-10 represent only a few of the many useful solutions

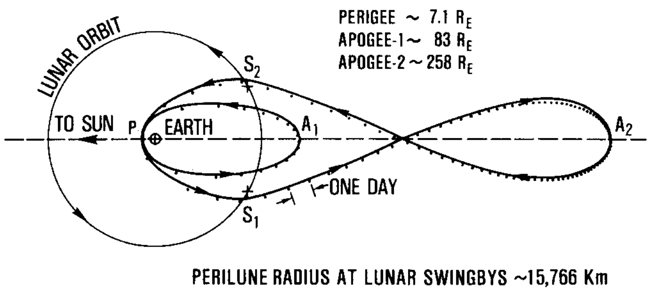

Fig. 9 Sun-synchronous periodic orbit using double lunar swingby, [1,1,3] class.

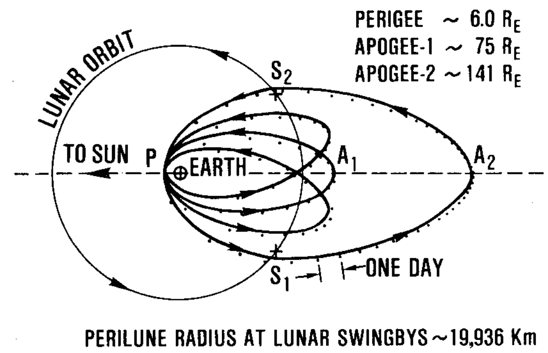

Fig. 10 Sun-synchronous periodic orbit using double lunar swingby, [2,3,1] class.

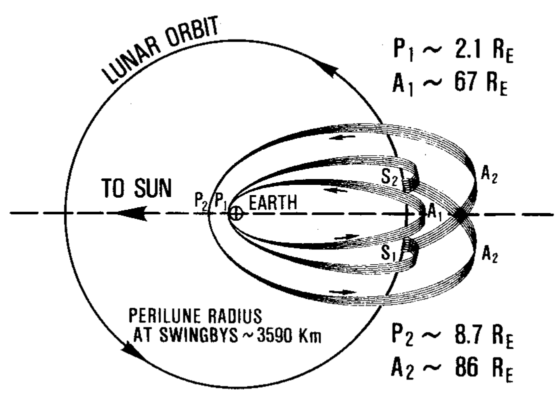

Fig. 11 Nearly sun-synchronous periodic orbit using double lunar swingby [ESA class].[10]

that can be realized with the new gravity-assist concept. These solutions are classified by using the shorthand notation, $[A,B,C]$, where A is the approximate number of months between lunar swingbys for the inner trajectory segment, B is the number of complete loops for the inner trajectory segment, and C is the approximate number of months between swingbys for the outer trajectory segment.

Key parameters for a selected listing of double lunar-swingby trajectories are given in Table 1. All of these trajectories have the desirable characteristics of alternating low- and high-apogee orbits. The comfortable altitude margins during passages of the Earth and the moon are also noteworthy.

Comparison with ESA Concept

Shortly after NASA revealed that it was defining a magnetotail mission for the mid-1980's, the European Space Agency (ESA) initiated a similar study effort. As a consequence of this curious situation, parallel investigations of trajectory concepts for the magnetotail mission were conducted by both organizations. The results of the two investigations, which were reported at about the same time,[2,10]

Table 1 Parameters for sun-synchronous periodic orbits using double lunar-swingby technique

Orbit class[a]	Perigee R_E	Apogee-1 R_E	Period of smaller orbit, days	Apogee-2 R_E	Perilune radius at swingbys, km
[1, 1, 1]	5.9	86.2	18.3	140.9	27,664
[1, 1, 2]	5.4	86.7	18.3	204.8	18,104
[1, 1, 3]	7.1	82.5	17.6	257.5	15,766
[2, 3, 1]	6.0	75.1	15.1	140.9	19,936
[2, 3, 2]	5.5	75.6	15.2	203.2	14,397
[2, 3, 3]	7.1	73.3	14.9	255.1	13,074
[3, 4, 1]	15.5	73.5	17.4	137.2	32,278
[4, 8, 1]	7.1	63.8	12.4	138.7	13,404

[a]For $A \leq 4$, and $C=1,2,3$, orbits exist for: $[1, 1, C]$, $[2, 3, C]$, $[2, 4, C]$, $[3, 4, C]$, $[3, 5, C]$, $[3, 6, C]$, $[3, 7, C]$, $[4, 8, C]$, and $[4, 9, C]$.

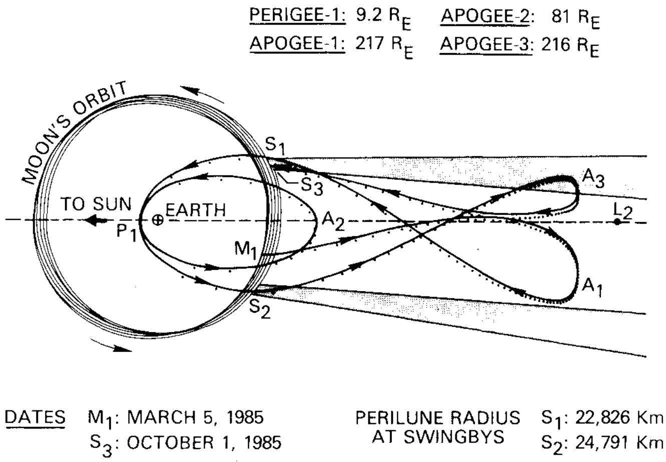

Fig. 12 Realistic simulation of double lunar-swingby trajectory; skewed 3-month outer loop → [1,1,3].

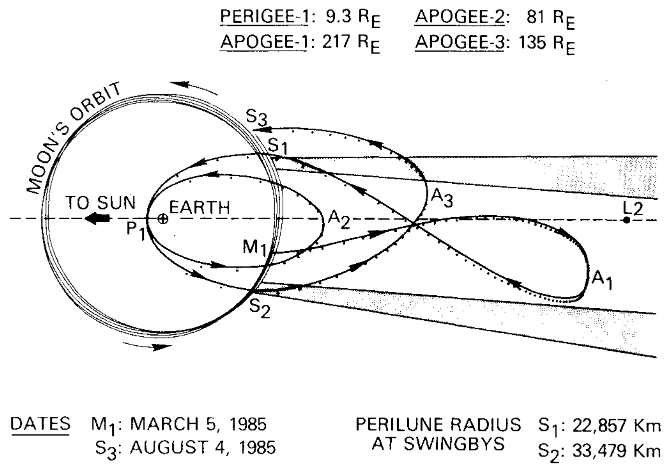

Fig. 14 Realistic simulation of double lunar-swingby trajectory; skewed 3-month outer loop → [1,1,1].

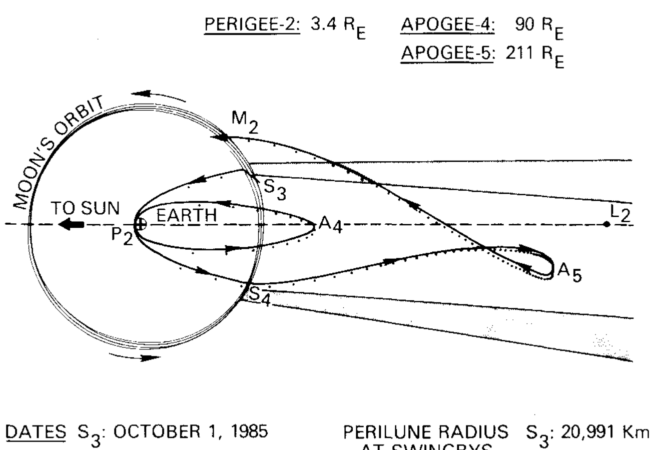

Fig. 13 Continuation of Fig. 12 trajectory, [1,1,3] → [1,1,3].

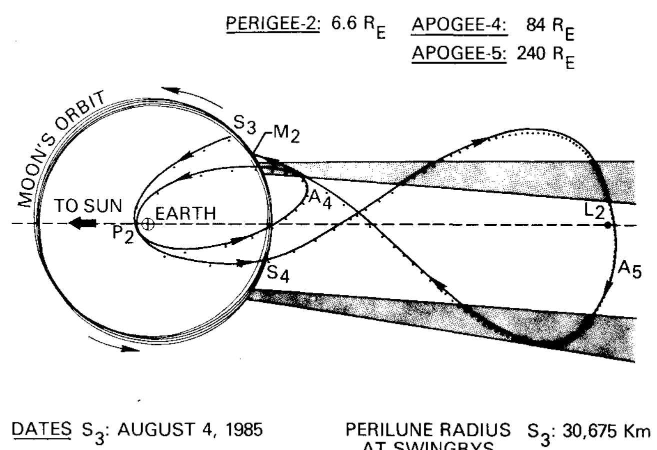

Fig. 15 Continuation of Fig. 14 trajectory, [1,1,1] → [1,1,4].

are quite different. The NASA findings were described in the previous section. A brief review of the ESA trajectory concept is given here.

Figure 11 shows a nearly sun-synchronous version of the ESA solution. Like the NASA plan, the ESA trajectory uses two lunar swingbys to control the apsidal rotation. However, the Egorov-type lunar swingbys that are used in the ESA design are not very effective. This swingby mode limits the maximum distance of the higher apogee to about 86 R_E. Therefore, the ESA trajectory is not suitable for deep-tail exploration.

A more serious defect arises because of the relatively close passages of the Earth at P_1 and the moon at S_1 and S_2. It is doubtful that these small altitude margins will hold up when the moon's orbital eccentricity and the sun's gravitational perturbations are taken into account. Thus, it appears that the ESA solution is not very practical.

Real-World Trajectories

Precision trajectory simulations of the double lunar-swingby technique are needed to demonstrate feasibility, evaluate magnetotail coverage, and identify potential mission-design problems. In this section, a real-world dynamical model is used to generate some representative magnetotail trajectories. The real-world model includes the three relevant gravity fields (sun, Earth, and moon), accurate ephemerides for the lunar orbit, solar radiation pressure, and so forth.

A sample trajectory profile for the magnetotail mission is illustrated in Figs. 12 and 13. The profile begins with both the moon and the spacecraft in the vicinity of M_1. A skewed three-month outer loop ($M_1A_1S_1$) is used for the initial orbit. This orbital segment has been tilted intentionally to compensate for the 4-deg offset of the nominal tail axis. Notice that the apogee (A_1) is about 40 R_E lower than the corresponding patched-conic value. The initial three-month outer loop is followed by two [1,1,3] trajectory legs, and the profile is concluded with the moon in position for another swingby at M_2. Because the moon's orbit is noncircular, the apsidal rotation of the spacecraft orbit is not exactly sun-synchronous. However, the oscillatory motion of the apsidal line actually improves the coverage of the magnetotail.

An alternate trajectory profile is shown in Fig. 14. The initial segment is the same one that was used in Fig. 12, but this time different swingby maneuvers are performed at S_1 and S_2. Instead of repeating the three-month outer loop, a [1,1,1] path is utilized. This leg is then followed by a [1,1,4] trajectory as shown in Fig. 15. The [1,1,4] leg gives about two months of continuous coverage in the deep tail between 210 and 240 R_E.

A wide variety of trajectory profiles can be constructed by using different combinations of the available orbit classes (see Table 1). The number of possible trajectories can be increased still further by including ΔV maneuvers. Finally, it should be mentioned that the shape and character of a particular orbit sequence can be changed substantially by simply using a different starting date.

Trajectory Control

In-flight modification of a baseline trajectory profile will generally cause the average apsidal rotation rate to deviate from the sun-synchronous value. This discrepancy can be corrected by changing the ensuing trajectory sequence and/or by adding ΔV maneuvers at appropriate locations. The determination of a preferred control strategy will involve a tradeoff between ΔV expenditure and the quality of the accompanying magnetotail coverage. A detailed treatment of this tradeoff is beyond the scope of this paper; however, preliminary studies have indicated that a ΔV budget of 100 m/s per year should be adequate for apsidal control.

The spacecraft's orbital inclination with respect to the ecliptic plane will also require some adjustments from time to time. These adjustments are needed to obtain out-of-plane scans in the magnetotail and to avoid the Earth's shadow zone. The required inclination control can usually be supplied by the lunar-swingby maneuvers.

Some ΔV maneuvers will also be needed to correct navigational errors. However, spacecraft position errors should be less than 10 km, and the lunar ephemeris can be predicted with great accuracy. Therefore, it is expected that ΔV costs associated with navigational uncertainties will be quite small.

Concluding Remarks

The double lunar-swingby technique is a unique trajectory concept, developed for a unique purpose—the exploration of the Earth's geomagnetic tail. It is fundamentally different from gravity-assist concepts formulated in other studies. When described in the context of a restricted three-body system, it can be used to generate orbits that are doubly periodic and sun synchronous.

Real-world simulations have demonstrated the utility of the new trajectory concept. By using the lunar swingbys in concert with solar gravitational perturbations, a wide selection of attractive magnetotail trajectories can be obtained. A comprehensive catalog of these trajectories is currently in preparation.

Acknowledgments

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