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ARTEMIS LUNAR ORBIT INSERTION AND SCIENCE ORBIT DESIGN THROUGH 2013

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As of late-July 2011, the ARTEMIS mission is transferring two spacecraft from Lissajous orbits around Earth-Moon Lagrange Point #1 into highly-eccentric lunar science orbits. This paper presents the trajectory design for the transfer from Lissajous orbit to lunar orbit insertion, the period reduction maneuvers, and the science orbits through 2013. The design accommodates large perturbations from Earth's gravity and restrictive spacecraft capabilities to enable opportunities for a range of heliophysics and planetary science measurements. The process used to design the highly-eccentric ARTEMIS science orbits is outlined. The approach may inform the design of future planetary moon missions.

INTRODUCTION

The Acceleration, Reconnection, Turbulence and Electrodynamics of the Moons Interaction with the Sun (ARTEMIS) mission is currently operating two spacecraft in lunar orbit under funding from the Heliophysics and Planetary Science Divisions with NASA's Science Missions Directorate. ARTEMIS is an extension to the successful Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission that has relocated two of the THEMIS spacecraft from Earth orbit to the Moon [1, 2]. ARTEMIS plans to conduct a variety of scientific studies at the Moon using the on-board particle and fields instrument package [3]. The final portion of the ARTEMIS transfers involves moving the two ARTEMIS spacecraft, known as P1 and P2, from Lissajous orbits around the Earth-Moon Lagrange Point #1 (EML1) to long-lived, eccentric lunar science orbits with periods of roughly 26 hr. This paper presents the design of this final transition and discusses how the various science objectives were achieved by the transfer and lunar orbit designs. As of this writing, the P1 and P2 spacecraft have both successfully performed their lunar orbit insertion (LOI) maneuvers (on June 27 and July 17, 2011, respectively). Both spacecraft are currently undergoing a series of period reduction maneuvers (PRMs) *en route* to their final science orbits.

Many aspects of the transfer from Lissajous to the science orbits contribute to the novelty of the design. Firstly, the ARTEMIS probes have been the first spacecraft to fly Lissajous orbit near the Earth-Moon Lagrange points and thus, they are the first to approach a traditional lunar orbit from this location. Second, the ARTEMIS probes plan to routinely operate in the most eccentric lunar science orbits of any mission to date[*]. These orbits are strongly perturbed by the Earth's gravity, which makes for interesting three-body dynamics

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[*]The SMART-1 spacecraft briefly flew a more eccentric orbit upon initial capture at the Moon, but the spacecraft quickly transitioned to a less eccentric science orbit.

that are usually thought of in the context of outer planet moon orbiter missions. Further, ARTEMIS plans four different science investigations while in lunar orbit, each of which have particular trajectory implications that must be satisfied. Finally, P1 and P2 were built as low-cost Earth orbiters; the spacecraft capabilities, particularly in the area of available thrust and ΔV, are less robust than they may have been if the lunar mission had been planned before launch.

First, the paper reviews the scientific objectives of the ARTEMIS mission and the implications for trajectory design. Next, the lunar orbit dynamics are discussed, along with the insights and simplifications found to be helpful in the design process. A discussion follows on the design limitations arising from spacecraft and mission constraints. The baseline design solutions for P1 and P2 are then presented, with a discussion of the methodology used to approach key design hurdles. The achieved science opportunities are then shown, confirming that the goals and constraints of the mission are met by the design.

LUNAR ORBIT PHASE SCIENCE OBJECTIVES

Both ARTEMIS spacecraft are equipped with an identical complement of particle and fields measurement instrumentation [4]. Because ARTEMIS is both a heliophysics and a planetary science mission, a wide range of science observations are planned for during the lunar orbit phase, including:

- 3-D mapping of the lunar wake induced by the solar wind at a range of downstream distances;
- Measurements of selected lunar crustal magnetic anomalies;
- Measurements of the lunar exosphere;
- Coordinated measurements of the lunar exosphere with NASA's forthcoming Lunar Atmosphere and Dust Environment Explorer (LADEE).

It is desired to get as many measurements as possible in each area so as to attain as much spatial resolution as possible, capture variations as the Moon moves in and out of the Earth's magnetotail, and observe variations over the 11 year solar cycle. By having two ARTEMIS spacecraft in orbit, simultaneous two-point measurements can be achieved at a range of spatial separations, calibration can be conducted, and an increased data volume is obtained.

The science objectives drive the design of the lunar science orbit and approach from Lissajous. To achieve the desired lunar wake measurements, the spacecraft should be in highly eccentric orbits that precess at rates different from each other and from the Sun direction. The mission duration should be long enough so that a full range of measurement altitudes and relative orientations can be achieved. To measure the crustal magnetic anomalies, periapsis altitudes must be less than 50 km for the on-board flux-gate magnetometer. Further, the low periapses must be located in the vicinity of the anomaly. Measurements of the lunar exosphere require a range of altitudes and orientations with respect to the Sun. The region below 200 km within 30 deg of the dawn terminator is expected to contain electostatically-elevated material, which is of particular interest. To coordinate exosphere measurements with LADEE, an ARTEMIS spacecraft must be in this region near the dawn terminator at least once during the 3-month LADEE science mission scheduled for sometime between July 2013 and March 2014, depending on launch date. Finally, to attain the most possible science in all areas and to leave open the possibility for additional investigations, the orbits should have long-term stability.

NATURAL DYNAMICS

The above discussion on the orbit necessary to achieve the ARTEMIS science goals necessitates a lunar orbit with a large semi-major axis and a high eccentricity. The following accelerations on the spacecraft were considered necessary for integrating the dynamics:

- Lunar pointmass potential;
- Earth pointmass potential;

- Lunar harmonic gravity terms (up to 20th degree and order);
- Solar pointmass potential;
- Solar radiation pressure (SRP, spherical spacecraft model).

Relativistic accelerations and a higher-order gravity terms for the Earth were also considered, but found to be small enough to neglect in the modeling. Figure 1 shows the relative magnitude of the various natural accelerations on the P2 spacecraft during its transfer from Lissajous through the science orbit; the accelerations on P1 are very similar. Note that the magnitude of the first three accelerations listed above oscillate over several

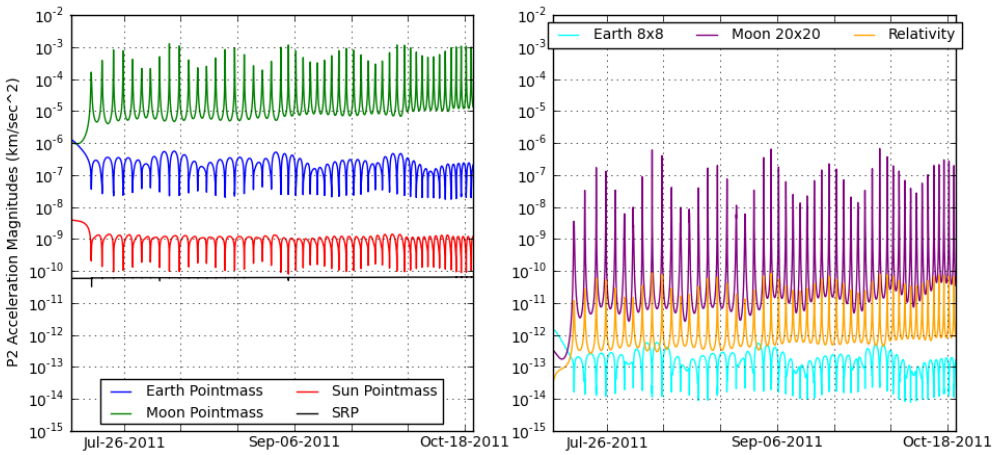


Figure 1. Magnitude of accelerations on the P2 spacecraft (relative to the Moon) during from four days before LOI through the end of the PRM sequence. The scale on both plots is identical; they are separated for clarity.

orders of magnitude as the spacecraft moves between periapsis and apoapsis (on the order of once per day). The Earth gravity magnitude also oscillates twice per lunar month as the spacecraft line of apsides rotates through 360 deg with respect to the Earth-Moon direction.

Also note from Figure 1 that the lunar and terrestrial pointmass gravitational accelerations are the dominant forces for most of the time. Much can be understood about the ARTEMIS science orbit dynamics by considering only these two accelerations in the context of the Hill three-body problem (H3BP). Such simplification allows for analytical expressions of the dynamics to inform the design process. When considered in this light, the ARTEMIS dynamics can be understood much the same ways that Jupiter and Saturn moon orbiters have been in the literature.

Firstly, the effect of the Earth's tidal acceleration on the orbit as a function of orbit orientation must be understood. When considering the Moon-centered H3BP dynamics where the frame rotates such that the Earth is always on the negative X axis, the acceleration on the spacecraft arising from the Earth's gravity is

$$\tilde{\mathbf{a}}_{tidal} = 3N^2\hat{x} - N^2\hat{z}, \tag{1}$$

where N is the mean motion of the Moon's orbit around the Earth. For a near-equatorial spacecraft orbit, the strongest accelerations occur near apoapsis. The maximum magnitude varies as the orbit line of apsides moves through 360 deg, which happens roughly every lunar orbit period. Depending on the angle of the acceleration vector with respect to the velocity vector, the next periapsis altitude is either raised or lowered, as shown in Figure 2. The net effect over one full lunar orbit period on both periapsis and semi-major axis is zero, but the intra-month oscillation magnitudes are on the order of 1000 km in periapsis altitude.

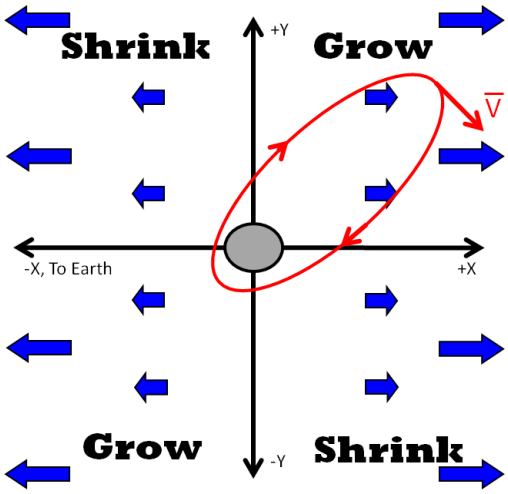


Figure 2. Diagram showing effect of Earth's tidal acceleration on semi-major axis and periapsis altitude for a retrograde lunar orbiter in the Earth-Moon rotating frame. The tidal force is strongest at aposelene. When aposelene velocity is aligned with the tidal force, the orbit grows; when it is opposed to the tidal force, the orbit shrinks. Note that a prograde orbit would exhibit the opposite effect in each quadrant since the velocity is in the opposite direction.

Secondly, the longer term effect of the Earth's gravity on the orbit elements can be understood through the secular Lagrange equations for orbit element dynamics in the H3BP (Eqns. (2)-(6)). As described in Scheeres *et al.* [5], these dynamics are derived by averaging the perturbing potential arising from the Earth's gravity: first over the spacecraft orbit period, then over the lunar orbit period. This averaged potential is then used in the general form of Lagrange Planetary Equations [6] to derive the secular dynamics of the spacecraft orbit elements in the rotating three-body frame,

$$\frac{da}{dt} = 0 \tag{2}$$

$$\frac{di}{dt} = -\frac{15}{16}\frac{N^2}{n}\frac{e^2}{\sqrt{1-e^2}}\sin 2i \sin 2\omega \tag{3}$$

$$\frac{d\Omega}{dt} = -\frac{3}{8}\frac{N^2}{n}\frac{\cos i}{\sqrt{1-e^2}}\left(2+3e^2-5e^2\cos 2\omega\right) \tag{4}$$

$$\frac{de}{dt} = \frac{15}{8}\frac{N^2}{n}e\sqrt{1-e^2}\sin^2 i \sin 2\omega \tag{5}$$

$$\frac{d\omega}{dt} = \frac{3}{8}\frac{N^2}{n}\frac{1}{\sqrt{1-e^2}}\left[5\cos^2 i - 1 + 5\sin^2 i \cos 2\omega + e^2\left(1-5\cos 2\omega\right)\right] \tag{6}$$

where a is the semi-major axis, e is the eccentricity, i is the inclination, ω is the argument of periselene, Ω is the longitude of the node, and $n = \sqrt{\mu_{Moon}/a^3}$ is the spacecraft orbit mean motion (where μ_{Moon} is the gravitational parameter of the Moon). Note that a similar effect arises from the solar gravity and SRP, though the oscillation period is longer and the amplitude is smaller magnitude.

SPACECRAFT AND MISSION CONSTRAINTS

In addition to the science goals and the natural dynamics, the trajectory design is also driven by the ARTEMIS spacecraft capabilities and the mission flight rules. A complete description of the spacecraft hardware capabilities can be found in Harvey *et al.* [7].

Foremost, P1 and P2 have limited on-board fuel reserves after completing the THEMIS mission objectives and moving to Lissajous orbit around EML1 [1], so ΔV must be used as sparingly as possible to ensure sufficient reserves for unforeseen contingencies and an eventual de-orbit of the spacecraft. The spacecraft are both spin-stabilized at a rate of roughly 19 rpm with thrusters mounted normal and parallel to the spin axis (see Figure 3). The ARTEMIS spacecraft use a blowdown propulsion system, so at this point in the mission each thruster can produce roughly a thrust of 1.5 newtons. When using the tangential thrusters (which are the most useful for almost all maneuvers), on-times must be pulsed because of the spacecraft spin which drops the effective thrust down to about 0.5 newtons. The spacecraft attitudes are nominal such that both $+Z$ axes point roughly toward the ecliptic south pole. These attitudes cannot be effectively changed by thrust due to the large inertia around the spacecraft spin axis (though gravity gradient torques precess the spin axis during lunar orbit). The on-board flight software requires all maneuvers to thrust in a fixed inertial direction, though

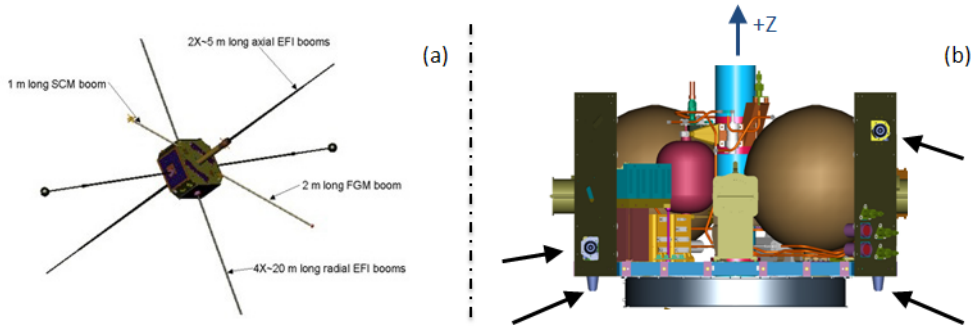


Figure 3. THEMIS/ARTEMIS Spacecraft Configuration. (a) On-orbit configuration with booms deployed, (b) spacecraft bus schematic with thruster locations (black arrows). The blue arrow indicates the spin axis ($+Z$). The two thrusters pointing in the $-Z$ are the "axial" thrusters and the two thrusters normal to $+Z$ are the "tangential" thrusters.

allows for execution of successive burn segments. Maneuvers cannot be executed during solar eclipse without significant pointing errors because the pulse timing relies on the sun sensor. The spacecraft cannot survive a solar eclipse of more than roughly 4 hr.

The ground team specifies maneuvers to the spacecraft as a number of pulses to fire. If the estimated spacecraft spin rate during the maneuver is off, the maneuver will take a different amount of time than expected. Thus, the ARTEMIS mission ops team has adopted the flight rule that a minimum of 3 min is required between thrust events. Also, for the purpose of being able to track key spacecraft activities during maneuvers, the spacecraft may not begin a maneuver less than 10 min before the start of a tracking occultation or less than 3 min after the end.

BASELINE DESIGN

Background

As part of the original ARTEMIS mission proposal in 2008 [8], a "proof-of-concept" baseline design for the P1 and P2 lunar science orbits was developed to address the heliophysics science objectives [1]. In this design, both orbiters were nearly planar with respect to the Moon's orbit around the Earth and had aposelene ranges of ~18000 km (which kept eclipse durations just under four hours). Periapsis altitudes were not a strong driver for the heliophysics goals; altitudes ranged between a few hundred to over 2000 km, though these altitudes had yet to be optimized. The P1 orbit was retrograde and the P2 orbit was prograde to induce a relative precession that varied the geometry of the lunar wake measurements.

When the time came to revisit the design at a higher fidelity in early 2011, a significant rework of the "proof-of-concept" lunar orbit plan from the 2008 proposal was required. Primarily the changes needed arose from the recognition that planetary science could be done by ARTEMIS in addition to heliophysics. The addition of these new goals called for the science orbit to be inclined out of the lunar orbit plane, for the number of periselenes under 50 km to be maximized, and for at least one of the spacecraft to be in place for joint exosphere measurements with the LADEE mission (see "Lunar Orbit Phase Science Objectives" above).

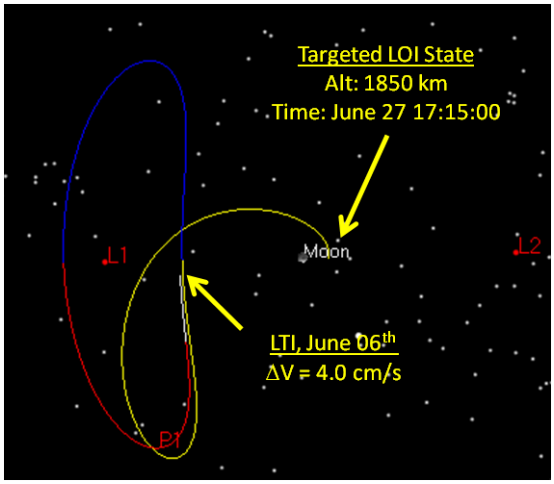
Baseline Description

The baseline trajectory design for the ARTEMIS P1 probe is shown in Figure 4. P1 begins its departure from the Lissajous orbit around EML1 on June 6, 2011 with the lunar transfer initiation (LTI) maneuver. The P1 lunar orbit insertion (LOI) maneuver occurred on June 27, 2011. The 150.5 min of maneuver pulsing duration for LOI was divided into three burn segments and targetted an orbit period of roughly 56 hours. Over the next 1.5 months, four period reduction maneuvers (PRMs) are planned to move P1 into a 29 hr science orbit. The total ΔV cost for the baseline P1 LOI and PRMs design is 94.2 m/s. The details of the PRM sequence for P1 are given in Table 1.

Burn Name	Date	Total ΔV (m/s)	# of segments	total thrust duration (min)	segment durations (min)
P1 LOI	June 27, 2011	50.2	3	150.5	43.6/56.6/50.2
P1 PRM-1	July 3, 2011	14.3	2	42.1	29.7/12.5
P1 PRM-2	July 7, 2011	1.4	1	4.0	n/a
P2 LOI	July 17, 2011	71.9	3	209.8	69.9/69.9/69.9
P2 PRM-1	July 23, 2011	8.2	2	23.6	11.8/11.8
P1 PRM-3	August 10, 2011	9.4	2	27.5	15.8/11.7
P1 PRM-4	August 13, 2011	18.9	3	54.8	24.5/18.2/12.2
P2 PRM-2	September 2, 2011	13.2	2	37.5	30.5/7.0
P2 PRM-3	October 3, 2011	14.0	2	39.5	33.4/6.1
P2 PRM-4	October 14, 2011	11.9	2	33.5	16.9/16.6

Table 1. LOI and PRM maneuver details for both spacecraft in chronological order.

The baseline trajectory design for the ARTEMIS P2 probe is shown in Figure 5. P2 began its departure from the Lissajous orbit around EML1 on June 20, 2011 with its LTI-1 maneuver, followed by the LTI-2 deterministic targeting maneuver on June 28, 2011. The P2 LOI maneuver occured on July 17, 2011. The 209.8 min of maneuver pulsing duration for LOI was divided into three burn segments and targeted a roughly 55 hr orbit. Over the next three months, four PRMs are planned to move P2 into a 27.5 hr science orbit. The total ΔV cost for the baseline P2 LOI and PRMs design is 119.2 m/s. The details of the PRM sequence for P2 are given in Table 1.



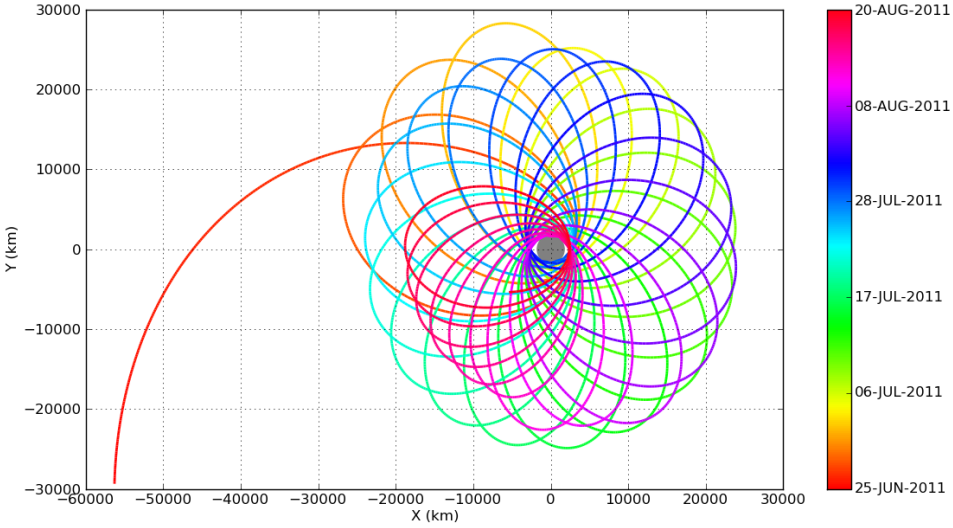
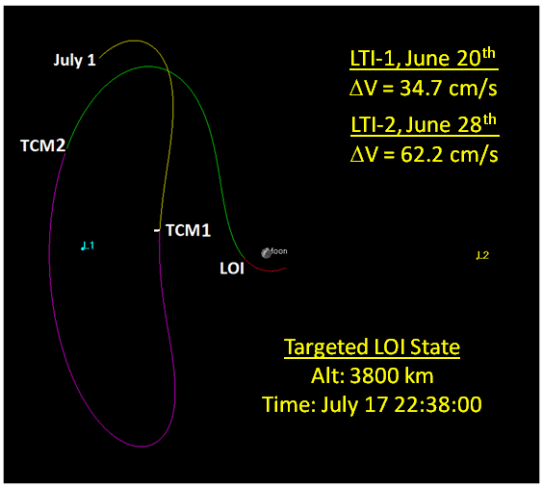


Figure 4. P1 transfer from Lissajous orbit around EML1 to the lunar science orbit (rotating frame where Earth is along the $-X$ axis to the left). (top) Transfer from Lissajous to LOI. (bottom) LOI to science orbit.



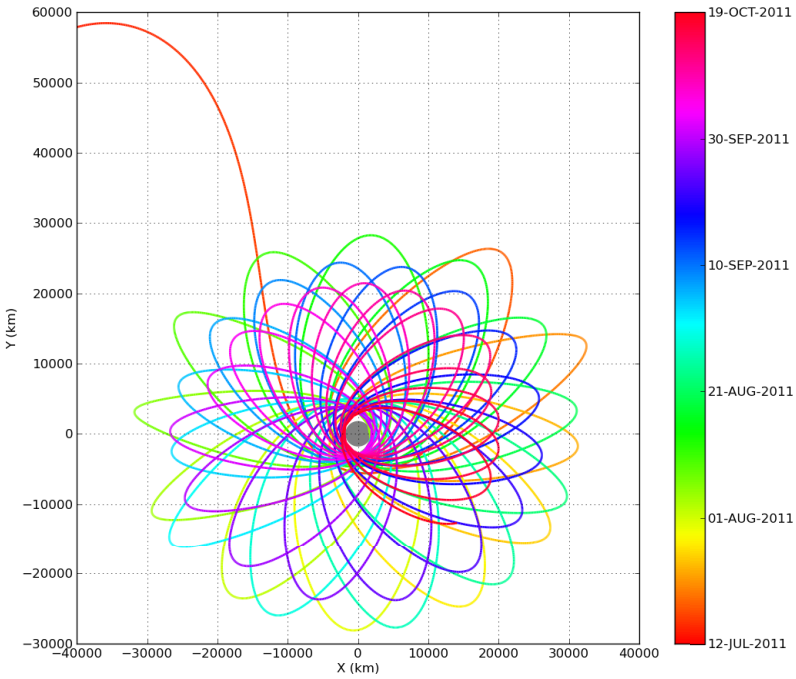


Figure 5. P2 transfer from Lissajous orbit around EML1 to the lunar science orbit (rotating frame where Earth is along the $-X$ axis to the left). (left) Transfer from Lissajous to LOI. (right) LOI to science orbit.

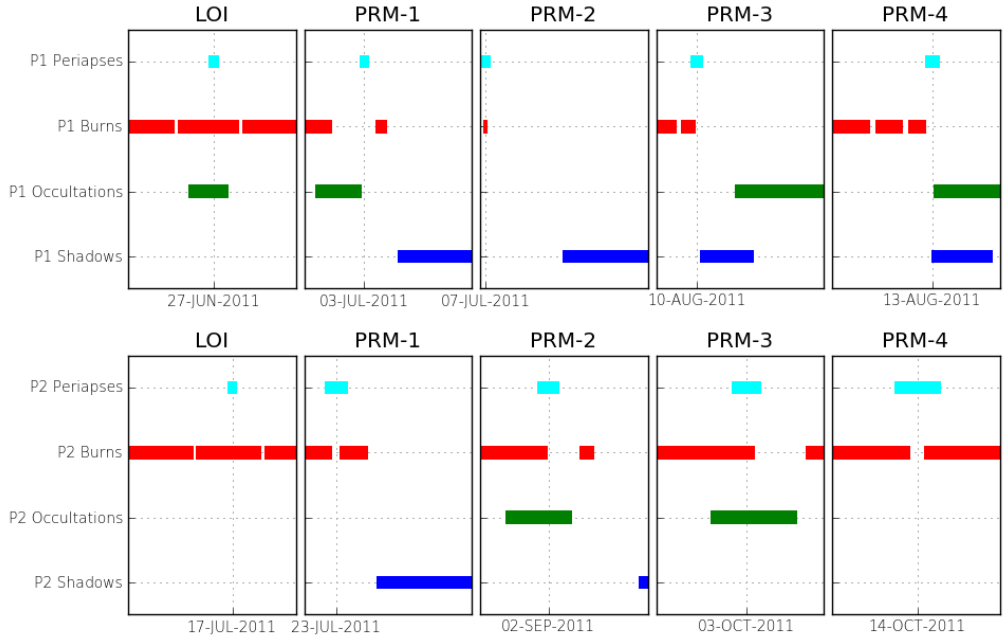


Figure 6. Placement of the P1 (top) and P2 (bottom) LOI and PRM burn segments with respect to occultations and eclipses. The cyan bar covers periapsis ± 5 min.

LOI and PRM placement and segmentation

The LOI and PRM sequence for each spacecraft must reduce the aposelene sufficiently to avoid long eclipses and leave periselene altitudes low (less than 50 km) while using as little of the remaining on-board fuel as possible. Because of the low available thrust, the transition to science orbit must be achieved over many periapsis maneuvers. The key to fuel efficiency is to select the best combination of periapses at which to apply maneuvers and allocate the total thrusting time between them so as to minimize gravity and steering losses. For ARTEMIS, the design choices are the initial LOI altitude, which periapses to allow a PRM at, the total burn time allocated for each burn location, and how many segments to use for each burn. This problem is difficult because small differences in phasing (i.e., the orbit periods between burns) or periapsis selection move the solution between the "domain of attraction" of the problem's many local minima. Given the resources of ARTEMIS, the best values of these inputs were determined through human tinkering and intuition supported by numerical optimization results from simplified sub-problems. Once the inputs are determined, the thrust directions and start/stop times are numerically optimized for each LOI or PRM individually. The integrated trajectory results are evaluated based on ΔV cost and science achieved. It should be noted that other intangibles factored into the "optimization" process. Foremost was consideration of the operations schedule. It was considered very important that P1 maneuver and maneuver preparation activities did not interfere with P2 similar activities and vice versa.

The total impulsive delta-V needed to transition both spacecraft from approach to the science orbits is roughly 100 m/s. Recall that the effective thrust that can be delivered by the tangential spacecraft thrusters is about 0.5 newtons, which corresponds to about 6 mm/s^2 acceleration for the 85 kg ARTEMIS spacecraft. Thus, each spacecraft must thrust for roughly 300 min to reach the science orbit. The fact that the spacecraft can only thrust in a constant inertial direction for each burn also introduces steering losses when the thrust is not directed along the anti-velocity direction. Finally, the presence of occultations and eclipses near periapsis increases gravity and steering losses by forcing burn times further from periapsis and/or forcing sub-optimal burn segmentations. The placement of the LOI and PRM maneuver segments for both spacecraft relative to periapsis, occultations, and eclipses is shown in Figure 6.

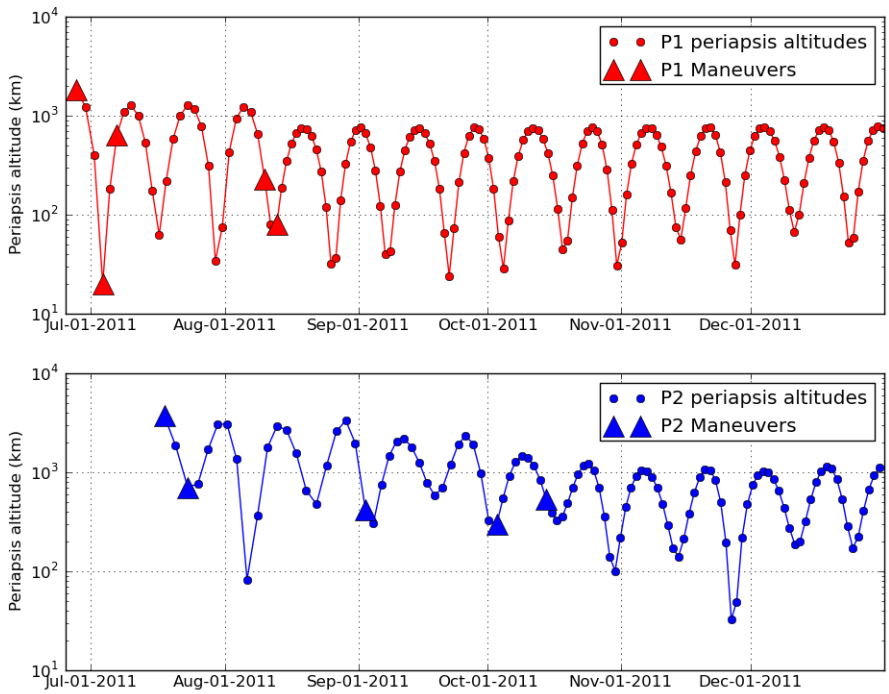


Figure 7. Baseline periapsis altitudes (km) and maneuver locations for P1 and P2 through the end of 2011.

LOI design The LOI burn for both spacecraft needed to be sufficiently large to capture into a conic lunar orbit with apoapsis low enough to avoid impact induced by Earth perturbations within the first few periapses. For both spacecraft, this required roughly half of the total thruster on-time be done at LOI. The altitude of the LOI periapsis was a free variable in the design. The lower the altitude, the more efficient the LOI would be, but depending on the initial orbit orientation relative to the 2-week periapsis cycle, the changes in the next few periapses prevented both spacecraft from starting too low. The ultimate design decision for a 150.46 min LOI at 1850 km for P1 and a 209.8 min burn at 3800 km for P2 suitably balanced impact risk and efficiency. A three segment implementation was chosen for both burns.

PRM placements The remaining ΔV needed to achieve the science orbit is allocated over various periapses as PRM burns. Not all periapsis locations are equally efficient. The higher the periapsis velocity is, the more efficient the burn is. The highest speeds are at the minimum periapsis altitudes, which vary over the lunar month (see Figures 2 and 7) and on a multi-month cycle with the mean eccentricity (Eqn. (5)). The altitude (i.e., efficiency) of the various periapsis locations also changes depending on what PRM activities occur before it. Finally, the relative location of the occultations and eclipses with respect to periapsis must be considered when considering the relative efficiency of one periapsis to another. In a large fraction of cases, the PRM or PRM segments cannot be centered on periapsis or cannot be optimally segmented because of these constraints. Figure 7 shows the time history of periapsis altitudes for P1 and P2 during the PRM phase with the LOI and PRM burn locations marked as triangles.

The choice of which periapses to use for performing PRMs can be used to manipulate the subsequent periapsis altitudes in an efficient way. When applied at the lowest periapsis in the 2 week periapsis altitude cycle (Figure 2), the resultant reduction in in apoapsis reduces the magnitude of the 2 week oscillation while

keeping the lowest altitude roughly fixed. PRMs at periapses that are not at the 2 week minimum altitude raise the subsequent 2 week oscillation minimum, which is useful when terrestrial or solar perturbations are driving the periapsis altitude down on a longer time scale. Apoapsis burns can also be used to change periapsis altitude more directly, but they are less efficient in removing orbit energy.

Reaching Crustal Magnetic Anomalies

The Moon's orbit around the Earth is inclined between 6.5 and 6.9 deg relative to the lunar equator from LOI through 2013. Thus, an orbit in the Moon's orbit plane can only flyover lunar surface locations up to 6.9 deg from the equator. Further, consideration of the bi-monthly oscillation in periapsis altitude (see the "Natural Dynamics" section and Figure 2) reveals that the lowest periselene altitudes will occur only near 90 and 270 deg longitude for P1 (retrograde), and only near 0 and 180 deg longitude for P2 (prograde). Because the spacecraft must generally be at < 50 km altitude to measure crustal magnetic anomalies, the anomalies measured must be near these longitudes. Table 2 lists the known magnetic anomaly targets for ARTEMIS.

Name	Longitude Extent	Latitude Extent
Oriental Antipode	$(85°E,\ 110°E)$	$(0°,\ 25°N)$
Unnamed	$(170°W,\ 175°W)$	$(10°N,\ 15°N)$
Unnamed	$(160°E,\ 165°E)$	$(7°S,\ 2°N)$
Descartes	$(13°E,\ 18°E)$	$(9°S,\ 12°S)$
Hartwig	$(76°W,\ 84°W)$	$(3°S,\ 17°S)$
Reiner Gamma	$(53°W,\ 62°W)$	$(3°N,\ 13°N)$
Rima Sirsalis	$(50°W,\ 60°W)$	$(2°N,\ 15°N)$
Crisium Antipode	$(118°W,\ 128°W)$	$(12°S,\ 25°S)$

Table 2. List of known crustal magnetic anomalies reachable by ARTEMIS.

While the longitudes of the sub-50 km periapses cannot be modified with the available thrust, the science orbit inclinations can be increased away from planar to enable higher latitude anomaly measurements. It was found that a large range of lunar orbit inclinations can be achieved for very little ΔV if the targeting is done while still in Lissajous orbit (especially compared to a traditional plane change in lunar orbit). For the ARTEMIS Lissajous orbits (which are maintained using the method described in [9]), a long-period oscillation in the out-of-plane (Z) coordinate was observed (see Figure 8). The trend progressed from larger oscillations, to smaller oscillations (a near planar orbit around late March 2011 for P1), back to large oscillations, and ultimately would have led to escape from Lissajous (without correction). The lunar science orbit inclination directly depends on the Z amplitude of the Lissajous orbit when the spacecraft leaves EML1. Two approaches were used to manipulate the science orbit inclination to improve crustal anomaly measurements. First, the exit from Lissajous orbit was postponed by 2.5-3 months on both spacecraft to wait for larger Z amplitudes, i.e., higher lunar orbit inclinations (as well as to allow more science gathering from Lissajous and time to design the lunar science orbit). Second, the phasing of the longer term oscillation in Figure 8 was adjusted to extend the duration of stable Lissajous operation and to fine tune the science orbit inclination. The sensitivity of the science orbit inclination with respect to out-of-plane ΔV in Lissajous orbit was found to be very high (see Figure 9).

The question of how much to incline the orbit can be addressed by the mean planetary equations given in Eqns. (2)-(6). First, Eqns. (3), (6), and (5) show that the periapses furthest from the lunar orbit plane occur when the inclination is at the minimum of its oscillation cycle (see confirmation in Figure 10). Thus, the science orbit inclination must be chosen large enough so that at its minimum it allows flyovers of the

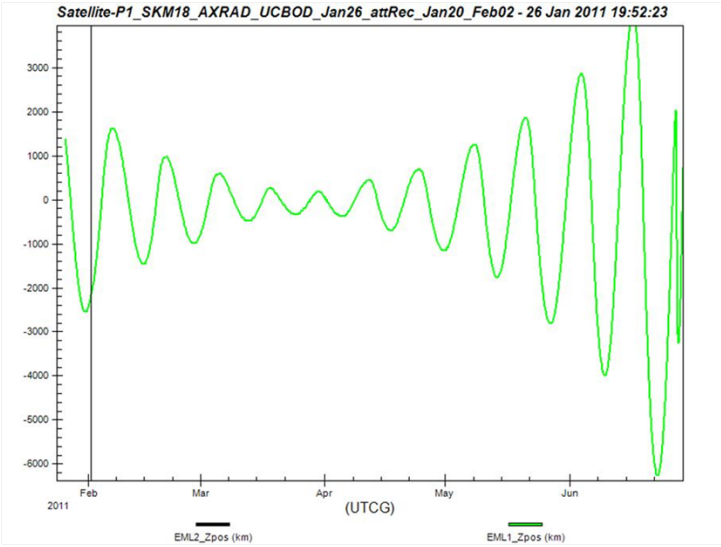


Figure 8. Time history of the P1 out-of-plane coordinate while in Lissajous orbit. The science orbit inclination was strongly tied to the Z oscillation magnitude at the time of LTI. The vertical black line shows the timing of the P1 maneuver to modify the science orbit inclination.

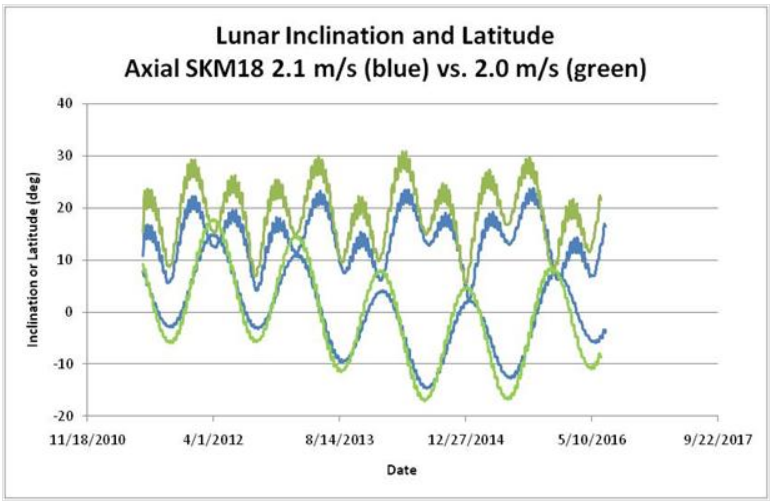


Figure 9. Figure shows variations in inclination (top lines) and periapsis latitude (bottom lines) with respect to the lunar equator resulting from a mere 10 cm/s change in an out-of-plane burn done in Lissajous orbit. Periapsis latitudes vary by up to 5 deg.

anomalies of interest. The inclination cannot be chosen too far from planar though or long-term stability is lost. Eqns. (2), (3), and (5) rely on a secularly increasing value of ω to remain stable, i.e., to oscillate between bounds. If ω instead oscillates, then the eccentricity tends towards a large value, resulting in impact. Algebraic manipulation of Eqn. (6) yields a critical value of inclination/co-inclination for ARTEMIS of about 70 deg ; inclinations below the value are stable, those above are unstable. This places an upper bound on allowable inclinations. Also note from Eqn. (5) that periapsis altitude oscillations increase in magnitude for larger inclinations, which interferes with achieving as many low periapses as possible.

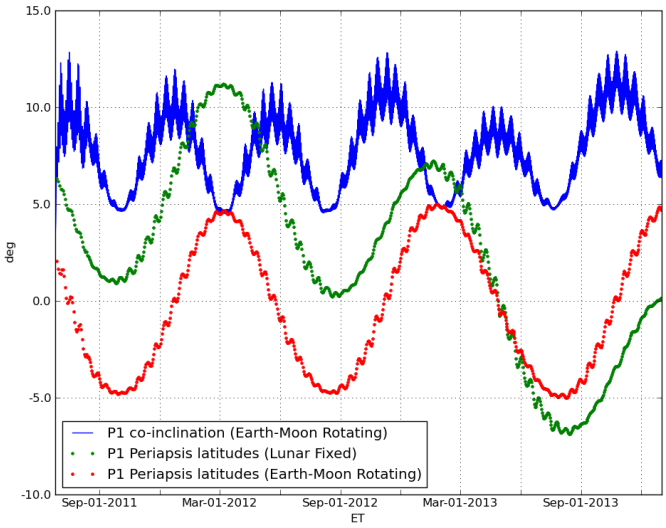


Figure 10. Evolution of the integrated P1 baseline trajectory inclination and periapsis latitudes over time. As predicted by the secular Lagrange equations, extreme periapsis latitudes (in the Earth-Moon rotating frame) occur when inclination is closest to planar. Periapsis latitudes are also shown in lunar surface fixed coordinates for reference.

The decision was ultimately made to execute the P1 plane change maneuver on February 1, 2011 as an axial burn (using thrusters along the spacecraft Z axis) of 2.1 m/s. The P2 plane change was achieved over three axial maneuvers executed in January and February 2011 totaling 1.2 m/s of out-of-plane $\Delta V^{\dagger}$. With these maneuvers, the P1 spacecraft can reach lunar latitudes up to 12 deg and P2 can reach latitudes up to 17 deg.

Placing ARTEMIS line of apsides at dawn during LADEE science

The LADEE mission science phase is planned for a 3-month duration in a low-altitude circular polar orbit. The nominally planned May 2013 launch places the science phase from mid-July to mid-October and the latest possible launch puts the science phase from mid-December to mid-March 2014. The ARTEMIS science orbits should be designed such that at least one of the spacecraft will be within 30 deg of the dawn terminator plane at an altitude under 200 km during the LADEE science phase regardless of when launch occurs. The P1 (retrograde) orbit line of apsides completes a full rotation relative to the Sun approximately every 9.5 months. The P2 (prograde) orbit requires about 17 months for a full rotation. Because of this long precession period, careful phasing of the line of apsides precession and eccentricity oscillations is needed place a low periapsis near dawn during the time when LADEE may be at the Moon.

The 2008 "proof-of-concept" plan for the transfer from Lissajous to LOI was designed to minimize mission delta-V and the science orbit size was designed to satisfy the maximum eclipse duration constraint. With the original approach geometry and orbit size, P1 was found to have periapsis near the dawn terminator in late December 2013 / early January 2014, which would cover the later possible LADEE science orbits (see Figure 11). P2, however, was $60-120$ deg out of phase and did not have low altitude crossings of the dawn terminator during LADEE.

†These multi-purpose maneuver also stabilized the out-of-plane oscillations to extend Lissajous operations and tweaked the trajectory to avoid a long Earth eclipse.

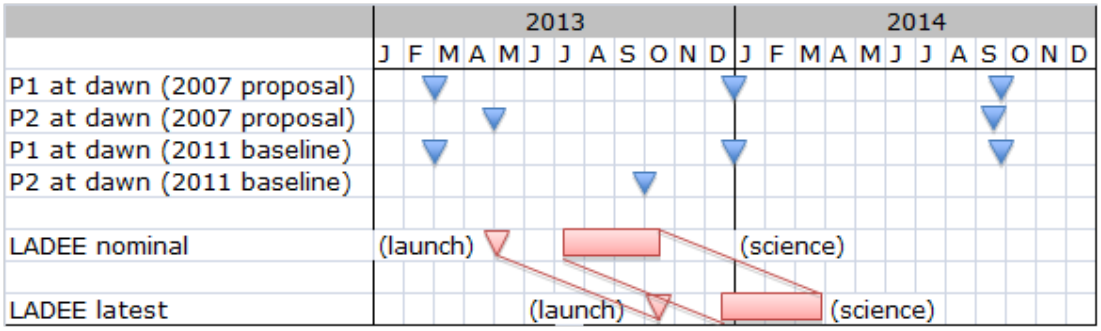


Figure 11. Timeline for planned LADEE mission operations compared with the 2008 proposed and the 2011 baseline lunar science orbit dawn terminator crossings. Each dawn crossing opportunity here actually represents a period of time when 5-15 measurement opportunities may occur.

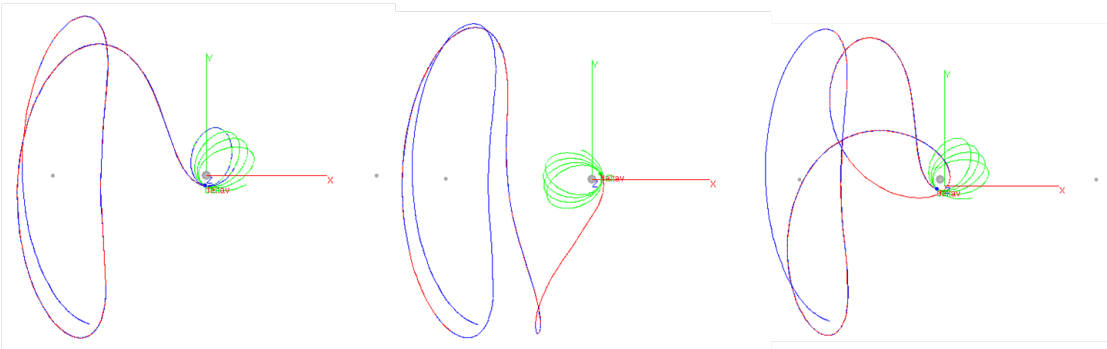


Figure 12. Three different approach geometry options for the P2 approach to a prograde orbit from Lissajous around EML1. ARTEMIS chose to implement the leftmost option.

To attain the desired P2 dawn terminator timing, the initial longitude of periapsis and/or the precession rate needed to be modified. There were many ways to modify one or both of these. Each additional Lissajous orbit flown before transferring to the lunar orbit can change the initial longitude of periapsis by 195 deg. Delaying the PRM sequence (after LOI) so that the orbit has an apoapsis radius near 30000 km for an extended period of time induces a difference in the precession rate relative to the nominal 18000 km science orbit of about 3 deg per month. For P2, the best approach was to change the initial longitude of node by changing the approach geometry from Lissajous orbit at EML1. Figure 12 shows three different trajectory geometries that can be used for the approach. The original plan called for the approach shown in the center, but the approach on the left was chosen to align P2 with LADEE in the September/October 2013 timeframe (Figure 11).

Since the dawn crossings altitudes must be less than 200 km, ARTEMIS must also be near a minimum in the multi-month periapsis altitude cycle described by the mean element equations (Eqns. (2)-(6)). Eccentricity (Eqn. (5)) should be at a maximum at the dawn terminator crossing. The oscillation in eccentricity is primarily driven by ω; if the rate of change in ω (Eqn. (6)) can be changed, then the timing of the maximum eccentricity can be phased appropriately. The most effective way to do this is to change the orbit mean motion n by tweaking the post-PRM semi-major axis. A 1000 km increase in the P2 semi-major axis changes $d\omega/dt$ by 7.5%. An increase on this order was effective in lining up P2 for low periapses at dawn during the LADEE mission. The increase in orbit inclination done to improve crustal anomaly measurements allowed the orbit size to be increased by this amount without violating the design requirement of a < 4 hr maximum eclipse duration.

Planetary enhancement burns

Finally, once into the lunar science orbit, small maneuvers are planned to be done from time-to-time to optimize periapsis altitudes and phasing for planetary science objectives. These maneuvers are called Planetary Enhancement Burns (PEBs). They are needed to keep the minimum periapsis altitudes low throughout the lunar orbit phase because solar effects introduce a long-term oscillation that otherwise reduces the quality of the measurement opportunities. The PEBs are planned to occur in the 2012-2013 timeframe and are not yet finalized.

SCIENCE OPPORTUNITIES

The baseline designs allow for the desired science measurement opportunities within the limitations of the dynamics and on-board fuel. This section describes the trajectory characteristics with respect to the desired science opportunities.

Lunar wake crossings

The primary heliophysics goal for the lunar orbit science phase is to measure the backfill of the solar wind behind the non-magnetized Moon. This is achieved by flying the spacecraft over the Moon's dark side at a variety of altitudes to map out the wake and its variations over different spatial scales with different P1 to P2 separations. Figure 13 shows the crossings of the lunar wake expected for both spacecraft through the end of 2013. Many measurement opportunities exist as the relative orientation of P1 and P2 varies throughout the mission.

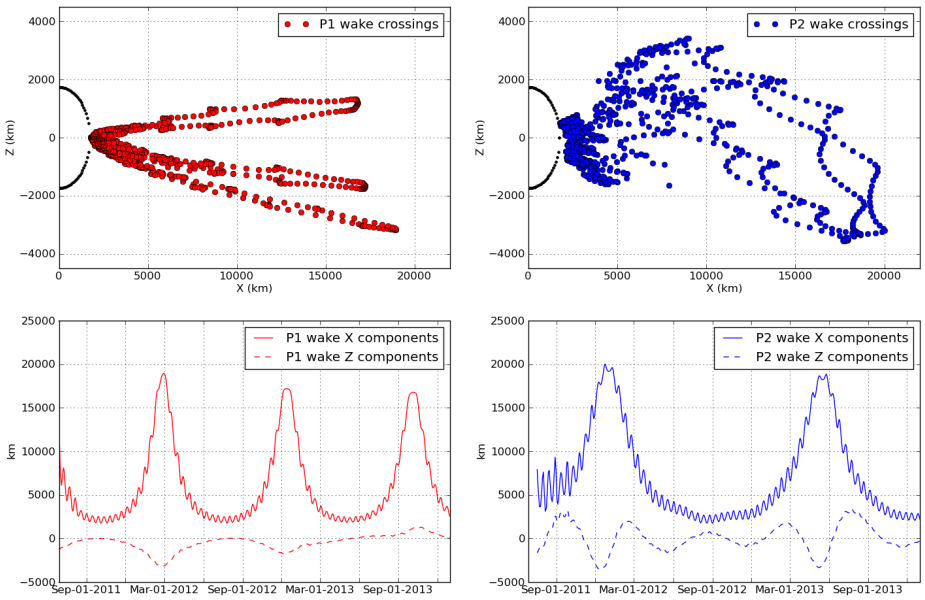


Figure 13. Wake crossing geometries and coordinates with respect to time in a Sun-Moon synodic frame through the end of 2013. Each point corresponds to an instantaneous wake center, but in reality represents an orbit arc within and around the wake, ranging in length from a few thousand to tens of thousands of km, and having a wide variety of orientations and scales.

Crustal magnetic anomalies

Figure 14 shows periapsis locations (in lunar surface coordinates) and altitudes of the baseline P1 and P2 trajectories with respect to the crustal magnetic anomalies in Table 2. The magnetic anomalies and their approximate extent are shown as transparent colored rectangles. Recall that periapses should be under 50 km altitude and either directly above or within a small displacement in longitude from the anomaly for optimal measurements. During the first few years of the mission, P1 has many more measurement opportunities than P2. The P2 orbit is significantly more perturbed by the Sun due to its prograde precession which makes consistently low altitude difficult to achieve. Plans are currently under study to reduce the apoapsis altitude for P2 if LADEE launch slips beyond early August 2013, which will increase the number and quality of magnetic anomaly encounters by P2. Furthermore, a small fuel expenditure (order of 5m/s) is being considered to reduce periapsis for a period of time (one to two months) after the PRMs have been completed to increase the number of low P2 periapses.

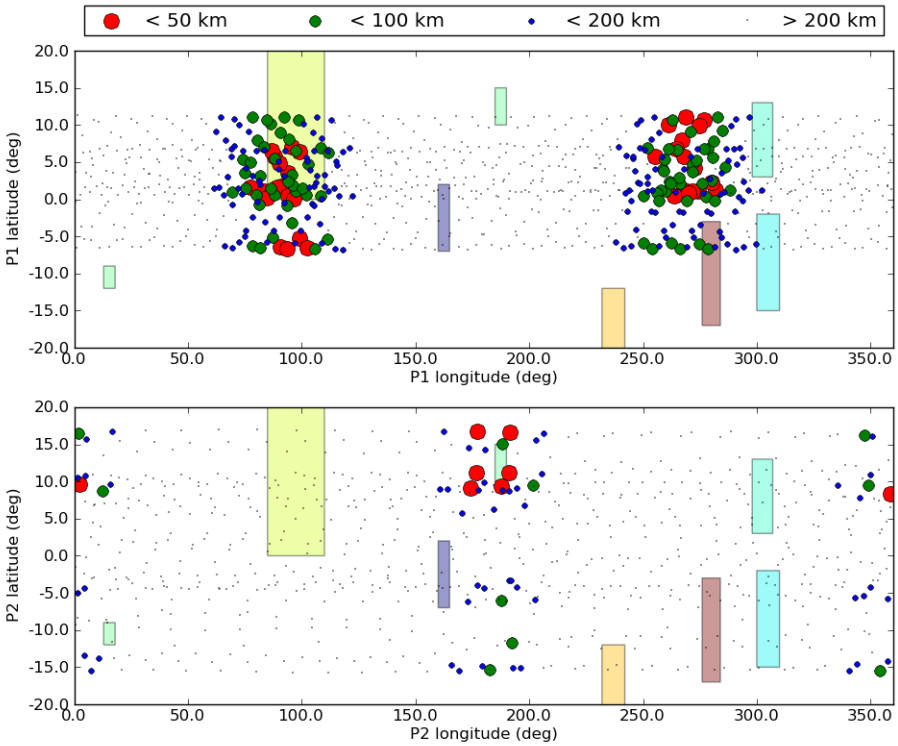


Figure 14. ARTEMIS periapsis locations and altitudes (dots) through mid-2014 with respect to the crustal magnetic anomalies in Table 2 (colored rectangles).

Exosphere measurements and alignment with LADEE

Figure 15 shows exosphere measurement opportunities near the dawn terminator crossings for P1 and P2 that result from the baseline trajectories. The figure demonstrates the long precession period for both spacecraft; these measurement opportunities only occur once every 9.5 months for P1 and once every 17 months for P2. Note that these precession periods are properly aligned to allow coordinated measurements with LADEE in late 2013 / early 2014. Exosphere measurements are also useful across a range of altitudes from 100s to 1000s of km at varying local solar times. Figure 16 shows the periapsis altitudes achieved through 2014. The achieved periapses cover a range of altitudes and local solar times.

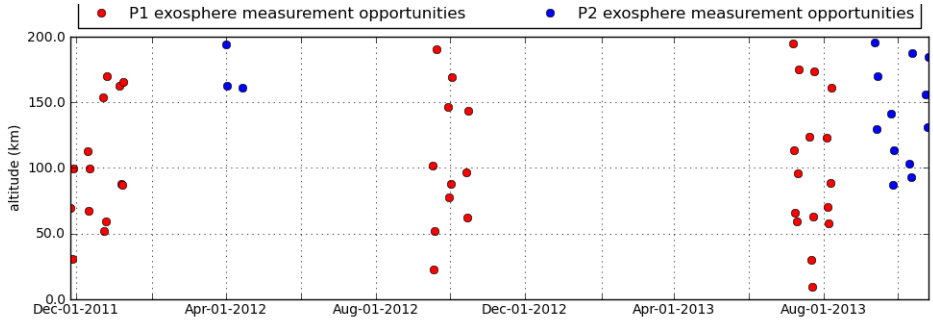


Figure 15. ARTEMIS exosphere measurement opportunities (i.e., when periapsis is less than 200 km and within 30 deg of the dawn terminator). The opportunity rich periods in late 2013 and early 2014 correspond to the earliest and latest expected LADEE science phase, respectively.

MISSION STATUS

At the time of this writing, both P1 and P2 are in the midst of the transition from Lissajous orbit around EML1 to their respective science orbits. P1 has successfully completed a three-segment LOI burn on June 27, 2011 and the two-segment PRM-1 burn on July 3, 2011. Because the P1 LOI burn was approximately 6% hot, the planned PRM sequence has been modified somewhat from the baseline design presented here (though the baseline design is still representative). The upcoming burns now scheduled for P1 are PRM-2 on July 31, PEB-1 on August 3, PRM-3 on August 12, and PRM-4 on September 7. P2 has also successfully completed its LOI maneuver on July 17, 2011. Performance of the maneuver was very near nominal and the PRM sequence is planned to continue as described in the baseline.

CONCLUSIONS

The baseline design for the ARTEMIS lunar orbit phase takes advantage of (and endures) complex three-body dynamics to achieve a number of science objectives with limited fuel costs. The baseline designs for the ARTEMIS P1 and P2 spacecraft trajectories from Lissajous orbit around the Earth-Moon L1 point through the lunar orbit science phase have been presented. The trajectory design methodologies used to ensure satisfaction of the heliophysics and planetary science goals have been outlined. The insights presented in this paper will be of interest to other missions considering eccentric orbits to planetary moons. Finally, a preview of the expected science measurement opportunities that arise from the trajectory design has been presented.

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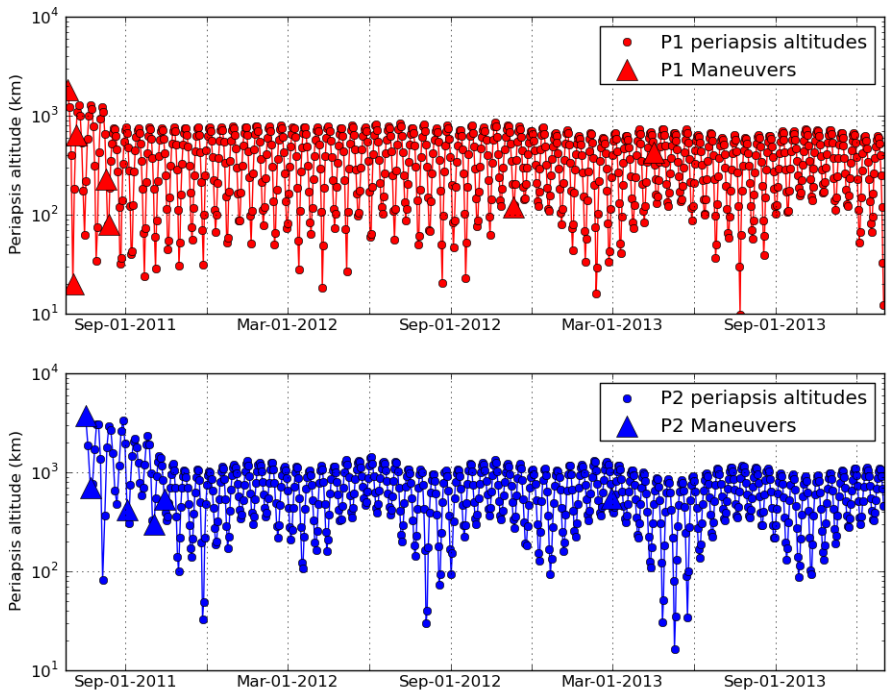

Figure 16. ARTEMIS planned periapsis altitudes for P1 (top) and P2 (bottom) through 2014.

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