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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 eccentric orbiter missions at planetary moons.

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 [1] that has relocated two of the THEMIS spacecraft from Earth orbit to the Moon [2, 3, 4]. ARTEMIS plans to conduct a variety of scientific studies at the Moon using the on-board particle and fields instrument package [5, 6]. 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 28 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 transitioned a more eccentric orbit upon initial capture at the Moon *en route* to a less eccentric operational orbit [7].

that are more typically considered in the context of outer planet moon orbiters. Further, ARTEMIS plans a number of different science investigations while in lunar orbit [5, 6], many 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.

The paper begins with a review of the scientific objectives for ARTEMIS and the implications for trajectory design. Next, the lunar orbit dynamics are discussed, along with the qualitative 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

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 [6], 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 and surface charging;
- Coordinated measurements with NASA's forthcoming Lunar Atmosphere and Dust Environment Explorer (LADEE) to characterize the near-terminator exosphere.

It is desired to get as many measurements as possible in each area so as to maximize spatial resolution, capture variations as the Moon moves in and out of the Earth's magnetotail, and observe under varying solar wind conditions. 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 above science measurement objectives directly drive the design of the lunar science orbit and approach from Lissajous. To achieve the desired lunar wake measurements, the two 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 and in the vicinity of the anomaly. Each anomaly dictates a minimum orbit inclination required to achieve this. Measurements of the lunar exosphere require a range of altitudes and orientations with respect to the Sun. To coordinate near-terminator exosphere investigations with LADEE, an ARTEMIS spacecraft must be below 200 km within 30 deg of the dawn terminator at least once during the 3-month LADEE science mission scheduled for 100 days between July 2013 and March 2014 (depending on launch date) [8, 9]. Finally, to maximize the quantity of all measurements, the orbits should have long-term stability.

SPACECRAFT DYNAMICS

Dynamic Model for Trajectory Integration

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 are used to accurately integrate the spacecraft dynamics in the design process:

- 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);
- Spacecraft thrust.

Relativistic accelerations and a higher-order gravity terms for the Earth are 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 qualitatively similar). The magnitude of the first three accelerations listed above oscillate over several 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. The relative solar gravity oscillates every 9.5 or 17 months (P1 and P2, respectively), primarily driven by variation in the distance between the spacecraft and the Earth. The SRP acceleration oscillates annually, primarily driven by the range between the Earth and Sun.

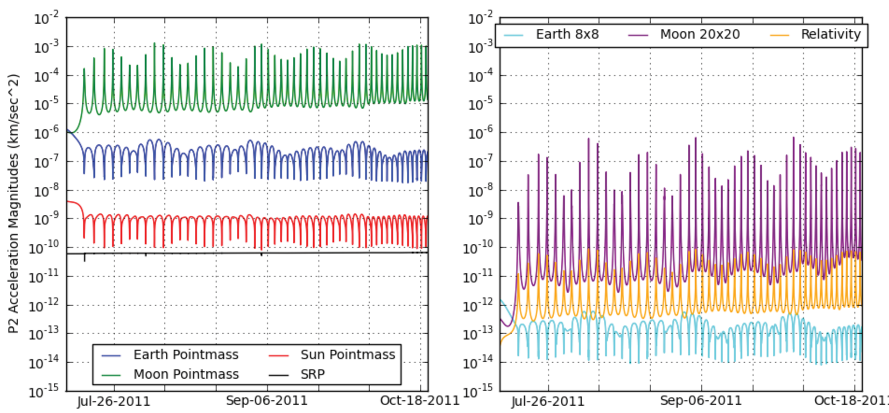


Figure 1. Magnitude of accelerations on the P2 spacecraft (relative to the Moon) from four days before LOI through the end of the PRM sequence. The logarithmic scale for the y-axis on both plots is identical; they are separated for clarity.

Qualitative Dynamical Insights

Figure 1 shows that the lunar and terrestrial pointmass gravities are the dominant accelerations in the dynamics. The non-Keplerian motion of the ARTEMIS probes while in lunar orbit can be qualitatively understood by considering only these two accelerations in the context of the Hill three-body problem (H3BP)† [10]. 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 [11, 12, 13].

Firstly, the short-period influence of the Earth's gravity as a function of orbit orientation should be understood. When considering the Moon-centered H3BP dynamics in a frame that rotates so the Earth is always

†The H3BP relies on the assumptions that the second primary is much smaller than the first and that spacecraft motion occurs very close to the second primary to simplify the dynamics of the circular-restricted three-body problem. For the ARTEMIS orbits in the Earth-Moon system, these assumptions are not sufficiently satisfied to allow for accurate integration using the H3BP equations of motion. However, the qualitative behavior of the H3BP is found to represent the full integrated dynamics well.

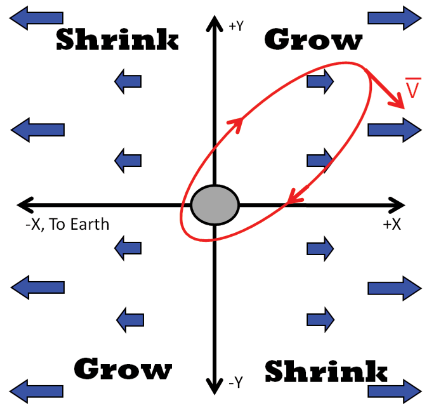


Figure 2. Diagram showing effect of Earth's gravity on semi-major axis and periapsis altitude for a retrograde lunar orbiter in the Earth-Moon rotating frame. The tidal force is strongest at aposelene. When aposelene velocity is aligned with the tidal force, the orbit grows; when it is opposed to the 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.

on the negative X axis, the combined acceleration arising from the Earth's gravity and the rotating frame that perturbs the Keplerian dynamics of the spacecraft is

$$\tilde{\mathbf{a}}_{perturbation} = \left(3N^2x + 2N\dot{y}\right)\hat{x} - \left(2N\dot{x}\right)\hat{y} - N^2z\hat{z}, \tag{1}$$

where N is the mean motion of the Moon's orbit around the Earth, and x, y, z are the spacecraft coordinates in the rotating frame. For the near-equatorial orbits used by P1 and P2, the strongest energy-changing perturbations generally occur near apoapsis. The magnitude of the apoapsis perturbation varies as the orbit line of apsides moves through 360 deg relative to the Earth roughly every lunar orbit period. Depending on the orientation of the acceleration vector with respect to the apoapsis velocity vector, the subsequent periapsis altitude is either raised or lowered relative to the Keplerian solution, as illustrated in Figure 2. The net effect over one full lunar orbit period on both periapsis and semi-major axis is zero, but the bi-monthly oscillation magnitudes are on the order of 1000 km in periapsis altitude.

Secondly, the longer term effect of the Earth's gravity on the orbit elements is understood using the secular Lagrange equations for orbit element dynamics in the H3BP (Eqns. (2)-(6)). As described in Scheeres *et al.* [11], 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 potential is then used in the general form of the Lagrange Planetary Equations [14] to derive the averaged 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).

Two different regimes of motion exist in these equations: a general situation where ω monotonically increases though 360 deg and another where ω librates around 90 or 270 deg if the orbit is sufficiently inclined and has the correct initial conditions [15, 12]. Both situations result in oscillatory behavior in eccentricity and inclination, though the magnitude of the oscillations varies. For the librating case, periapsis will always be in the same hemisphere (since ω remains near 90 or 270 deg) while in the general case, periapses will occur in both hemispheres [13]. "Frozen" orbits exist as a special case of the librating ω situation where e, i, and w are fixed for all time with an appropriate choice of initial conditions [12, 16]. In all cases, the averaged semi-major axis is conserved.

SPACECRAFT AND MISSION CONSTRAINTS

In addition to the science goals and the spacecraft dynamics, the trajectory design is also driven by the ARTEMIS spacecraft capabilities and the mission flight rules. A more complete description of the spacecraft hardware, instruments, and capabilities can be found in Harvey *et al.* [17].

Foremost, P1 and P2 have limited on-board fuel reserves after completing the THEMIS mission objectives and moving to Lissajous orbit around EML1 [4], so ΔV must be used sparingly 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 have a blowdown propulsion system and at this point in the mission each thruster can produce roughly 1.5 newtons of thrust. 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 during the lunar orbits are nominally 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 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 greater than 50% solar eclipse for more than roughly 4 hr.

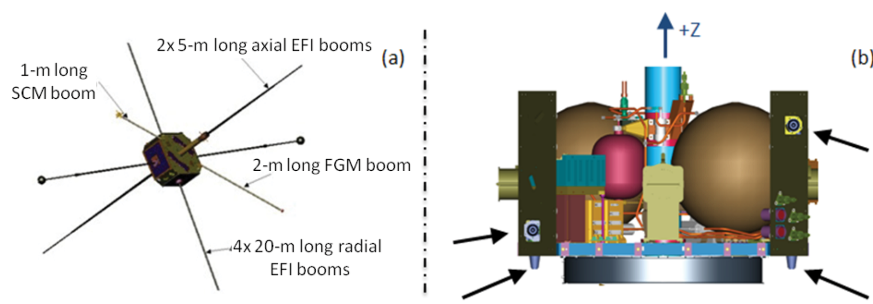


Figure 3. THEMIS/ARTEMIS Spacecraft Configuration. (a) On-orbit configuration (image credit: NASA, (*http://www.nasa.gov/images/content/164405main_-THEMIS-Spacecraft_bus2.jpg*); (b) spacecraft bus schematic with thruster locations (black arrows). The blue arrow indicates the spin axis ($+Z$). The two thrusters pointing along $-Z$ are the "axial" thrusters and the two thrusters pointing normal to $+Z$ are the "tangential" thrusters.

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 miscalculated, 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 communications blackout due to occultation by the Moon or less than 3 min after the end.

BASELINE DESIGN

Background

As part of the original ARTEMIS mission proposal in 2008, a "proof-of-concept" baseline design for the P1 and P2 lunar science orbits was developed to address the heliophysics science objectives [2]. 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 the maximum eclipse duration just under 4 hr). 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 illustrated in Figure 4. P1 began 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 thrusting duration for LOI was divided into three burn segments and targeted an orbit period of roughly 56 hr. 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.

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 occurred on July 17, 2011. The 209.8 min of thrusting duration for LOI was divided into three burn segments and targeted an orbit period of roughly 55 hr. Over the following 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.

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. The best values

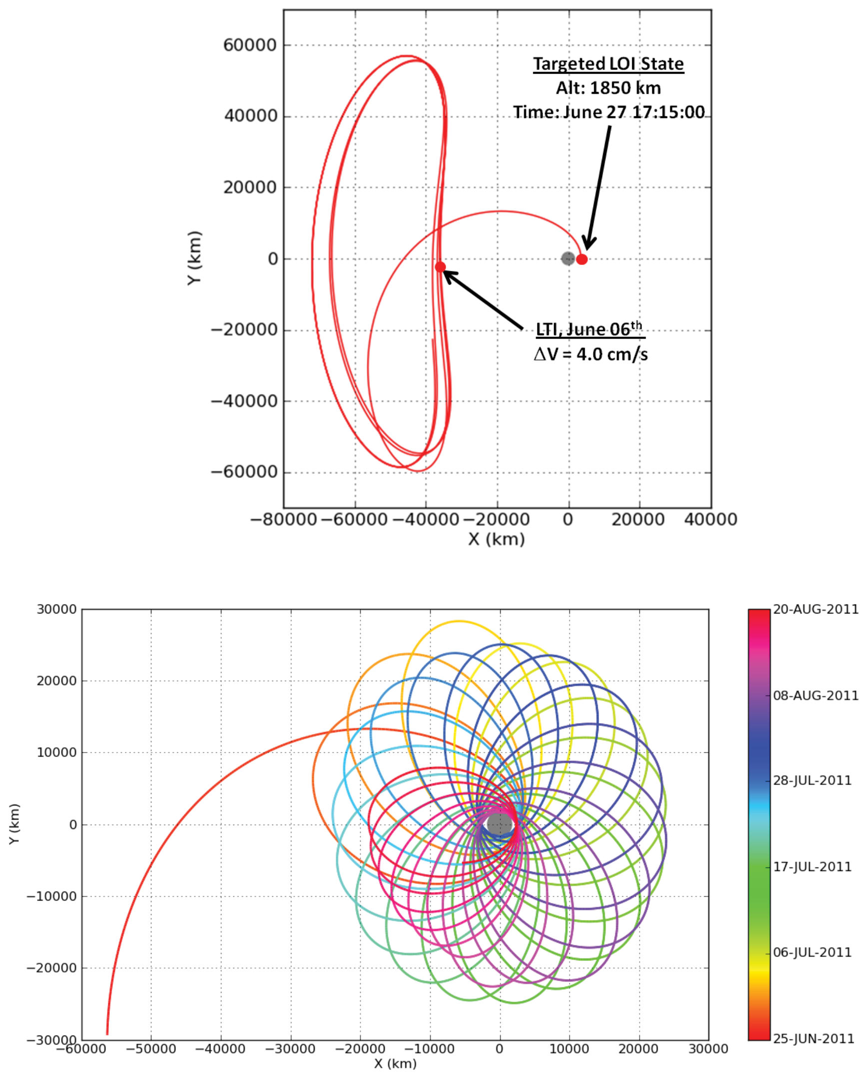
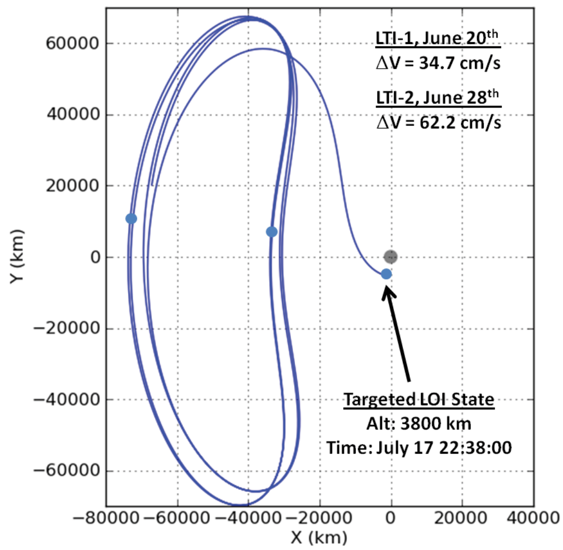


Figure 4. P1 transfer from Lissajous orbit around EML1 to the lunar science orbit (in a rotating frame where Earth is along the $-X$ axis to the left). (top) Transfer from Lissajous to LOI. (bottom) LOI to science orbit.



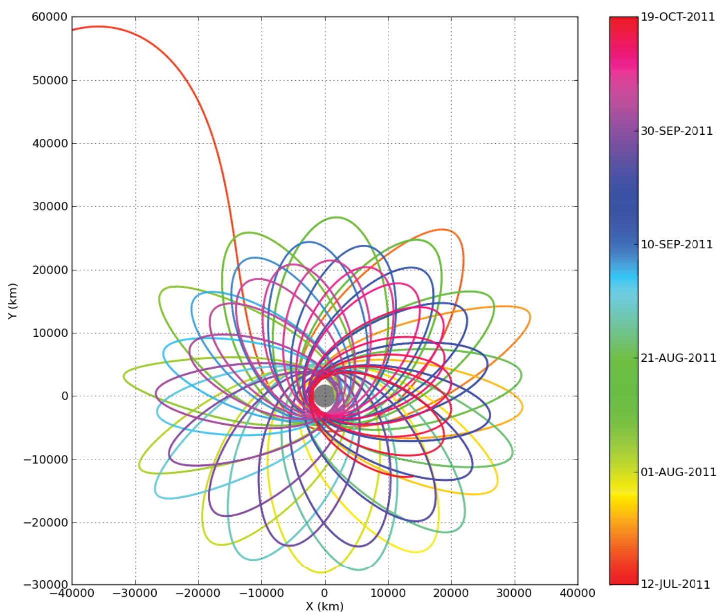


Figure 5. P2 transfer from Lissajous orbit around EML1 to the lunar science orbit (in a rotating frame where Earth is along the $-X$ axis to the left). (left) Transfer from Lissajous to LOI. (right) LOI to science orbit.

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	4.0
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.

of these inputs for ARTEMIS were determined through human tinkering and intuition with support from numerical optimization of simplified sub-problems. Once the above design choices were made, the thrust directions and start/stop times are numerically optimized for each LOI or PRM individually to maximize efficiency and ensure compliance with constraints. The integrated trajectory results were then evaluated based on ΔV cost, science achieved, and operations schedule. It was considered very important that P1 maneuver and maneuver preparation activities did not interfere with similar activities on P2 and vice versa.

Roughly speaking, the total impulsive delta-V needed to transition both spacecraft from approach to the science orbits is about 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. This implies significant gravity losses may occur depending on how the thrust time is divided between periapsis burns. 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 communications occultations and eclipses near periapsis increases gravity and steering losses by forcing burn times further from periapsis and/or forcing sub-optimal burn segmentations.

LOI design The LOI burn for both spacecraft needed to be sufficiently large to capture into 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 thrust duration for the LOI and PRM sequence 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 (see Figure 2), the changes in the next few periapses prevented both spacecraft from starting too low. The ultimate design decision for a 150.5 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 6) 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

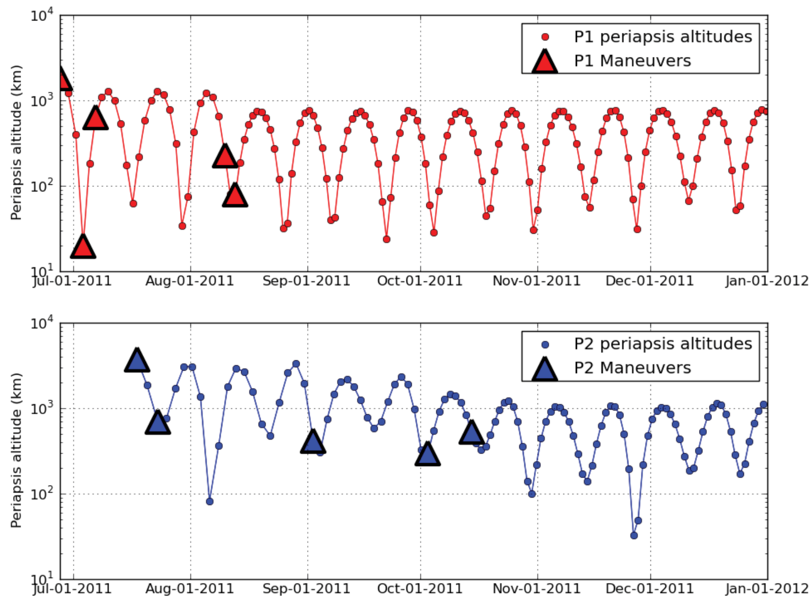


Figure 6. Periapsis altitudes (km) and maneuver locations for the P1 and P2 baseline designs through the end of 2011.

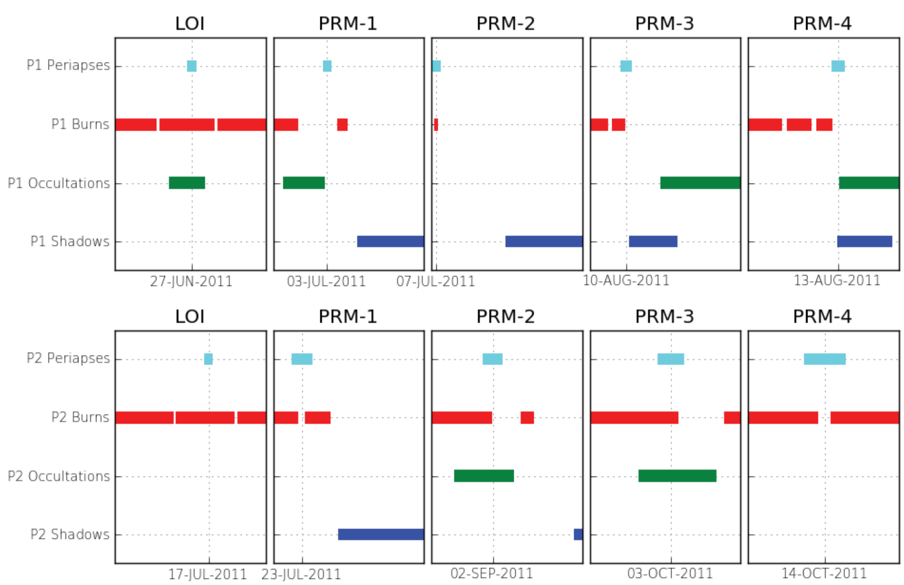


Figure 7. Placement of the P1 (top) and P2 (bottom) LOI and PRM burn segments with respect to occultations (i.e., communications blackout due to spacecraft being behind the Moon) and eclipses. The cyan bar covers periapsis ± 5 min. No thrusting is permitted during eclipse ± 3 min and burns must begin at least 10 min before or 3 min after any communications loss due to occultation.

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 6 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 placement of the LOI and PRM maneuver segments for both spacecraft relative to periapsis, communications occultations, and eclipses is shown in Figure 7.

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 fly over crustal magnetic anomalies up to 6.9 deg from the equator. Further, consideration of the bi-monthly oscillation in periapsis altitude (see the "Spacecraft 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). ARTEMIS can only measure anomalies near these longitudes because the spacecraft must be at <50 km for good measurements and the altitude oscillation magnitude is roughly 1000 km. Table 2 lists potential 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 modifying the longitudes of the sub-50 km periapses cannot be justified given the available ΔV, the science orbit inclinations can be increased away from planar to enable anomaly measurements at higher latitudes. It was found that a large change in lunar orbit inclination can be achieved for very little ΔV if the targeting is done while still in Lissajous orbit (see Figure 8), especially when compared to a traditional plane change in lunar orbit. For the ARTEMIS Lissajous orbits (which are maintained using the method described in [18]), a long-period oscillation in the out-of-plane (Z) coordinate was observed (see Figure 9). 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 out-of-plane motion of the Lissajous orbit when the spacecraft leaves EML1. Two approaches were used to manipulate the science orbit inclination to expand the latitude range for crustal anomaly measurements. First, the exit from Lissajous orbit was postponed by 2.5-3 months on both spacecraft to wait for larger out-of-plane 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 9 was adjusted to extend the duration of stable Lissajous operation and to fine tune the science orbit inclination.

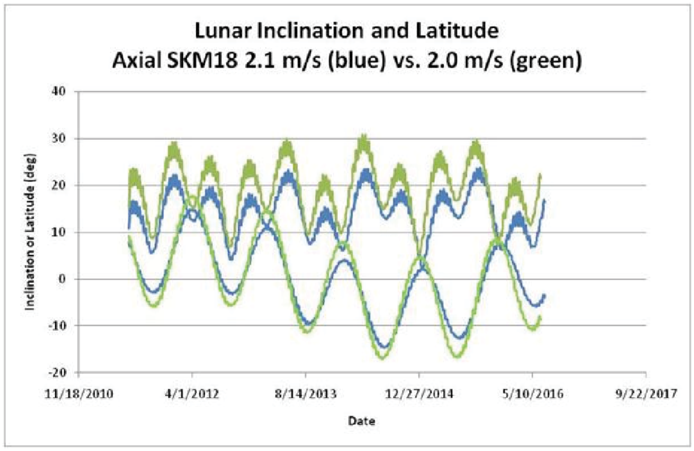


Figure 8. Figure shows variations in inclination (top lines) and periapsis latitude (bottom lines) with respect to the lunar equator resulting from a mere 10 cm/s change in an out-of-plane burn done in Lissajous orbit. Periapsis latitudes vary by up to 5 deg.

The question of how much to incline the orbit can be informed by the mean planetary equations given in Eqns. (2)-(6). First, Eqns. (3), (5), and (6) show that the periapses furthest from the lunar orbit plane (i.e., when ω is 90 or 270 deg) 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 anomalies of interest. However, too high an inclination is not desirable because periapsis altitude oscillations increase in magnitude for larger inclinations, which interferes with the goal of achieving as many sub50 km altitude periapses as possible. Also, if the inclination is too large, then opportunities for downstream lunar wake measurements would be lost during certain time periods as the orbits precess relative to the Sun.

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 ΔV[‡]. With these maneuvers, the P1 spacecraft can reach periapsis latitudes up to 12 deg and P2 can reach up to 17 deg away from the lunar equator.

Placing ARTEMIS line of apsides at dawn during LADEE science

The LADEE mission science phase is planned for a 100-day duration in a low-altitude circular polar orbit [8]. The nominally planned May 2013 launch places the science phase from mid-July to mid-October 2013 and the latest possible launch puts the science phase from mid-December 2013 to mid-March 2014 [9]. To allow for a coordinated exosphere investigation, at least one of the ARTEMIS probes should be within 30 deg of the dawn terminator plane at an altitude under 200 km during the LADEE science phase, regardless

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

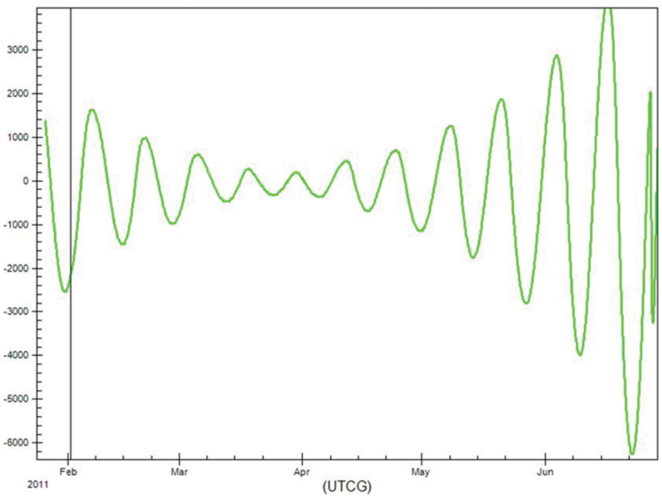


Figure 9. Time history of the P1 out-of-plane coordinate while in Lissajous orbit. The science orbit inclination was strongly tied to the out-of-plane oscillation magnitude at the time of LTI. The vertical black line shows the timing of the P1 maneuver to modify the science orbit inclination.

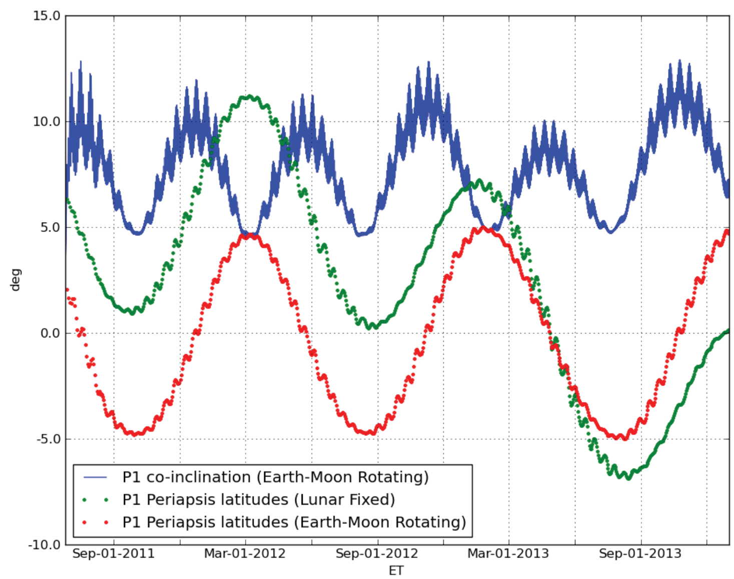


Figure 10. Evolution of the integrated P1 baseline trajectory inclination and periapsis latitudes over time. As predicted by the secular Lagrange equations, extreme periapsis latitudes (in the Earth-Moon rotating frame) occur when inclination is closest to planar. Periapsis latitudes are also shown in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

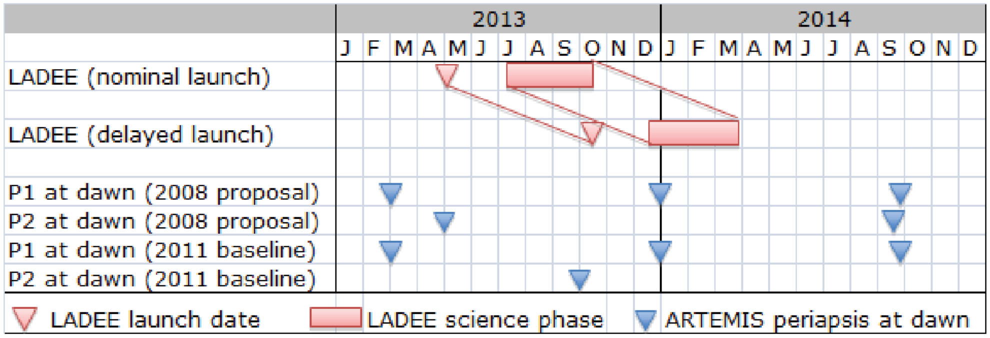


Figure 11. Timeline for planned LADEE mission operations compared with the 2008 proposed and the 2011 baseline lunar science orbit dawn terminator crossings. Each dawn crossing opportunity here actually represents a period of time when 5-15 opportunities for coordinated measurements may occur.

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 to enable the coordinated investigations.

The 2008 "proof-of-concept" plan for the transfer from Lissajous to LOI was designed to minimize mission ΔV and the science orbit size was chosen 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.

To attain the desired P2 dawn terminator timing, the initial longitude of periapsis and/or the precession rate had 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 relative to the Sun. 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 for coordinated measurements with LADEE in the September/October 2013 timeframe (Figure 11).

Since the dawn crossings altitudes must be less than 200 km, the ARTEMIS mean eccentricity (Eqn. (5)) should also be near a maximum in the multi-month periapsis altitude cycle 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.

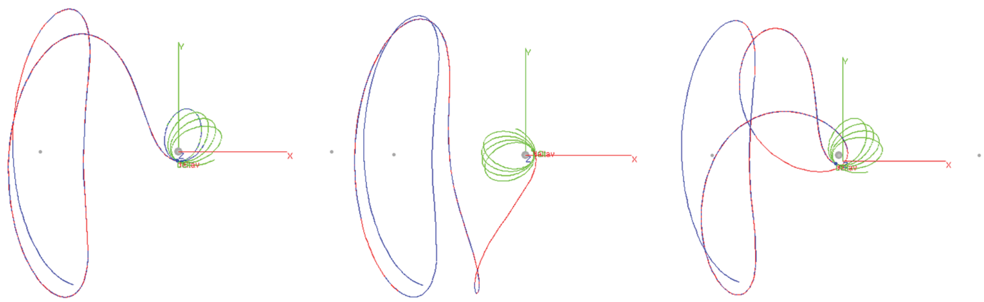


Figure 12. Three different geometry options for the P2 approach to a prograde lunar orbit from Lissajous around EML1. ARTEMIS implemented the leftmost option on P2.

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 number of measurement opportunities and would cause impact with the lunar surface if not corrected. 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 ARTEMIS 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 and interprobe separations to map out the wake and its variations over different spatial and temporal scales. Figure 13 shows the crossings of the lunar wake expected for both spacecraft through the end of 2013. Many measurement opportunities exist between 10 and 19000 km altitude and the relative positioning of P1 and P2 varies throughout the mission.

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 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. Many opportunities for measurements exist. 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 slower precession rate which makes consistently low periapsis altitudes 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 5 m/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.

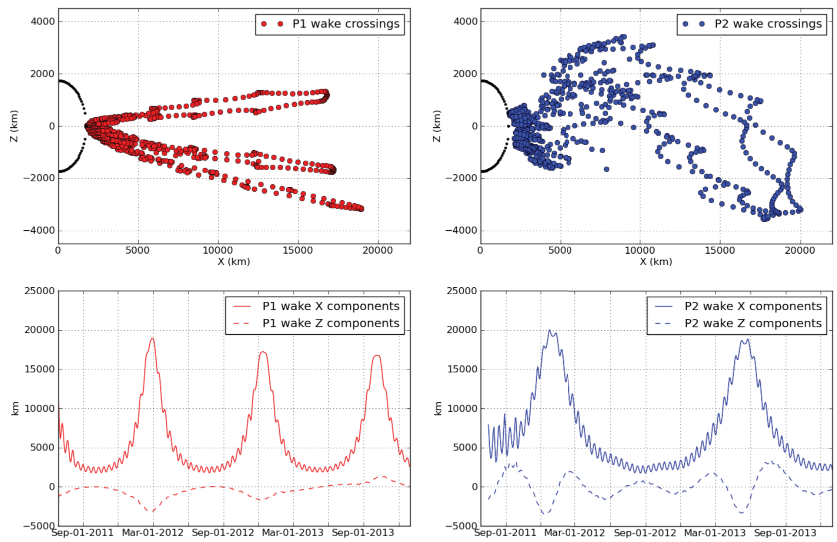


Figure 13. Wake crossing geometries and coordinates through the end of 2013 in a Moon-centered rotating frame with the Sun on the negative X-axis. Each point corresponds to an instantaneous wake center, but in reality represents an orbit arc within and around the wake, ranging in length from a few thousand to tens of thousands of km with a variety of orientations.

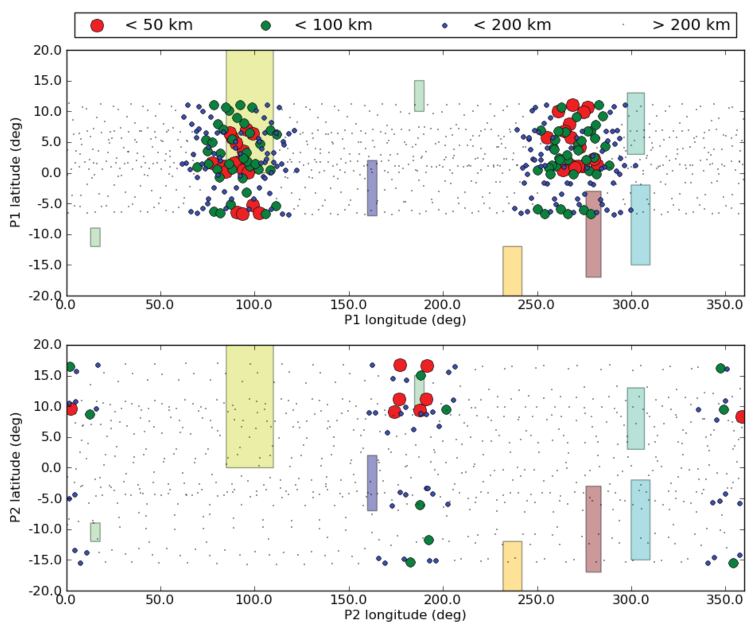


Figure 14. ARTEMIS periapsis locations and altitudes (dots) through 2013 with respect to the crustal magnetic anomalies in Table 2 (colored rectangles).

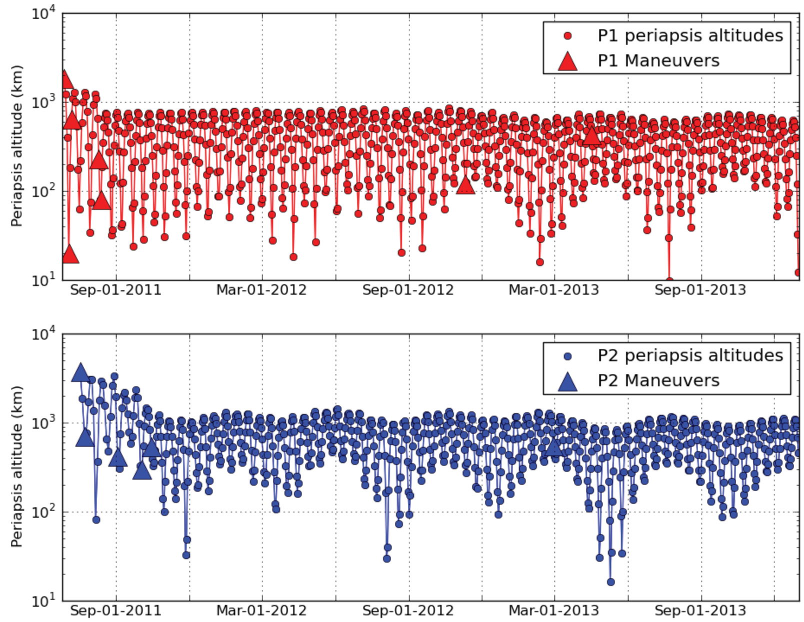


Figure 15. ARTEMIS planned periapsis altitudes for P1 (top) and P2 (bottom) through January 2014.

Exosphere measurements and alignment with LADEE

Measurements to support exosphere and surface charging investigations can be taken across a range of altitudes from 100s to 1000s of km and a complete range of local solar times is desired. Figure 15 shows the periapsis altitudes achieved by the two spacecraft through 2013. The achieved periapses cover an appropriate range of altitudes and the local solar times precesses through 24 hrs approximately every 9.5 months for P1 and once every 17 months for P2. Figure 11 shows that ARTEMIS has been aligned such that the precession in local solar time brings periapsis to the dawn terminator for at least one of probes during the LADEE science phase.

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 fundamental design problem for the lunar orbit phase of ARTEMIS was determining how ~5 hr of thrust (at ~0.5 N) should be distributed amongst multiple maneuvers to complete a transfer from lunar Lissajous orbit to an eccentric lunar science orbit for each of two spacecraft. Candidate solutions were required to maximize fuel efficiency, conform to the capabilities of the spacecraft, be manageable with a small operations team, and enable a wide variety of science investigations. This paper documents the baseline solutions developed by the ARTEMIS mission team and the anticipated science measurement opportunities enabled. These solutions were adopted by the mission and the two spacecraft are currently in the midst of executing the maneuver sequence on-board. As of this writing, the maneuvers to date have been successful and science data is actively being collected.

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