PRELIMINARY TRAJECTORY DESIGN FOR THE ARTEMIS LUNAR MISSION

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The ARTEMIS mission is an extension to the THEMIS mission that will send two of the Earth-orbiting THEMIS spacecraft on a circuitous route to the Moon beginning in July 2009. This paper describes the ARTEMIS trajectory design proposed to the NASA Heliophysics Senior Review in April 2008 (and accepted in May 2008). The trajectory design problem for ARTEMIS is very challenging due to the constraints imposed by the capabilities of the orbiting hardware. Nonetheless, the mission science objectives are successfully addressed by two unique trajectory solutions which include multiple lunar approaches, lunar flybys, low-energy trajectory segments, lunar Lissajous orbits, and low-lunar orbits.

INTRODUCTION

NASA's Time History of Events and Macroscale Interactions during Substorms (**THEMIS**) mission is a medium-class Explorer mission that was launched in February of 2007 to improve understanding of solar substorms in the Earth's magnetosphere [1]. The mission consists of five identical Earth-orbiting spacecraft that are equipped with particle and fields instrumentation [2]. As of the time of this writing, the baseline mission science objectives have been achieved and all five spacecraft (and their instruments) are fully functional.

In April of 2008, the Acceleration, Reconnection, Turbulence and Electrodynamics of the Moons Interaction with the Sun (**ARTEMIS**) mission was proposed as an extension to the THEMIS mission to the NASA 2008 Heliophysics Senior Review [3]. The ARTEMIS mission proposed to send the two outermost spacecraft of the THEMIS constellation to low-lunar orbit by way of two circuitous transfers that take about one and a half years each. The proposal represented the combined efforts of the THEMIS science team, the University of California - Berkeley Space Science Laboratory (**UCB-SSL**), the NASA Goddard Space Flight Center (**GSFC**), and the Jet Propulsion Laboratory at the California Institute of Technology (**JPL**). This proposal was accepted for implementation in May of 2008. This paper presents the trajectory design as it was proposed to the NASA 2008 Heliophysics Senior Review.

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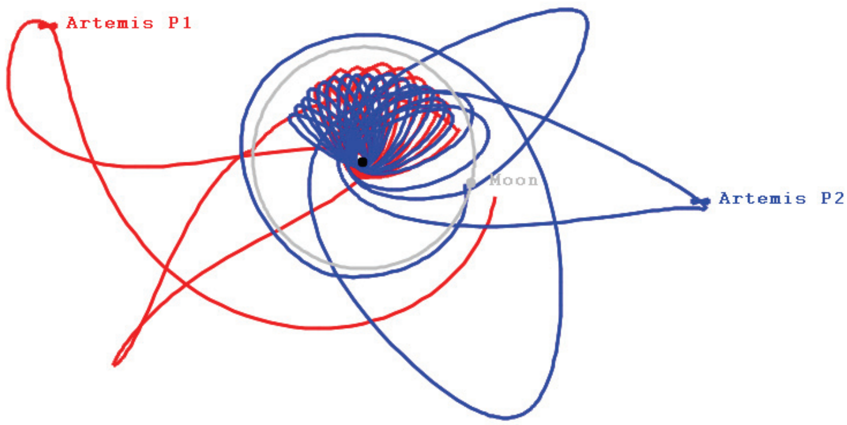

Figure 1 ARTEMIS trans-lunar trajectories in the ecliptic plane. The coordinate frame here rotates such that the Sun is always to the left. The red line shows the P1 trajectory and the blue line shows the P2 trajectory. The Earth is at the center of the figure and the Moon's orbit is shown in gray. Spacecraft labels correspond to the planned positions on June 25, 2010.

Numerous challenges were introduced to the ARTEMIS trajectory design problem by the limited capabilities of the existing THEMIS spacecraft. First, a limited amount of on-board fuel was projected to remain after the THEMIS baseline mission is completed. The THEMIS-B spacecraft (also known as "Probe-1" or "P1") was to be in a 4-day Earth orbit with ~ 324 m/s of propellant remaining and the THEMIS-C spacecraft (also known as "Probe-2" or "P2") was to be in a 2-day Earth orbit with ~ 475 m/s of propellant remaining. Since the on-board fuel tanks were to be largely depleted, the available thrust would be reduced; each of four thrusters on each spacecraft were expected to be capable of producing between 1.6 and 2.4 N during the ARTEMIS mission. Further, available thrust directions are limited to one hemisphere due to thruster configuration and an on-off duty cycle is imposed due to the spinning spacecraft bus that limits effective thrust in the spin plane. Finally, the spacecraft can only withstand up to a 4-hour shadow. If nothing is done at the end of the THEMIS baseline mission, long eclipses will neutralize the P1 spacecraft within about eight months [4].

This paper begins by describing the projected capabilities and configuration of the THEMIS spacecraft at the end of the nominal THEMIS mission. Next, the history of the ARTEMIS concept is described, as well as the science goals of the mission. The bulk of the paper describes the P1 and P2 trajectory designs that take the spacecraft from low-Earth orbit to low-lunar orbit. This transfer utilizes numerous lunar perturbations, lunar fly-bys, low-energy segments that extend towards the Earth-Sun Lagrange points, and lunar Lissajous orbits. Figure 1 previews the ARTEMIS preliminary trajectory design that sends P1 and P2 from their respective end-of-THEMIS orbits to insertion into lunar Lissajous orbit. Quantitative discussion of how well the proposed trajectory satisfies the mission constraints follows. The final section of the paper briefly describes the activity on the ARTEMIS mission since being accepted for implementation.

The ARTEMIS mission is now underway, as the first maneuvers for both spacecraft were successfully executed in late July and early August of 2009.

SPACECRAFT OVERVIEW

On February 17th, 2007, the five spacecraft of the THEMIS mission were launched together on a Delta-II 7925 rocket into a 1.3-day Earth orbit with perigee at 437 km altitude and apogee at ~ 87500 km altitude [1].

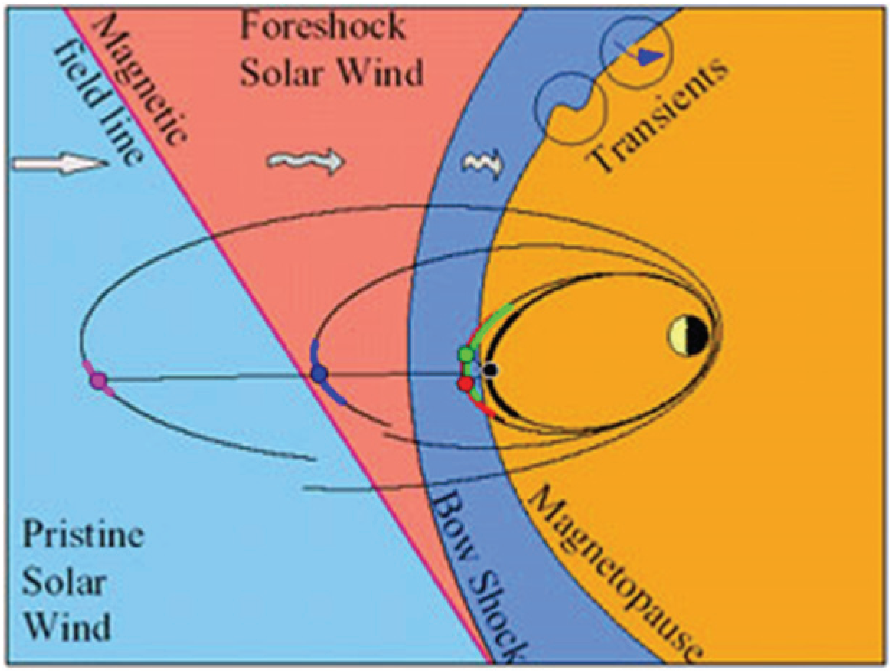

Figure 2 THEMIS Mission Orbit Configuration (*http://themis.ssl.berkeley.edu/-images/orbitMap.jpg*). Filled circles represent the THEMIS spacecraft locations during a day-side conjunction (Pink: P1 4-day orbit, Blue: P2 2-day orbit, Red: P3 1-day orbit, Green: P4 1-day orbit, Black: P5 1-day orbit). The orbit geometries are indicated by black lines.

Based on initial on-orbit performance, the spacecraft THEMIS-B was assigned to a 4-day orbit, THEMIS-C was assigned to a 2-day orbit, and THEMIS-A, D, and E were assigned to 1-day orbits as required to achieve the THEMIS mission science goals (Figure 2) [1]. After orbiting the Earth for 29 months, the two spacecraft in the outermost orbits would be called on to continue their journey on to the Moon as part of the ARTEMIS mission. For the ARTEMIS mission, the spacecraft are generally known by their orbit location, i.e., the THEMIS-B spacecraft in the 4-day orbit is known as P1 and the THEMIS-C spacecraft in the 2-day orbit is known as P2.

The five THEMIS spacecraft were built to be identical at launch. Each spacecraft had 134 kg mass (including 49 kg of hydrazine fuel) and measured approximately 0.8x0.8x1.0 meters at launch [2]. On orbit, each spacecraft has deployed a number of instrument booms and is spin-stabilized at ~ 20 RPM. Figure 3(a) shows a THEMIS spacecraft with booms deployed. Figure 3(b) shows a schematic of the bus design. The blue arrow indicates the spin vector and shall be referred to as the spacecraft $+Z$ direction.

Each spacecraft has four 4.4 N thrusters with locations indicated by the black arrows in Figure 3(b). Two thrusters provide axial thrust (acceleration in $+Z$ direction) for large ΔV maneuvers and attitude control. The two other thrusters provide tangential thrust in the spin plane for small ΔV maneuvers and spin rate control. Note that the spacecraft cannot apply acceleration in the $-Z$ direction. At launch, each spacecraft had 960 m/s total ΔV capability [2]. Because of fuel usage during THEMIS, approximately 324 m/s ΔV for P1 and 475 m/s for P2 were expected to be available at the end of the nominal THEMIS mission*. Because

*Remaining fuel prediction reported at the ARTEMIS Independent Integrated Review at NASA Goddard Space Flight Center, February 24, 2009.

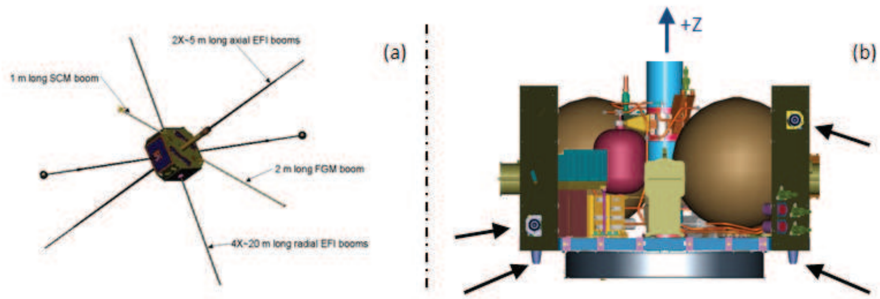

Figure 3 THEMIS/ARTEMIS Spacecraft Configuration. The spacecraft buses were manufactured by ATK Space Systems (formerly Swales Aerospace) and the instruments were manufactured under the leadership of the University of California, Berkeley with both domestic and international collaborators. (a) On-orbit configuration with booms deployed (*http://www.nasa.gov/images/content/164405main_THEMIS-Spacecraft_bus2.jpg*), (b) spacecraft bus schematic. Black arrows indicate locations of the 4.4 N hydrazine thrusters. Blue arrow indicates spin axis.

of fuel tank depressurization, each thruster is expected to produce between 1.6 and 2.4 N force during the ARTEMIS mission.

The thermal and power systems have been designed to withstand shadowing of the Sun for up to three hours [2]. However, it was demonstrated in March of 2009 that a 4-hour shadow is survivable with appropriate precautions.

ARTEMIS CONCEPT DEVELOPMENT

From the design of the baseline THEMIS mission, it was expected that the P1 spacecraft would experience an 8-hour eclipse in March 2010. Given the 4-hour shadow capability of the spacecraft, this would most likely render P1 inoperable. To satisfy requirements on Earth orbiters, P1 would have to execute a burn that would lead to re-entry before this time.

However in 2005, the idea of sending P1 "up" instead of "down" was hatched and studied by the THEMIS science team and at JPL. With the instrumentation on the THEMIS spacecraft, compelling science could be conducted at the Moon with a single spacecraft. Initial trajectory studies found that a direct transfer from the P1 Earth orbit to a 1500 km altitude by 18000 km radius polar orbit would require ~ 500 m/s of ΔV (not including margin or losses associated with long thrust arcs). This was well beyond the expected ΔV capability of the P1 spacecraft at the end of the baseline mission. However, the remaining fuel did appear to be sufficient to transfer from the P1 Earth orbit to an eccentric polar lunar orbit by way of a lunar swing-by and low-energy transfer [5]. The fuel reserves on P2 offered similar capability, suggesting the possibility of sending two THEMIS spacecraft to the Moon.

With the encouraging initial trajectory design results in hand, proposals for funding were made in 2006 and 2007 to support a detailed low-energy trans-lunar trajectory design study, feasibility studies related to the THEMIS hardware, and optimization of the remaining THEMIS mission for P1 and P2. These proposals were not selected for funding, but concept development continued by the science team as time permitted.

In the summer of 2007, internal JPL funding became available to support an Explorer progam Mission of Opportunity proposal for the THEMIS mission extension that would become ARTEMIS. A team from the JPL Inner Planets Mission Analysis group was convened to do a trajectory design to the Moon for the P1 and P2 spacecraft. Building on the work done in 2005, the JPL team (working closely with the THEMIS principal investigator and science team) developed a workable trajectory with respect to the THEMIS spacecraft constraints described in the previous section that provided opportunity for a high extended-mission science yield. This paper describes the trajectory design that came out of that effort.

ARTEMIS SCIENCE GOALS

Each spacecraft is equipped with a suite of five particle and fields instruments that have been used to study geo-magnetic substorm activity during the nominal THEMIS mission. These instruments include a Fluxgate Magnetometer, a Search Coil Magnetometer, an Electric Field Instrument, an Electrostatic Analyzer, and a Solid State Telescope [1]. This instrumentation suite allows the spacecraft to study the interaction between the Earth's magnetic field and the Sun. Multiple instrumented spacecraft in different places allow the evolution of phenomenon of interest to be observed both temporally and spatially. The ARTEMIS mission plans to use these instruments to take two-point measurements of the pristine solar wind upstream of the Earth's magnetosphere, the distant magneto-tail of the Earth, and the wake behind the Moon at a variety of relative geometries and scales. To achieve these goals, the two ARTEMIS spacecraft must travel from the Earth to the Moon and operate in a number of relative geometries.

ARTEMIS PRELIMINARY TRAJECTORY DESIGN

Figure 1 shows the ARTEMIS preliminary trajectory design that sends P1 and P2 from their respective end-of-THEMIS orbits to insertion into lunar Lissajous orbit. The P1 trajectory is shown in red and the P2 trajectory is shown in blue. The design is feasible given the trajectory constraints imposed by the spacecraft capabilities and permits a variety of desirable scientific observations.

In the following subsections, the trajectory is broken up into phases for detailed discussion. These phases include the Earth-Orbiting Phase, the Trans-Lunar Phase, the Lissajous Orbit Phase, and the Lunar Orbit Phase. An integrated timeline of the events for P1 and P2 in these four mission phases can be found in the Appendix.

Earth-Orbiting Phase Trajectories

Figure 4 shows the ARTEMIS P1 preliminary design trajectory from the end of the nominal THEMIS mission through the first close lunar flyby. In the figure, the red line represents the ARTEMIS P1 trajectory, the black ellipse represents the end-of-THEMIS orbit for P1, and the gray circle indicates the Moon's orbit. The plot is centered on the Earth and shown in the Sun-Earth synodic coordinate frame, which rotates such that the Sun is fixed along the negative X axis (to the left) and the Z axis is aligned with the angular momentum of the Earth's heliocentric orbit. As time passes, the P1 geocentric orbit line of apsides rotates clockwise in the main figure. The insert in the bottom left shows the motion of P1 out of the ecliptic plane. The labels on the plot provide information about key events during this phase of the mission.

Following Figure 4, the ARTEMIS P1 trajectory begins in the 4-day Earth orbit it occupied during THEMIS, which has significant inclination relative to the Moon's orbit (see inset of Figure 4). Six days after the end of the nominal THEMIS mission, a 100.3 m/s orbit raise maneuver (**ORM**) is executed which significantly raises the orbit apogee. The approach used here is to raise the apogee just enough so that the trajectory can be altered by the Moon's gravity when it passes once per month. This approach allows minimization of the required ΔV, which is critical in order to design feasible lunar transfers for P1 and P2. Phasing of the lunar perturbations is very important because the post-lunar perturbation trajectory period must be such that the spacecraft is positioned for another energy boost (and not a decrease) in subsequent months. After the ORM, P1 gets two energy boosts and plane changes from the Moon in November and December of 2009, which set up (combined with a small fly-by targeting maneuver (**FTM**)) a 3200 km range ($\sim$ 1500 km altitude) lunar flyby in January of 2010. At this point, 109 days after the end of the nominal THEMIS mission, the Earth-orbiting phase for P1 is complete.

Figure 5 shows the P2 preliminary design trajectory from the end of the nominal THEMIS mission through the first close lunar flyby. The coordinate frame and figure layout are the same as in Figure 4; the only difference is that the P2 trajectory is blue instead of red. The P2 Earth-orbit phase design follows a similar philosophy as P1; the trajectory uses multiple lunar approaches to add energy and change the orbit plane as needed instead of using ΔV. The details of the trajectory can be seen in the figure. Of particular note is

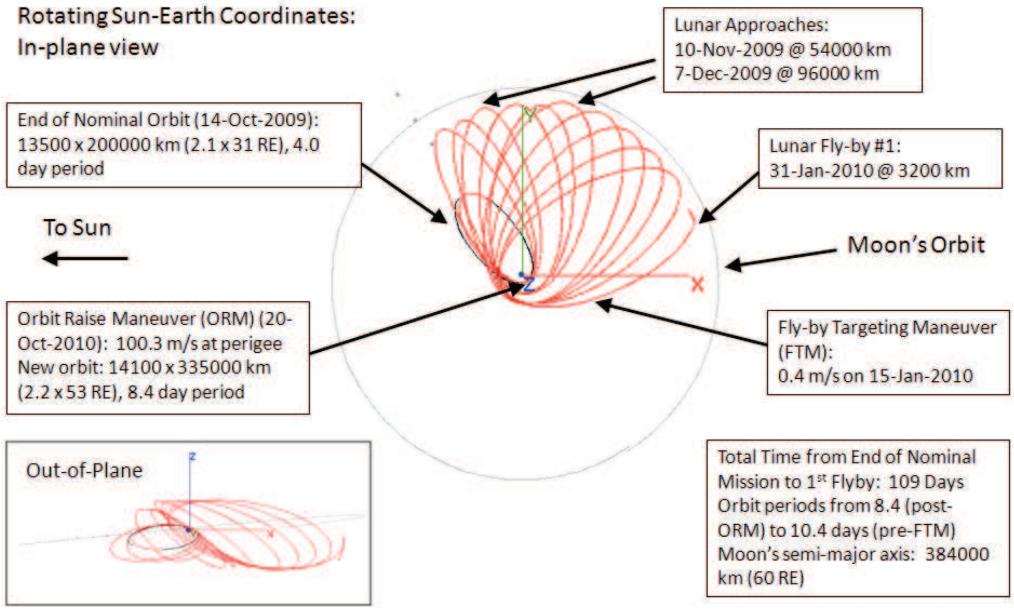

Figure 4 Earth-orbiting portion of the P1 preliminary trajectory design. Distances quoted are ranges measured from the center of mass of the Earth or Moon.

that the ORM for P2 requires 179.7 m/s, which is significantly more than for P1. This is because P2 starts in a 2-day orbit instead of a 4-day orbit †. The Earth-orbiting phase for P2 ends with a lunar flyby about two months after P1 on March 28, 2010.

Trans-Lunar Phase Trajectories

The trans-lunar phase of the ARTEMIS trajectory for each spacecraft extends from the first close lunar flyby to insertion into the target Lissajous orbit.

Figure 6 describes the trans-lunar phase of the ARTEMIS preliminary trajectory design for the P1 spacecraft. The trajectory is again shown in the same Sun-Earth synodic coordinate frame used in Figures 4 and 5. The trajectory begins on the right hand side of the plot with "Lunar Fly-by #1". The P1 trajectory makes use of a "back-flip" trajectory, which uses the first lunar fly-by to set up a second lunar fly-by on the opposite side of the Moon's orbit ~ 14 days later. The back-flip can be seen clearly in the out-of-plane view insert in the bottom left. This second flyby has an altitude of ~ 2800 km and raises the apogee significantly, throwing the spacecraft out into interplanetary space towards the Sun. This begins the low-energy trajectory leg for P1, which is characterized by the significant gravitational perturbation imparted on the spacecraft by the Sun. This low-energy trajectory has two deep-space legs that approach the Earth-Sun Lagrange point #1 (**EL1**) and includes one relatively small deep-space maneuver (**DSM**). After the second leg, the orbit perigee has been raised to lunar distance and the phasing with the Moon's orbit is such that the spacecraft moves into a lunar Lissajous orbit around Lunar Lagrange point #2 (**LL2**) without requiring any deterministic insertion maneuver. By the time P1 reaches the Lissajous orbit in August of 2010, 313 days have elapsed since the end of the nominal THEMIS mission.

† The assumption of an impulsive ORM (given the capability of spacecraft propulsion system) ultimately turned out to be a source of difficulty in the final trajectory design for both spacecraft; P2 was particularly difficult because of the larger size of this maneuver.

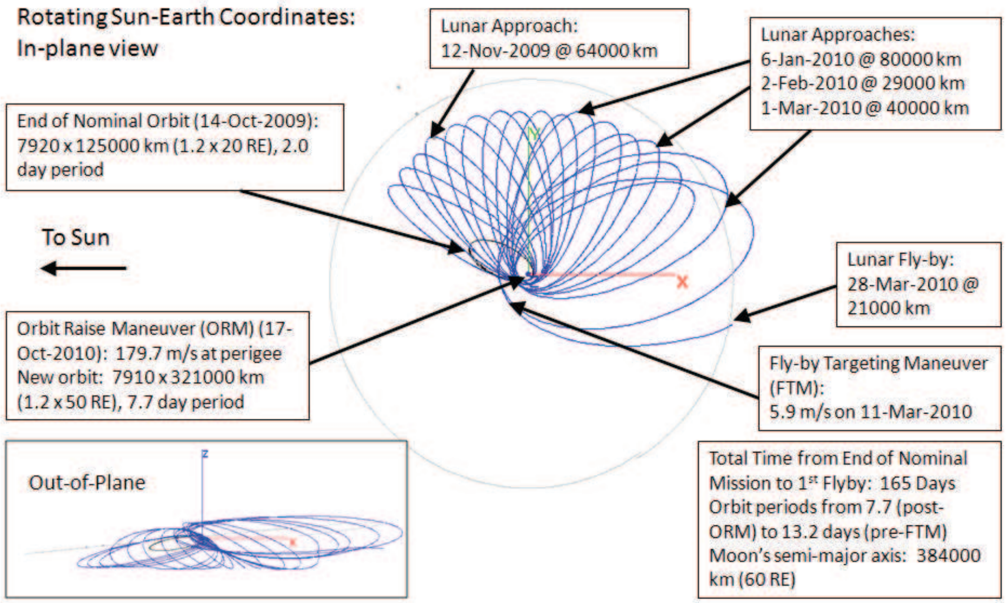

Figure 5 Earth-orbiting portion of the P2 preliminary trajectory design. Distances quoted are ranges measured from the center of mass of the Earth or Moon.

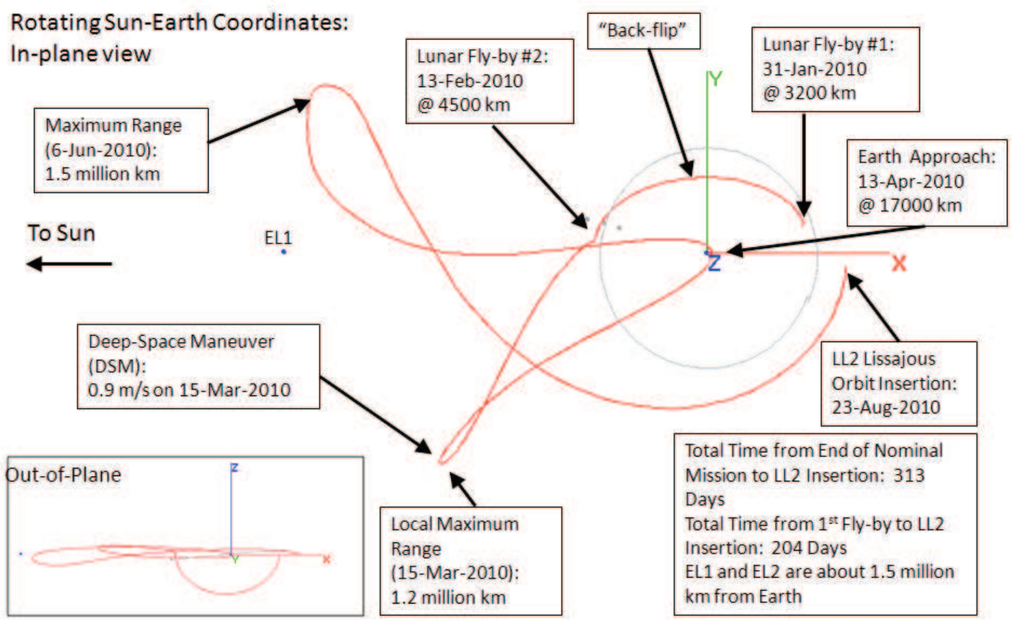

Figure 6 Trans-lunar portion of the P1 preliminary trajectory design. Distances quoted are ranges measured from the center of mass of the Earth or Moon.

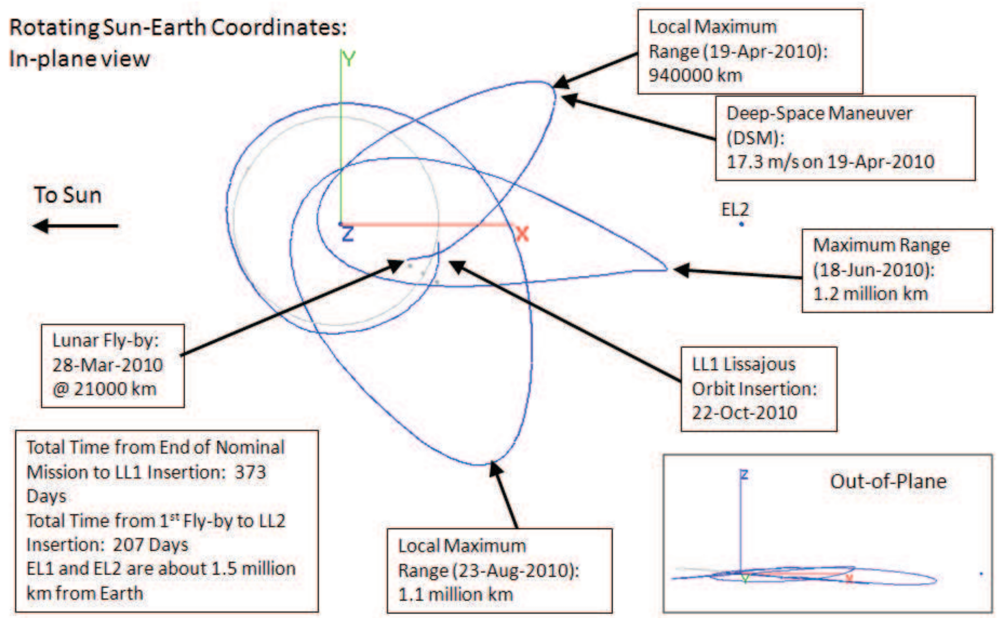

Figure 7 Trans-lunar portion of the P2 preliminary trajectory design. Distances quoted are ranges measured from the center of mass of the Earth or Moon.

Figure 7 shows the trans-lunar preliminary trajectory design for P2. The P2 trajectory only includes one lunar fly-by, which sends the spacecraft towards the Earth-Sun Lagrange point #2 (**EL2**) and into the influence of the solar gravity. Similarly to the P1 trans-lunar trajectory design, P2 follows a low-energy trajectory that includes three deep-space legs before entering a lunar Lissajous orbit around Lunar Lagrange Point #1 (**LL1**) without any deterministic thrusting. The P2 trajectory does include a relatively large deep-space maneuver (**DSM**) of 17.3 m/s on the first deep-space leg. P2 arrives in Lissajous orbit about 2 months after P1, requiring a total of 373 days after the end of the nominal THEMIS mission to reach this stage.

Lissajous Orbit Phase Trajectories

The Lissajous orbit phase of ARTEMIS permits the first (distant) observations of the lunar wake. For the first ~ 1.5 months of this phase from August 22 to October 2, 2010, the P1 spacecraft is alone at the Moon in orbit around the LL2 point while P2 is still *en route*. P2 then arrives, making a partial orbit around LL2 on its way to Lissajous orbit at LL1. For the next ~ 2.3 months, P1 orbits LL1 while P2 orbits LL2. During this phase, the trajectories permit 16 independent observations of the lunar wake when crossing behind the Moon on the anti-Sun side, observations of the distant Earth magneto-tail once per month when the Moon's orbit passes through it, and observations of the pristine solar wind when out of the influence of both. These two point measurements occur at separation scales ~ 100000 km when the spacecraft are in orbit around different Lagrange points and ~ 50000 km when both spacecraft orbit LL1. Distant magneto-tail measurements can also be correlated with concurrent measurements from THEMIS-A, THEMIS-D, and THEMIS-E in low-Earth orbit.

Figure 8 shows the P1 trajectory design during the Lissajous orbit phase. In this figure, the Moon is at the origin and the trajectory is drawn in the Earth-Moon synodic coordinate frame, which rotates such that the Earth is always to the left along the negative X axis. The Z axis is aligned with the angular momentum vector of the Moon's geocentric orbit. The main figure on the left side shows the view looking down on the geocentric orbital plane of the Moon and the two insets show perspectives from within the Moon's orbital plane. The LL1 and LL2 points are marked in the figure.

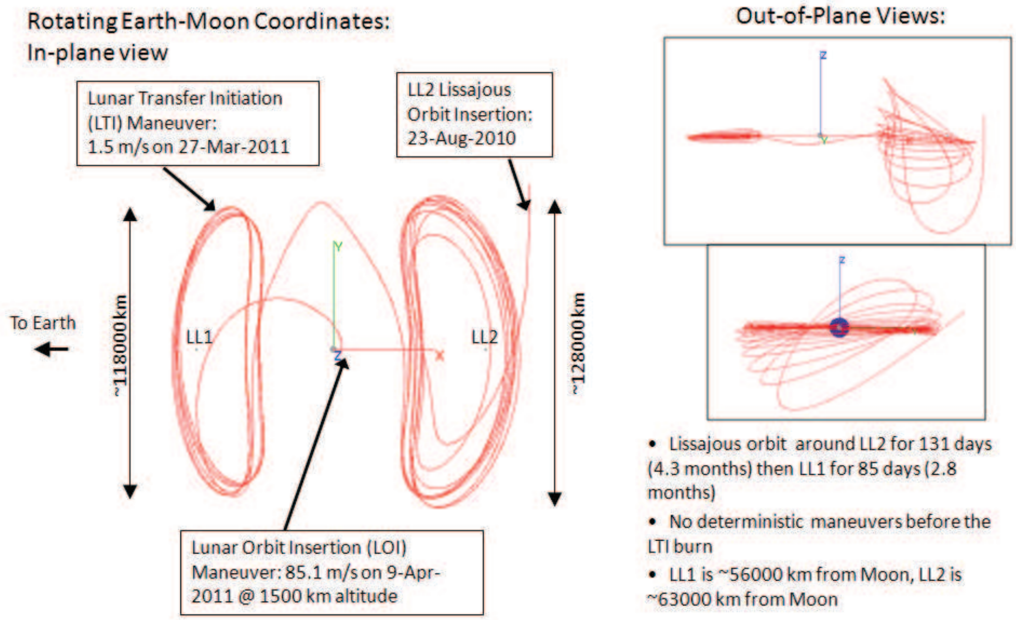

Figure 8 Lissajous Orbit Phase of the P1 preliminary trajectory design. Distances given are ranges measured from the lunar center of mass unless otherwise specified.

P1 enters Lissajous orbit around LL2 on August 23, 2010 without a deterministic maneuver. The initial Lissajous orbit is somewhat inclined with respect to the Moon's geocentric orbit plane, but the orbit flattens after a few orbits (see Figure 8 inserts). After ~ 131 days in orbit around LL2, the trajectory follows the unstable orbit manifold along a heteroclinic connection to a Lissajous orbit around LL1 [6, 7]. This transfer requires no deterministic ΔV for initiation or insertion. P1 then spends 85 days orbiting LL1 before executing a small maneuver to depart the Lissajous orbit. The spacecraft descends to a 1500 km altitude periselene, where the lunar-orbit insertion (**LOI**) maneuver is executed, which begins the Lunar Orbit Phase. At the time of LOI, P1 will have operated for 541 days since the end of the nominal THEMIS mission.

Figure 9 shows the P2 trajectory during the Lissajous orbit phase. P2 enters Lissajous orbit around LL1 on October 22, 2010. Like P1, this insertion is achieved without any deterministic ΔV because the incoming trans-lunar trajectory approaches on the stable manifold of this particular Lissajous orbit. P2 stays in this nearly planar Lissajous orbit for about 5 months before initiating descent to a 1500 km altitude periselene on March 31, 2011. The LOI maneuver for P2 begins on April 19, 2011, at which time P2 will have been operating for 551 days since the end of the nominal THEMIS mission.

The Lissajous Orbit Phase of the ARTEMIS mission is particularly exciting because ARTEMIS will be the first spacecraft to ever fly in a lunar Lissajous orbit. Flying these orbits will be a challenge for the operations and maneuver design teams because Lissajous orbits are inherently very unstable. Small (and unavoidable) deviations from the Lissajous orbit are amplified to problematic proportions after approximately one revolution (~ 14 days). This leaves little room for error in the operations. Because of this instability, correction maneuvers need to be executed regularly to keep the spacecraft on orbit. So when it is said that these orbits require no deterministic ΔV, it is true, but there will certainly be orbit maintenance ΔV required.

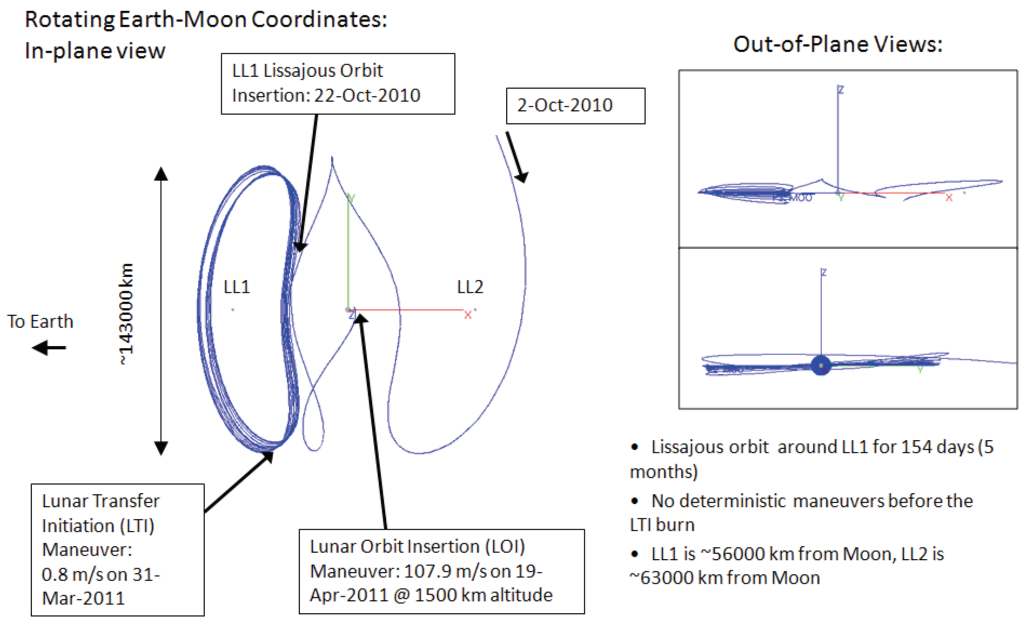

Figure 9 Lissajous Orbit Phase of the P2 preliminary trajectory design. Distances given are ranges measured from the lunar center of mass unless otherwise specified.

Lunar Orbit Phase Trajectories

The bulk of the scientific observations of the lunar wake occur during the Lunar Orbit Phase, which nominally lasts $1.5\ yrs$. Both spacecraft are placed into nearly equatorial orbits with roughly 1500 km altitude periselene and 18000 km radius aposelene. The size of the orbit oscillates over time due primarily to the gravitational influence of the Earth. The orbit period is roughly 27 hours. The orbit of P1 is retrograde and the orbit of P2 is direct to maximize the relative nodal precession rate between the two spacecraft. Combined with the significant eccentricity of the orbits, this enables observations at a wide range of different spacecraft separations from ~ 500 to ~ 30000 km and geometries to be achieved during this phase. Figure 10 shows the range from the Moon's center in the anti-Sun direction of the lunar wake crossing observation opportunities for P1 and P2 as a function of time. Note the large number of potential measurements, the variety of down-Sun ranges, and the variety of relative geometries of P1 and P2.

Finite-burn LOI design For the proposal, the LOI was modeled as a finite-burn maneuver instead of impulsive so that potential large ΔV penalties on this burn could be understood. Because the small tangential thrusters would be used to execute the LOI, the maneuver needed to be split into a number of fairly long burns which incur significant gravity losses and thrust inefficiencies due to spacecraft rotation. An existence proof of a workable solution was developed to give credibility to the proposed design.

A finite-burn LOI is challenging for the ARTEMIS spacecraft because the thrusters only produce between 1.5 and 1.8 N of thrust each at this point in the mission. Further, thrust cannot be applied continuously because the tangential thrusters are used for this maneuver; a precession to use the axial thrusters is prohibitively expensive in ΔV. Nonetheless, a significant ΔV must be applied at the first periapsis to capture into a low enough lunar orbit so that the Earth's gravity perturbation does not cause the spacecraft to impact at subsequent periselenes. For fuel efficiency purposes, all maneuvers after the first capture burn should be small and near periselene. However, these maneuvers still need careful attention because the Earth's gravitational influence creates a persistent oscillation in the spacecraft periselene altitude. This oscillation does have

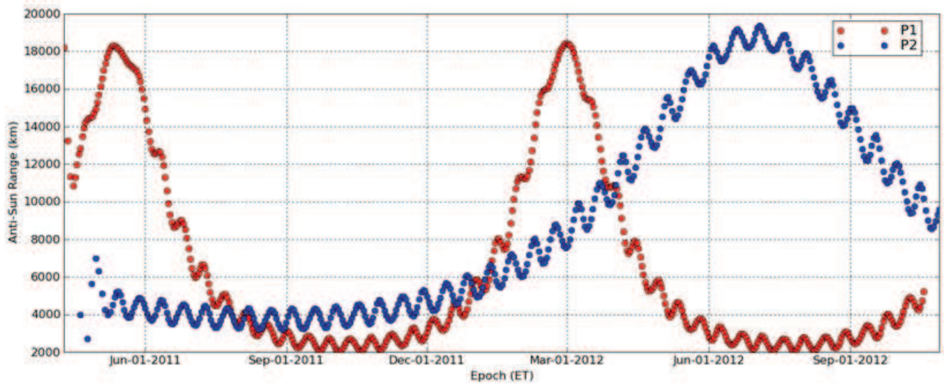

Figure 10 P1 (red) and P2 (blue) lunar wake observation opportunities during LOI and the Lunar Orbit Phase. Anti-Sun Range on the vertical axis is the component of the spacecraft position relative to the Moon along the anti-Sun direction at the center of each wake crossing.

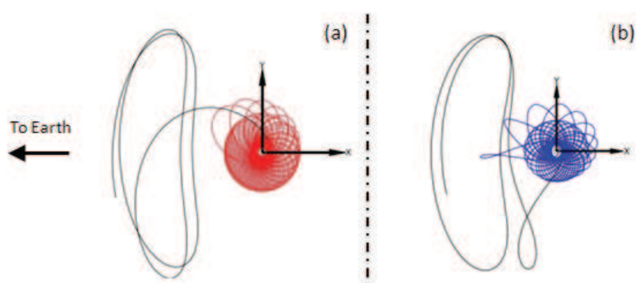

Figure 11 LOI and low-lunar orbit trajectories for (a) P1 and (b) P2 in the rotating Moon-centered frame. LL1 Lissajous orbits shown for scale.

an upside though - thrusting at the lower periselene altitudes that occur in this oscillation cycle allows for improved LOI efficiency.

An initial LOI design using finite burns for both P1 and P2 serves as an existence proof and guide to the expected ΔV required for LOI. Figure 11(a)-(b) shows the LOI trajectories (and subsequent lunar orbits) in the Earth-Moon synodic coordinate frame with the Earth fixed on the negative X axis. Both designs made use of a $1/6$ rotation duty cycle with the 2 tangential thrusters (95.5% efficient). Thrust was assumed to be applied in a 60 deg arc centered around the anti-velocity vector. The P1 design (Figure 11(a)) incurred only a 4.8 m/s finite-burn penalty on the 85.1 m/s impulsive LOI design. The P1 LOI design consists of 6 periselene burns, the first being 135 minutes and the others being 30 minutes in duration. The P2 design (Figure 11(b)) incurred 9.2 m/s finite-burn penalty relative to the 107.9 m/s impulsive LOI solution. The P2 LOI was broken up into 10 periselene burns, the first being 120 minutes and subsequent burns of 30 minutes each.

Evaluation of Trajectory Constraints

The preliminary trajectory design described in the preceding subsections includes 5 deterministic maneuvers for each spacecraft. For P1, these maneuvers total 193.0 m/s and for P2, these maneuvers total 320.1 m/s.

Table 1 describes the required deterministic maneuvers. The total ΔV required for each spacecraft comes in well under the projected fuel remaining after the nominal THEMIS mission (324 m/s for P1 and 425 m/s for P2). This level of margin was needed however to allow room for trajectory refinement after the proposal was selected and for statistical maneuvers to keep the spacecraft on track.

Description	Magnitude (m/s)	Declination (deg) EMO2000	Right Ascension (deg) EMO2000
P1 Orbit Raise Maneuver	100.3	-21.2	55.1
P1 Fly-by Targeting Maneuver	0.4	37.6	242.2
P1 Deep-space Maneuver	0.9	-84.3	110.4
P1 Lunar Transfer Initiation	1.5	4.2	358.5
P1 Lunar Orbit Insertion	89.9	-2.1	149.6
P2 Orbit Raise Maneuver	179.7	-17.6	78.7
P2 Fly-by Targeting Maneuver	5.9	-22.1	90.9
P2 Deep-space Maneuver	17.3	-84.7	314.4
P2 Lunar Transfer Initiation	0.8	0.2	270.5
P2 Lunar Orbit Insertion	117.1	-4.4	172.0

Table 1. P1 and P2 maneuver details.

The $+Z$ rotation axis of the P1 and P2 spacecraft (see Figure 3) are expected to point roughly along the $-Z$ direction of the inertial Earth-Mean-Ecliptic coordinate frame of J2000 (**EMO2000**). Hence, because of the thruster orientation constraints, all maneuvers must have negative declination in the EMO2000 frame to avoid costly precession maneuvers. Table 1 includes information on the direction of each burn. It can be seen that the majority of burns have negative declinations, thus satisfying the constraints. Both Lunar Transfer Initiation burns have a very small positive inclination, which was not considered to be a concern because the burn can be placed on the other side of the Lissajous or the lunar approach can be modified a few degrees without significant mission impact. The one maneuver in violation of this constraint was the 0.4 m/s FTM for P1. Small scale optimizations were done that showed minimal ΔV penalty for eliminating the positive declination component of this burn.

Figure 12 shows the duration of umbral shadows during the mission. Recall that for spacecraft safety, shadows could not exceed 4 hours in duration. It can be seen that no umbral shadow duration exceeds 3.5 hours in this design, which satisfies the requirement.

MISSION STATUS

A significant amount of additional trajectory design work (among other things) was done on the preliminary design described here between the time the proposal was accepted in May 2008 and the first maneuvers in July 2009 to make the trajectory ready for flight. These tasks have included: converting impulsive maneuvers to finite burns, modifying the trajectories to respect thrust direction constraints for all maneuvers, increasing the dynamical model fidelity (i.e., added solar radiation pressure model and higher order lunar gravity field on the translunar trajectory), increasing the spacecraft model fidelity (e.g., spin axis precession model, pulse width models, Isp modeling, and mass tracking), incorporating updated estimates of the end of THEMIS state and orientation (significant), and splitting burns as to avoid thrusting during shadows.

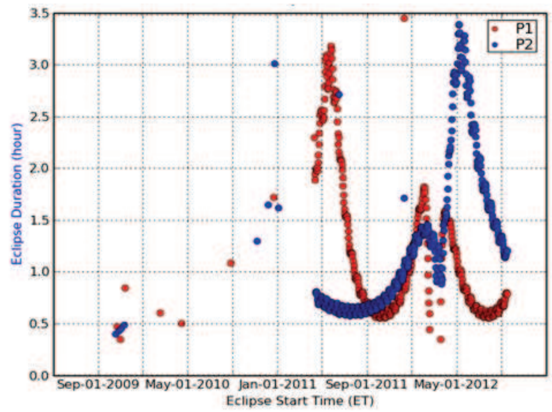

Figure 12. Umbral shadow durations for the P1 and P2 preliminary trajectory designs.

Most significant of all has been the ORM sequence design. These large ΔV maneuvers presented an extreme challenge in the final design. The extreme sensitivity of the trajectory with respect to the post-ORM state, the spacecraft constraints (no thrusting in shadow, on-board fuel, small thrusters), and a shift in the THEMIS end-of-mission state resulted in a very challenging ORM design effort. Ultimately, for P1, 13 finite-burn maneuvers beginning on August 1, 2009 were designed to take the spacecraft from the end-of-THEMIS orbit to the first lunar flyby. For P2, ~ 40 maneuvers beginning on July 21, 2009 were designed to achieve the first lunar flyby! This remarkable design that has made ARTEMIS a reality will be the subject of future publications.

As of August 5, 2009, both the P1 and P2 spacecraft have successfully executed the first burns of their respective ORM sequences. The spacecraft are completely healthy and all instruments are functional.

CONCLUSIONS

The ARTEMIS mission trajectory design that was proposed to the NASA 2008 Heliophysics Senior Review has been presented here. The design sends two spacecraft from Earth orbit to the Moon via a ~ 1.5 year transfer that involves numerous lunar approaches and flybys, low-energy trajectory legs in the Earth-Sun system, Lissajous orbits around lunar Lagrange points #1 and #2, and finally low-lunar orbits. The constraints imposed on the design by the limitations of the THEMIS spacecraft (which were designed for an Earth-orbiting mission), including thruster orientation, available ΔV, maximum shadow capability, and thruster capabilities, necessitated an innovative design. Ultimately, the design acceptably satisfied all mission constraints and offers a variety of scientific measurement opportunities that offer the potential to enhance understanding of the Earth-Moon-Sun interactions.

Both ARTEMIS spacecraft have begun their missions and are now in the midst of maneuvers designed to raise the apogee of their original Earth orbits. The spacecraft are expected to arrive in lunar Lissajous orbit late Summer / early Fall of 2010 and are expected to enter low-lunar orbit in March of 2011.

ACKNOWLEDGEMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors would like to recognize and complement the outstanding contributions of the THEMIS/ARTEMIS science team, the ARTEMIS navigation and maneuver design team at Goddard Space Flight Center, and the THEMIS/ARTEMIS navigation, maneuver design, and operations team at the University of California-Berkeley Space Science Laboratory to the successful development of the ARTEMIS mission. The challenges and successes experienced by these teams will be the subject of future ARTEMIS publications. The authors would also like to acknowledge the irreplaceable contribution of Gregory J. Whiffen of the Jet Propulsion Laboratory, California Institute of Technology to the refinement of the ARTEMIS preliminary design into a flight-ready trajectory.

APPENDIX: INTEGRATED MISSION TIMELINE

Table 2 lists trajectory events for the P1 and P2 spacecraft in the preliminary design in chronological order.

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Earth-Orbit Phase	Oct 17, 2009	P2 Orbit Raise Maneuver
Earth-Orbit Phase	Oct 20, 2009	P1 Orbit Raise Maneuver
Earth-Orbit Phase	Jan 15, 2010	P1 Fly-by Targetting Maneuver
Earth-Orbit Phase / Trans-Lunar Phase	Jan 31, 2010	P1 Lunar Fly-by #1 (min Range = 3200 km)
Trans-Lunar Phase	Feb 13, 2010	P1 Lunar Fly-by #2 (min Range = 4500 km)
Earth-Orbit Phase	Mar 11, 2010	P2 Fly-by Targetting Maneuver
Trans-Lunar Phase	Mar 15, 2010	P1 Deep-space Maneuver (+ Local Maximum Range = 1200000 km to Earth)
Earth-Orbit Phase / Trans-Lunar Phase	Mar 28, 2010	P2 Lunar Fly-by (min Range = 21000 km)
Trans-Lunar Phase	Apr 13, 2010	P1 Earth Fly-by (min Range = 17000 km)
Trans-Lunar Phase	Apr 19, 2010	P2 Deep-space Maneuver (+Local Maximum Range = 940000 km to Earth)
Trans-Lunar Phase	May 11, 2010	P2 Earth Fly-by #1 (min Range = 86000 km)
Trans-Lunar Phase	Jun 06, 2010	P1 Maximum Range (1500000 km to Earth)
Trans-Lunar Phase	Jun 18, 2010	P2 Maximum Range (1200000 km to Earth)
Trans-Lunar Phase	Jul 27, 2010	P2 Earth Fly-by #2 (min Range = 170000 km)
Trans-Lunar Phase / Lissajous Orbit Phase	Aug 23, 2010	P1 LL2 Insertion
Trans-Lunar Phase	Aug 23, 2010	P2 Local Maximum Range (1100000 km to Earth)
Trans-Lunar Phase / Lissajous Orbit Phase	Oct 22, 2010	P2 LL1 Insertion
Lissajous Orbit Phase	Jan 1, 2011	P1 Departs LL2
Lissajous Orbit Phase	Jan 08, 2011	P1 LL1 Insertion
Lissajous Orbit Phase	Mar 25, 2011	P2 Lunar Transfer Initiation
Lissajous Orbit Phase	Apr 03, 2011	P1 Lunar Transfer Initiation
Lissajous Orbit Phase / Lunar Orbit Phase	Apr 08, 2011	P2 LOI (1500 km alt)
Lissajous Orbit Phase / Lunar Orbit Phase	Apr 20, 2011	P1 LOI (1500 km alt)
Lunar Orbit Phase	Oct 08, 2012	P2 End of 1.5 year Lunar Orbit Phase
Lunar Orbit Phase	Oct 19, 2012	P1 End of 1.5 year Lunar Orbit Phase

Table 2. Integrated preliminary trajectory design timeline.