ARTEMIS Operations – Experiences and Lessons Learned

Manfred Bester, Daniel Cosgrove, Sabine Frey, Jeffrey Marchese, Aaron Burgart,
Mark Lewis, Bryce Roberts, Jeremy Thorsness, John McDonald, Deron Pease,
Gregory Picard, Martha Eckert, and Renee Dumlao
Space Sciences Laboratory
University of California, Berkeley
7 Gauss Way
Berkeley, CA 94720-7450
510-643-1014
mbester, cosgrove, sfrey, jem, aburgart, markl, broberts, jfthors,
jmcd, pease, picard, marty, rdumlao@ssl.berkeley.edu

***Abstract*—THEMIS, a constellation of five spacecraft, referred to as probes, was launched in 2007 to study the physical processes leading to the aurora. In 2009, THEMIS successfully completed its primary mission phase. As an ambitious mission extension, the constellation was then split into two new missions – THEMIS-Low and ARTEMIS. THEMIS-Low refers to three of the five probes that continued magnetospheric observations in Earth orbits while the remaining two probes started a new lunar mission called ARTEMIS. The two ARTEMIS probes were transferred from Earth to lunar orbits via low-energy trajectories with Earth and lunar gravity assists. The complex mission design and navigation operations took the two probes on trajectories along weak stability boundary manifolds, venturing out as far as 1,500,000 km and 1,200,000 km from Earth, respectively. Upon arrival in the lunar environment, both probes were first inserted into libration point orbits where they spent up to ten months collecting science data. Periodic stationkeeping maneuvers were executed to ensure the two probes would not be ejected from these unstable orbits. In 2011, both probes were successfully inserted into stable, retrograde and prograde lunar orbits, respectively. We report on the challenges with executing the complex navigation plans, discuss experiences and lessons learned from operating two spacecraft in lunar libration point orbits for the first time ever, and finally cover mission planning and science operations in the lunar environment.**

TABLE OF CONTENTS

1. INTRODUCTION 1
2. ARTEMIS CONCEPT OF OPERATIONS 2
3. MISSION DESIGN 4
4. NAVIGATION OPERATIONS 5
5. EXECUTING THE NAVIGATION PLANS 7
6. GROUND SYSTEMS 9
7. MISSION OPERATIONS 10
8. SCIENCE OPERATIONS 10
9. EXPERIENCES AND LESSONS LEARNED 11
10. SUMMARY 12
REFERENCES 13
BIOGRAPHY 14
ACKNOWLEDGEMENTS 15
APPENDIX 16

1. INTRODUCTION

The Time History of Events and Macroscale Interactions During Substorms (THEMIS) mission is a NASA Medium-class Explorer, consisting of five identical spacecraft, hereafter referred to as *probes*. [1]

Following launch in 2007, the five probes were maneuvered into highly elliptical, low-inclination Earth orbits with synchronized periods of approximately 1, 2, and 4 sidereal days. As illustrated in Figure 1, a string-of-pearls orbit configuration formed along the magnetospheric tail every four days and allowed multi-point observations to be made to investigate the physics of substorms that lead to the aurora. The probes were labeled P1-P5, counting from the longest to the shortest orbit period at the time of completion of the initial constellation deployment in early 2008. [2,3]

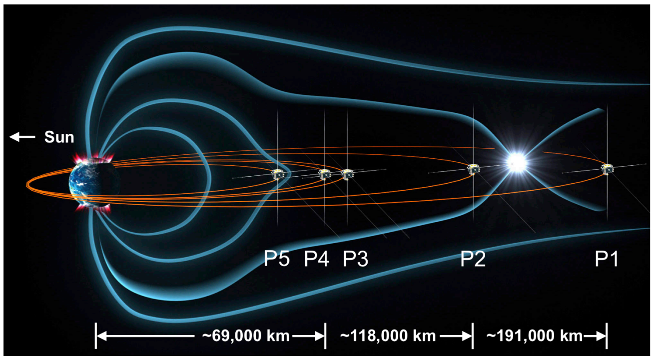


Figure 1 – Artist's conception of the THEMIS mission orbits. The white flash represents energy released during a magnetospheric substorm. Credit: NASA.

THEMIS successfully completed its primary mission phase in 2009. For the extended mission, THEMIS was split into two new missions. Three of the five probes with orbit periods of the order one day became THEMIS-Low, and continued their magnetospheric observations in Earth orbits. Probes P1 and P2 with the largest orbit periods of four and two days, respectively, formed the new Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission. [4]

978-1-4799-1622-1/14/$31.00 ©2014 IEEE

The goal of the ARTEMIS mission included transfer of probes P1 and P2 from Earth to lunar orbits to address key science questions related to both heliophysics and planetary science. The driving motivation behind taking these two probes out of Earth orbits was the limited ability of the thermal and electrical power systems for surviving extreme shadow durations. The probes were originally designed for shadow durations up to 3 h. On-orbit performance was demonstrated to handle up to 4-h long shadows. However, predicted shadow durations after the end of the THEMIS prime mission were as long as 8 h.

During the exploration of a potential ARTEMIS mission design concept, discussed in more detail below, it was realized that given the robust fuel reserves from the THEMIS primary mission, a transfer from Earth to lunar orbits was a feasible approach to escape the long shadows. The solution was a low-energy trajectory, uniquely designed for each of the two probes, with several Earth and lunar gravity assists at moderate ΔV expenditure. Constraints in the propulsion systems of the two probes required a rather complex navigation operations scenario to execute the trajectory design.

ARTEMIS was proposed to the NASA Heliophysics Senior Review in early 2008 as part of a THEMIS mission extension, and was approved by the review panel. ARTEMIS operations formally commenced on 2009/07/20, coinciding with the 40th anniversary of the first manned lunar landing.

This paper describes the efforts and challenges encountered with transferring two spacecraft, designed to operate in Earth orbits, to lunar orbits via a series of thrust maneuvers, deep space trajectory excursions, and stationkeeping in lunar libration point orbits. It also discusses experiences and lessons learned from conducting mission and science operations of two spacecraft in lunar orbits for more than two years. The continuation of the THEMIS-Low mission is discussed elsewhere.

2. ARTEMIS CONCEPT OF OPERATIONS

This section describes project roles and responsibilities, and the concept of operations for ARTEMIS.

Roles and Responsibilities

Roles and responsibilities for the ARTEMIS mission were distributed across four different organizations:

(1) The University of California, Los Angeles (UCLA) was the principal investigator institution.

(2) The University of California, Berkeley (UCB) managed all aspects of mission and science operations, flight control functions, executed navigation plans, performed propellant management, and orbit and attitude determination from the Mission and Science Operations Center (MSOC).

(3) NASA Jet Propulsion Laboratory (JPL) provided the baseline trajectory design and determined the required thrust maneuver sequences.

(4) NASA Goddard Space Flight Center (GSFC) supported trajectory design functions, particularly during the libration point orbit phase, and performed navigation error analysis, as well as back-up orbit determination.

Concept of Operations

Since ARTEMIS was a spin-off from an already existing mission, the new concept of operations inherited the design, capabilities, and constraints of already operating spacecraft. [3,5]

The THEMIS and ARTEMIS probes were designed and implemented as spin-stabilized instrument platforms with a nominal spin rate of 20 rpm. Two pairs of spin-plane wire booms extending out to ±25 m and ±20 m, respectively, two axial stacer booms, and two magnetometer booms were deployed on orbit. Figure 2 shows an artist's rendering of the two ARTEMIS probes in their deployed configuration.

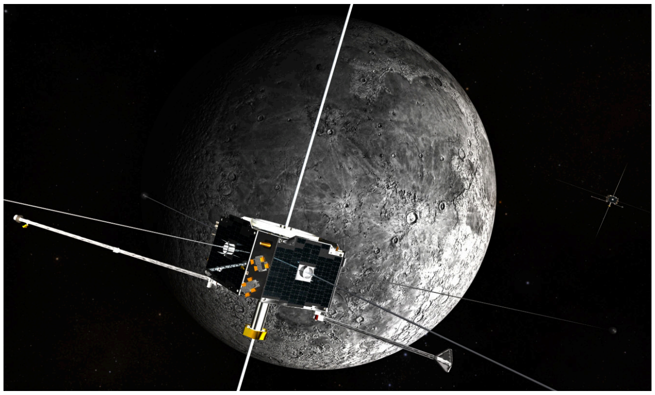


Figure 2 – Artist's rendering of the ARTEMIS probes in their deployed configuration. Credit: NASA.

In general terms, the ARTEMIS concept of operations was similar to THEMIS in the sense that all five probes were still operated from the same control center and shared the same resources. Ground systems, such as the spacecraft command and control systems were identical, and ARTEMIS was operated in store-and-forward mode for science and engineering data recovery. ARTEMIS did require new capabilities to support deep space navigation, so these functions were added without disrupting ongoing operations. More details are provided further below.

Network Communications

Much like THEMIS, ARTEMIS used communications at S-band with ten selectable telemetry data rates, involving support by the following networks:

(1) NASA Near-Earth Network (NEN)

(2) NASA Space Network (SN)

(3) NASA Deep Space Network (DSN)

(4) Universal Space Network (USN)

(5) Berkeley Ground Station (BGS), co-located with the MSOC at Space Sciences Laboratory (SSL)

The Space Network supported ARTEMIS during the Earth departure phase. The DSN was integrated into the mission network to allow for deep space communications, two-way Doppler tracking, and ranging support during the transfer trajectory and libration point orbit phases, and for increased science data recovery from lunar distances. [6]

Initial tracking and ranging tests with the DSN 34-m subnet stations began in December 2008, and were able to prove that the DSN sequential ranging scheme was compatible with the probe transponders. The fact that ranging data could be available in addition to two-way Doppler tracking data was a critical piece of information. Orbit determination could now become sufficiently accurate to allow for planning and executing small trajectory correction maneuvers with ΔV magnitudes of a few cm/s.

Navigation Capabilities and Constraints

The probes were equipped with a simple hydrazine blow-down Reaction Control System (RCS) that was pressurized with helium. Main RCS components, shown in Figure 3, included two spherical propellant tanks, a pyro-actuated re-pressurization tank, two latch valves, and four 4.5-N thrusters (Aerojet MR-111C). [7]

Two of the four thrusters were mounted parallel to the spin axis, and were hence referred to as axial thrusters (A1, A2). The other two thrusters were mounted in the spin plane and were termed tangential thrusters (T1, T2).

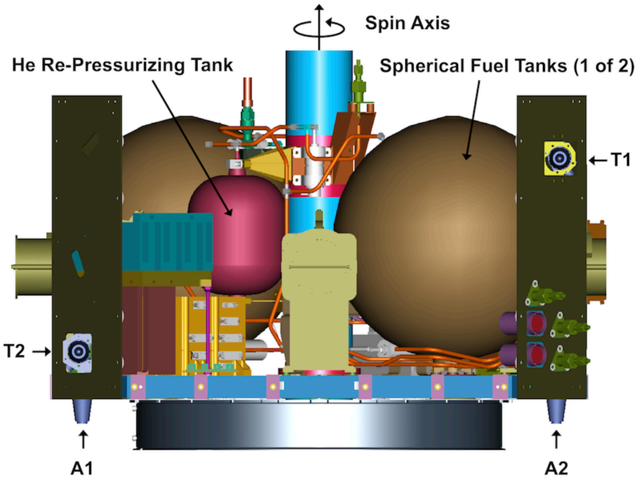


Figure 3 – Layout of the ARTEMIS probe buses with the major RCS components.

Axial thrusters were fired in continuous thrust mode to achieve a ΔV along the spin axis, while tangential thrusters were fired simultaneously in sun synchronous pulsed mode to achieve a ΔV goal perpendicular to the spin axis. Attitude precession maneuvers were executed by firing one of the axial thrusters in sun synchronous pulsed mode, and spin rate changes were achieved by firing one of the tangential thrusters in pulsed mode. Certain flight rules for the pulse durations were applied to ensure that dynamics of the spinning probes remained stable throughout any pulsed maneuver. Main concerns were wire boom oscillations and fuel slosh resonances. [3]

Prior to the deployment of the spin-plane wire booms the moments of inertia of the probes were small enough to allow attitude maneuvers to be performed so that the axial thrusters could be oriented in any direction at only a small expense of fuel. However, with the wire booms deployed, the moments of inertia were so large that it was prohibitive to change the attitudes to and from an ideal axial firing attitude. These constraints needed to be taken into account when designing the ARTEMIS mission trajectories. Another side effect was that even small thruster misalignments and asymmetrical mass properties of the probes typically caused noticeable changes in attitudes and spin rates with each ΔV maneuver.

Available fuel reserves further constrained the complex ARTEMIS mission design. Fuel loads and ΔV capacity of the two probes at launch, and reserves at the end of the THEMIS prime mission are summarized in Table 1. Differences in initial ΔV capacity between the two probes were due to the fact that different amounts of fuel were required for attitude precession and spin rate control maneuvers during the initial deployment of the THEMIS constellation.

Table 1. Summary of THEMIS P1 and P2 Estimated End-of-prime-mission Fuel Loads and ΔV Capacity.

Parameter	P1	P2
Initial Fuel Load at Launch [kg]	48.780	48.810
Remaining Fuel [kg]	14.547	21.140
Remaining Fuel [%]	29.8	43.3
Initial ΔV Capacity [m/s]	1019.357	1002.312
Remaining ΔV Capacity [m/s]	307.195	449.931

Other Operations Considerations

In general, preparation of ARTEMIS operations did not require any flight software changes. However, probe specific configurations were changed to better support maneuver operations. In addition, flight procedures were revised or rewritten to plan and execute critical maneuvers that could not be missed. Further details are given in the following sections.

Science Operations

ARTEMIS science operations were very similar to those of THEMIS, except that instrument configuration and data collection modes were tailored to the new space environment to meet science goals. Data volumes were adjusted so that complete science data recovery was achieved within available telemetry bandwidth constraints.

The probes carried identical sets of five science instruments to measure fields and particles:

(1) Fluxgate Magnetometer (FGM) to measure ambient low-frequency (DC−64 Hz) magnetic fields in 3D

(2) Search Coil Magnetometer (SCM) to measure ambient high-frequency (1 Hz − 4 kHz) magnetic fields in 3D

(3) Electrostatic Analyzer (ESA) to measure thermal ions (5 eV − 25 keV) and electrons (5 eV – 30 keV)

(4) Solid State Telescope (SST) with dual sensor heads to measure the angular distribution of super-thermal ions (25 keV – 6 MeV) and electrons (25 keV – 1 MeV)

(5) Electric Field Instrument (EFI) to measure the ambient (DC−8 kHz, 100−400 kHz) electric field in 3D

The deployed configuration of the probes is illustrated in Figure 4. Details on science planning and operations are described in more detail in Section 8.

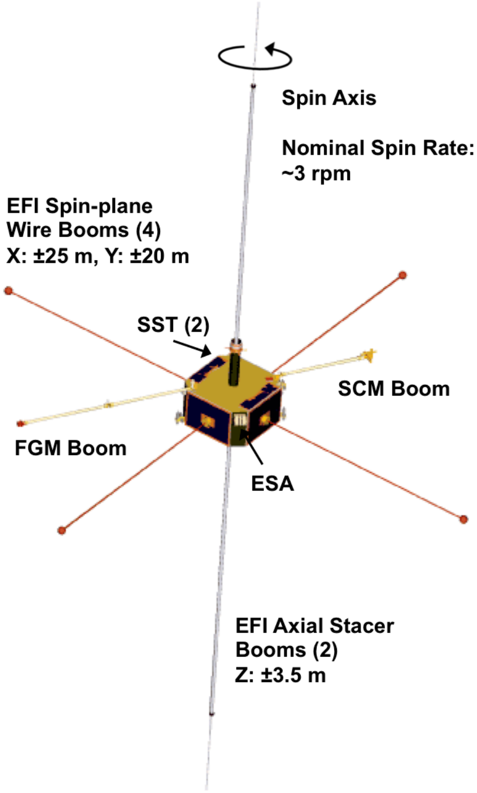


Figure 4 – Probe and science instruments in deployed configuration (not to scale).

3. MISSION DESIGN

Motivation and Drivers

As early as 2005, a team of navigation experts at JPL began studying options to rescue THEMIS probes P1 and P2 from freezing in long Earth shadows in March 2010, or 3 years into the THEMIS mission. It was determined that with the existing fuel reserves both probes had the ability to escape Earth orbits and embark on a new lunar science mission, ARTEMIS. [4]

While both probes had a sufficient ΔV capability to reach the Moon, a direct lunar orbit insertion was not feasible without flying a significantly more complex trajectory. The general solution was to approach the Moon by matching its position and velocity along its orbit around Earth.

The goal of the ARTEMIS trajectory design was to first transfer probes P1 and P2 from Earth orbits to lunar libration point orbits by way of low-energy trajectories with gravity assists. The next step would be to insert both probes from libration point orbits into stable lunar orbits. A number of constraints, such as available fuel reserves, limited RCS capabilities, maximum shadow durations, communications, and mission science goals were taken into account. [8]

Trajectory Design

The trajectory design was broken into four distinct phases:

(1) Earth Orbit Phase

(2) Trans-lunar Phase

(3) Lunar Libration Point Orbit Phase

(4) Lunar Orbit Phase

During the Earth Orbit Phase the apogees of the probes were gradually raised by executing a series of Orbit Raise Maneuvers (ORMs) near perigee, until lunar gravity led to a sequence of lunar approaches and flybys that pulled the probes out of their Earth orbits.

The lunar flybys marked the beginning of the Trans-lunar Phase that took the two probes on different trajectories through interplanetary space, passing near the Sun-Earth (SE) Lagrange points – SE L_1 in case of P1 and SE L_2 in case of P2 – where the trajectories were significantly affected by solar gravity. The end-to-end design of the trans-lunar trajectories targeted the Earth-Moon (EM) libration point orbit insertion with minimal energy required for each probe. Deterministic maneuvers, here called Deep Space Maneuvers (DSMs), were placed by design near the Sun-Earth weak stability regions to provide opportunities for mid-course corrections where different sections of the complex trajectories had to be stitched together. This design approach allowed the probes to travel along existing manifolds in the multi-body dynamical environment and eventually achieve EM L_1 and L_2 libration point orbits. [9]

The Lunar Libration Point Orbit Phase was characterized by performing periodic Stationkeeping Maneuvers (SKMs) for active orbit control to ensure the probes were not ejected from these inherently unstable orbits near the collinear EM L_1 and L_2 locations. Probe P1 initially spent about 3 months in the L_2 orbit before joining P2 on the L_1 side. In total, the two probes collected science data for 9-10 months in these libration point orbits that also served as staging points in preparation for the lunar orbit insertion.

Lunar Orbit Insertion (LOI) was targeted out of the libration point orbits, with P1 entering into a retrograde and P2 into a prograde lunar orbit, using sequences of Lunar Transfer Initiation (LTI) and LOI burns. Retrograde and prograde orbits were chosen so that the differential precession of the elliptical orbits swept the relative alignment of the lines of apsides over a full 360 deg circle within approximately 2 years. This orbit arrangement allowed exploration of the lunar environment over a wide range of geometrical conditions, as explained in more detail further below.

Once in lunar orbit, the aposelene altitudes were lowered through a series of phasing burns, termed Period Reduction Maneuvers (PRMs), to increase orbit stability and to set up for the lunar science phase.

Inflight Trajectory Corrections

During the Earth Orbit Phase, a number of statistical Flyby Targeting Maneuvers (FTMs) were inserted into the trajectory to compensate for execution errors from previous maneuvers, and for navigation errors arising from imperfect orbit determination and force modeling. Similarly, a number of Trajectory Correction Maneuvers (TCMs) were also inserted into the maneuver sequence during the Trans-lunar Phase to keep the probes' flight paths as close as possible to their baseline design trajectories.

Mission Timeline

The following timeline summarizes key ARTEMIS mission events. Dates refer to Universal Time Coordinated (UTC), and minimum ranges r_{min} refer to body centers:

- 2009/07/21 P2 initiation of the Earth departure
- 2009/08/01 P1 initiation of the Earth departure
- 2009/09/17 P1 lunar approach #1 (r_{min} = 45,679 km)
- 2009/12/07 P1 lunar approach #2 (r_{min} = 18,577 km)
- 2010/01/31 P1 lunar flyby #1 (r_{min} = 14,132 km)
- 2010/02/13 P1 lunar flyby #2 (r_{min} = 5,020 km)
- 2010/03/28 P2 lunar flyby (r_{min} = 9,808 km)
- 2010/04/13 P1 Earth flyby (r_{min} = 23,378 km)
- 2010/05/11 P2 Earth flyby #1 (r_{min} = 92,400 km)
- 2010/06/06 P1 largest range from Earth (1.5×10^6 km)
- 2010/06/18 P2 largest range from Earth (1.2×10^6 km)
- 2010/07/27 P2 Earth flyby #2 (r_{min} = 176,400 km)
- 2010/08/25 P1 EM L_2 libration point orbit insertion
- 2010/10/22 P2 EM L_1 libration point orbit insertion
- 2011/01/08 P1 transfer EM L_2 to EM L_1 orbit
- 2011/06/06 P1 transfer initiation EM L_1 to lunar orbit
- 2011/06/21 P2 transfer initiation EM L_1 to lunar orbit
- 2011/06/27 P1 lunar orbit insertion
- 2011/07/17 P2 lunar orbit insertion
- 2011/09/08 P1 lunar orbit phasing completion
- 2011/11/07 P2 lunar orbit phasing completion

A storybook with trajectory plots illustrating the complex flight paths of the two probes is included in the Appendix.

The following sections describe how these navigation plans were implemented and executed, and what challenges were encountered and had to be resolved in preparation for and during this complex mission extension.

4. NAVIGATION OPERATIONS

Navigation Process

With nearly 300 thrust maneuvers and numerous orbit and attitude solutions completed prior to the start of ARTEMIS, the THEMIS navigation processes were well established. For ARTEMIS, additional requirements had to be met to send two probes that were designed for operation in Earth orbits into the interplanetary and lunar environment. Furthermore, both probes had to be accurately navigated along complex trajectories and into partly unknown territory.

While keeping well tested software tools and processes in place, a number of significant upgrades had to be made to support the new and unique navigation requirements, but without compromising operations of the still ongoing THEMIS prime mission. The following list represents the major task areas:

(1) Integrate the DSN as a new communications network into the existing multi-mission environment and certify new network elements for two-way Doppler tracking and ranging.

(2) Implement new capabilities for orbit determination in gravitational regimes that require different strategies and more advanced force modeling.

(3) Implement an attitude determination scheme that only requires sun sensor data, but no FGM data.

(4) Refine navigation accuracies for planning, execution, and post-processing of thrust maneuvers by at least an order of magnitude.

(5) Implement measures to reduce the risks of missing maneuvers, particularly those that are mission critical.

Integrated THEMIS navigation software tools at UCB included the Goddard Trajectory Determination System (GTDS), the General Maneuver Program (GMAN), and the in-house developed Mission Design Tool (MDT). These tools were reused for ARTEMIS with relatively minor modifications. However, UCB needed to implement new interfaces to exchange navigation data with the GSFC and JPL teams who used other mission design and optimization tools, such as the General Mission Analysis Tool (GMAT), Analytical Graphics' Astrogator, and Mystic. [9-11]

Orbit Determination and Tracking Requirements

Much like with THEMIS, orbit determination (OD) for ARTEMIS was based on range and range-rate observations from a number of ground stations. During the Earth Orbit Phase the NEN, USN, and BGS facilities provided two-way

Doppler tracking data that were augmented by DSN range and range rate observations.

Due to the large ranges associated with the deep space excursions within the Trans-lunar Phase, OD solutions were based on DSN tracks exclusively. The nominal requirement was that DSN would provide for each probe a 3.5-h long track every 48 h, alternating between northern and southern latitude ground stations. Tracking coverage was increased to 9-h long continuous tracks around lunar and Earth flybys, followed by 8 h per day for 3 days after each flyby.

Initial plans for OD in libration point orbits were also based on a nominal scheme with one 3.5-h long DSN track every other day for each probe. Due to the sparseness of tracking data it was originally expected that OD arcs had to include stationkeeping maneuvers and that corresponding thrust forces would have to be modeled, which would require special software algorithms. However, this problem was avoided by augmenting the DSN observations with two-way Doppler tracks from smaller 11-13 m class antennas, such as the Berkeley and USN ground stations. This approach simplified the OD process, as arcs could be broken with each stationkeeping maneuver, and UCB was able to continue using GTDS. Results are presented further below.

Requirements for LOI support included 24-h long tracks centered on the LOI burns. Nominal plans for the Lunar Orbit Phase were similar to the Trans-lunar Phase, although the actual tracking scheme eventually deviated from the original plans due to working around resource contention, as described further below.

Attitude Determination and Attitude Control

During the THEMIS prime mission, attitude determination (AD) was based on data provided by a Miniature Spinning Sun Sensor (MSSS) and magnetic field vectors measured with the FGM near perigee. These data were processed with the Multi-mission Spin-axis Stabilized Spacecraft (MSASS) software, a Matlab based tool developed at NASA/GSFC. MSASS uses a Kalman filter to determine the inertial orientation of the spin axis. However, once the probes departed Earth orbits, useful magnetic field data were no longer available for AD. As a workaround, MSASS was further developed by GSFC to support the Fuzzycones AD algorithm that derives the inertial attitude by maximum likelihood modeling of MSSS data alone, observed over periods of several weeks to months. [11,12]

Attitude control requirements for the inertial direction of the spin axis were waived for ARTEMIS to conserve fuel and to avoid imparting even small ΔV components that typically accompanied an attitude precession maneuver and would disturb the sensitive trajectory design. Likewise, ΔV maneuvers caused attitude precession torques and spin rate changes resulting from thruster misalignment and center of mass offsets. Requirements to counteract these attitude perturbations were waived also. Once in lunar orbit, spin axis precession was dominated by gravity gradient torques.

Improvements in Propellant Estimation

During the THEMIS prime mission, propellant bookkeeping relied primarily on the fuel usage estimation by the GMAN software for each executed thrust maneuver. Upon detailed investigation, it was found that the polynomial model for the relationship between tank pressure P and specific impulse I_{sp} did not match the relationship provided by the thruster manufacturer. In addition, thrust scale factors of one had been used throughout the THEMIS prime mission, which led to an overestimation of the amount of propellant mass expended. Also, fuel tank temperature telemetry instead of fuel tank pressure telemetry had been used to relate pressure-volume-temperature (PVT) and remaining fuel mass. In preparation for ARTEMIS navigation operations, a significant effort was undertaken to improve the accuracy of fuel mass estimation by cleaning up the PVT based estimation and by implementing thermal gauging as a third technique. [13]

Improvements in Maneuver Targeting Accuracy

With the much tighter navigation accuracy requirements for ARTEMIS, additional efforts needed to focus on reducing maneuver execution errors by an order of magnitude. A large improvement in the prediction of thruster performance scale factors was achieved by taking into account tank heater temperature cycling profiles.

Tank heaters were thermostatically controlled and turned on automatically when a fixed low-temperature threshold was reached. Key to success was the correct estimation of the temperature profile 24 to 48 h in advance of a burn. In a number of cases several maneuver plans with different tank temperatures were prepared, tested on the flight simulator, reviewed, and certified for execution. The thruster command sequence for the most likely expected tank temperature was uploaded well in advance of a burn. However, a revised and more optimal command sequence that more closely matched the tank temperature at the time of a burn could still be loaded shortly before the burn.

Other work focused on revisiting maneuver calibration, analyzing data from the large number of thrust maneuvers that had been executed during the THEMIS prime mission. For ARTEMIS a significant number of TCM, FTM, and SKM burns required firing thrusters with a small number of pulses for which calibration data were initially unavailable. [14]

During the THEMIS prime mission, pulse durations of tangential thrust maneuvers were typically fixed at jet firing arcs of either 40 or 60 deg, corresponding to pulse durations of 333 or 500 ms, respectively, at a nominal spin rate of 20 rpm. Depending upon tank pressure, a single pulse could provide a ΔV up to about 2 cm/s. For small ΔV maneuvers a quantization error of this magnitude would therefore be much larger than the desired execution error of 1%, as only integer numbers of thrust pulses could be fired for any given burn. Changes made to the maneuver planning software allowed for variable pulse durations and eliminated these quantization errors, as a fraction of a single pulse quantum could then be spread out evenly over all pulses. This way maneuvers could be targeted more accurately.

All of the above efforts were instrumental towards reducing maneuver execution errors from the 5% range seen during the THEMIS prime mission down to a level near 1%, which was the ARTEMIS goal. [3,11]

Maneuver Planning and Operations

Maneuver planning and navigation operations were closely coordinated between three organizations, namely JPL, GSFC, and UCB. Conference calls were held at least once per week. UCB typically provided latest OD and AD states from GTDS and MSASS runs as input to forward looking trajectory analyses, conducted at JPL and GSFC. Depending upon mission phase, JPL or GSFC then provided maneuver target states and thrust vectors that were ingested into the MDT software at UCB, acting as the common flight dynamics interface for generation of all subsequent planning products and thruster command sheets. Both JPL and GSFC then reviewed the final maneuver plans generated by UCB. In many cases multiple iterations were required, as more accurate trajectory information became available. GSFC also performed many statistical navigation error analyses to determine probabilities of projected maneuver results and to assess recovery options from hot or cold burns. [9]

5. EXECUTING THE NAVIGATION PLANS

Earth Departure

During the Earth Orbit Phase, JPL generated the updated maneuver targets for each ORM in form of a target state vector and a thrust vector, along with the burn center time and the thrust duration. Most of these near-perigee burns had to be shifted in mean anomaly, and many were split into two segments to occur outside of Earth shadows.

Once maneuver target information was received from JPL, UCB reprocessed these data with the MDT software to perform another optimization cycle, using the more accurate GMAN thruster model with updated thrust calibration factors, predicted tank temperatures, and the latest orbit and attitude states. In this process, execution errors from preceding maneuvers were taken into account to adjust target goals for upcoming maneuvers. This way both probes could follow their prescribed, time-critical trajectories as accurately as possible, so that lunar approach and flyby conditions were met within allowed tolerances.

Final maneuver preparation was typically performed within 24-36 h of the maneuver execution time to optimize performance and limit execution errors. Verification and validation of each maneuver sequence was run in real-time on the flight simulator. Flight controllers then uploaded command sequence tables to the probe and enabled the propulsion bus well in advance of a thrust maneuver to allow for autonomous on-board execution, in case real-time, two-way communications dropped out. At least one back-up load opportunity was scheduled for each maneuver, and multiple back-ups were coordinated for all critical maneuvers, as described further below.

To depart Earth, the two probes started from significantly different orbits, with probe P2 having the lower apogee:

- P1 required 5 ORMs, starting with a 4-day period orbit (195,703 × 1,936 km altitude, 31.7 × 1.3 R_E geocentric).
- P2 required 27 ORMs, starting with a 2-day period orbit (117,438 × 3,201 km altitude, 19.4 × 1.5 R_E geocentric).

In addition to the much larger number of ORMs, probe P2 also required two Shadow Deflection Maneuvers (SDMs) embedded within its ORM sequence to avoid a 10-h long Earth shadow on 2010/03/22 (see Figure A-7 in the Appendix). Table A-1 summarizes all executed ARTEMIS maneuvers along with their fuel budgets and accumulated ΔV for each mission phase. [10,11]

Lunar Flyby Targeting

After completion of their ORM sequences, both probes were on track to navigate through the sensitive lunar approaches and flybys that resulted in the trans-lunar trajectories.

By far the most challenging part of the baseline trajectories was to navigate P1 through two lunar approaches, followed by a dual lunar flyby scenario. The entire sequence was set up by two FTMs, one each prior to the first and second lunar approach. The first lunar approach increased both apogee and perigee, but caused no significant plane change. However, the second lunar approach, resulted in a *knee* in the trajectory that changed the inclination from 10 to 58 deg, as is illustrated in Figures A-1 to A-3 in the Appendix.

The first lunar flyby of P1 occurred after completion of five high-inclination orbits with periods of about 11 days. This flyby took the probe out of Earth orbit along a southern *back-flip* trajectory to encounter the Moon a second time ~14 days later on the other side of the Earth. The second lunar flyby then sent the probe onto its trans-lunar trajectory toward SE L_1.

In addition to the two FTMs, P1 also required four TCMs to correct for navigation and maneuver execution errors. TCMs 1-3 were placed on the first, third, and fourth high-inclination orbit, prior to the first lunar flyby. While this flyby was achieved within B-plane tolerances, it was rather critical, as it also set up the conditions for the second flyby.

Initial concerns with tracking coverage during the back-flip arose because the S-band antenna, mounted on the southern side of the probe, was partly blocked by the spacecraft body for communications towards Earth in the northern direction. In addition, view of the probe at the center of the back-flip was limited to only one DSN complex in Canberra, Australia. Therefore it was important to determine the post-flyby state and perform TCM 4 as early as possible. A short 2-day, post-flyby tracking arc yielded position and velocity accuracies (1σ) of 1,500 m and 1 cm/s, respectively, that met the requirements for targeting the B-plane conditions for the second lunar flyby via TCM 4 (see Figure A-3).

By contrast, probe P2 required only one FTM and one TCM following the last ORM to set up for a single lunar flyby prior to entering its trans-lunar trajectory. [9,11]

Trans-lunar Trajectories

Following the dual lunar flyby, probe P1 required two deep space trajectory lobes and one Earth flyby to reach the lunar libration point region. Probe P2 had only one lunar flyby, but three deep space trajectory lobes and two Earth flybys. The deep space excursions of both probes are illustrated in Figures A-4, A-6, and A-9.

Navigation solutions obtained with GTDS during the Trans-lunar Phase used tracking arcs of 5-21 days in duration. Resulting uncertainties (1σ) were generally less than 50 m in position and less than 1 cm/s in velocity. [9]

S-band communications links were required to be closed out to 1,500,000 and 1,200,000 km for probes P1 and P2, respectively, to provide range and range rate data for orbit determination, to execute thrust maneuvers, and to check spacecraft state of health. With the 34-m DSN stations, the telemetry data rate of 4.096 kbps provided adequate link margin. [6]

Lunar Libration Point Orbits

Both probes arrived at their respective libration point orbit insertion targets, approaching the Moon from behind along its orbit around Earth, and matching its position and velocity states in general terms. The first SKM marked the beginning of this mission phase for each probe. Typical libration point orbit periods were 13.5-14.2 days around EM L_1 and 15.5 days around EM L_2. Libration point orbits for probe P1 are illustrated in Figure A-5.

The adopted stationkeeping strategy called for maneuvers every 7-14 days, so that a stable navigation solution could be obtained after each maneuver, and before the next maneuver was planned and executed. RCS constraints on thrust direction had to be taken into account, and dynamics of the Earth-Moon (and Sun) environment were accurately modeled at least 3 weeks into the future. Maneuvers placed near the XZ plane crossings in Earth-Moon rotating coordinates (where +X points from the Earth to the collinear libration points, and Z is perpendicular to the lunar orbit) resulted in 5 times lower costs of follow-on maneuvers than those placed near the Y component extremes of the kidney shaped orbits. Required ΔV magnitudes ranged from 1 to 38 cm/s. This approach resulted in an overall ΔV budget that was an order of magnitude lower than expected from prior modeling. Further details on stationkeeping operations and navigation error analysis are described elsewhere. [15-17]

During the Libration Point Orbit Phase, DSN tracks were augmented with tracks from smaller 11-13 m class antennas. OD accuracies achieved with the weighted batch least squares method and high-fidelity force model that GTDS employs were estimated to be less than 100 m and 0.1 cm/s. Even orbit accuracies of approximately 20 m and 0.002 cm/s were achievable. The optimal arc length was found to be 10 days. These accuracies met the requirements for planning and executing small stationkeeping maneuvers with magnitudes of the order few cm/s. [16,18,19]

Mass Ejection Anomaly

A mass ejection anomaly occurred on probe P1 during the Libration Point Orbit Phase. On 2010/10/14 the EFI sensor sphere at the end of one of the 25-m long wire booms departed. Subsequent analysis determined that the sphere with a mass of 92 g was likely severed off by one or more micrometeorid impacts. Through conservation of linear momentum the event imparted an approximate ΔV of 5.7 cm/s on the spacecraft body, similar in magnitude to a typical stationkeeping maneuver. The anomaly was initially discovered as a residual range rate bias on subsequent two-way Doppler tracks. The resulting mass imbalance created asymmetrical thrust arms between the tangential thrusters, leading to a torque that would cause significant spin rate changes during the upcoming LOI burn sequence. This unexpected problem needed to be taken into account in the planning and segmentation of the P1 LOI burn arc, as it affected the thrust pulse timing. [20]

Lunar Transfer Initiation

Departure from EM L_1 libration point orbits towards LOI was achieved by executing Lunar Transfer Initiation (LTI) burns. Probe P1 required one LTI burn (3.3 m/s) at LOI-21 days and two TCMs (0.5 m/s total) at LOI-10 and LOI-5 days, respectively, to accurately target the insertion conditions for the retrograde lunar orbit. Probe P2 required two LTI burns (1.0 m/s total) at LOI-26 and LOI-19 days, respectively, plus one TCM (0.1 m/s) at LOI-12 days to target the conditions for the prograde lunar orbit insertion.

Lunar Orbit Insertion

Insertion altitudes of 1,850 and 3,800 km for P1 and P2, respectively, and long LOI burn durations were selected to achieve an adequate post-insertion orbit stability, so the probes would not impact at the periselenes of the early lunar orbits. The resulting burn durations of 141 min ($\Delta V \approx 51.4$ m/s) for P1 and 192 min ($\Delta V \approx 74.8$ m/s) for P2 caused unavoidable gravity efficiency losses. To reduce steering losses, the burns were segmented into three parts, each with a fixed thrust direction, as the RCS design did not allow changing the thrust direction during a burn. [21]

A number of mission readiness tests and simulations were conducted to prepare the joint navigation and operations team for the complex LOI activities. Critical LOI event coverage was accomplished by using a prime and a hot back-up DSN 34-m antenna. The P1 LOI sequence was supported by the Goldstone Complex with a 12-h long, continuous track of DSS-24 as prime antenna. The P2 LOI coverage involved a hand-over from Canberra to Madrid. Telemetry streams from both the prime and the back-up antennas were delivered to different workstations at the MSOC, but only the prime antenna raised the command carrier. Commanding could be handed over, if needed. [22]

Both probes successfully completed their LOI sequences and were inserted into stable, equatorial lunar orbits with the following aposelene and periselene altitudes:

- P1: 25,260 × 1,760 km
- P2: 31,800 × 2,700 km

Lunar Orbit Phase

Once in lunar orbit, each probe required 5 PRMs to reduce aposelene altitudes and to perform the desired phasing for the science orbits. Evolution of the differential precession, illustrated in Figure 5, provided a wide range of geometrical conditions to perform science measurements. [21,22]

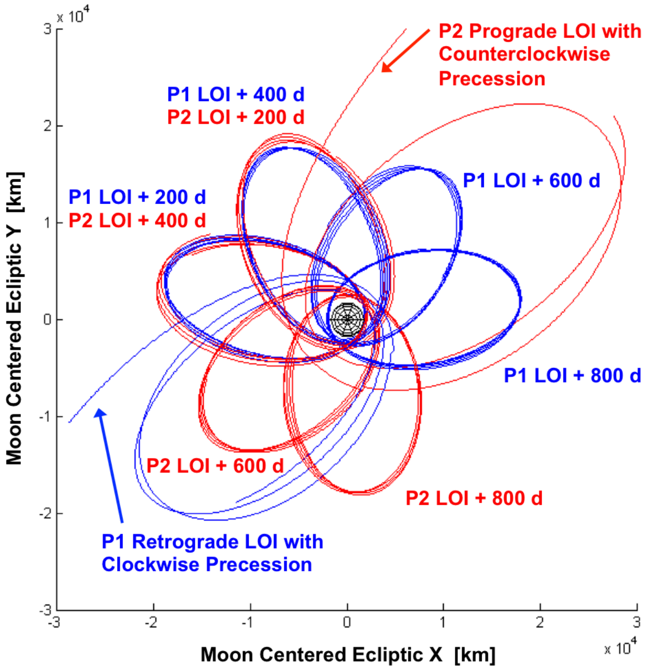


Figure 5 – Definitive lunar orbits of probe P1 (blue) and P2 (red), as seen from the north ecliptic pole. For each probe, five consecutive orbits are shown every 200 days to illustrate the differential precession of their orbits.

Periodic Orbit Maintenance Maneuvers (OMMs) were required mainly for two reasons: to ensure that periselene altitudes remained safe, nominally at least 10 km above terrain, and to avoid long Earth and lunar shadows. As an example, such a maneuver was executed on 2014/01/29. Without this OMM, probe P1 would have encountered a shadow of 512 min total duration (penumbra and umbra combined) on 2014/04/15. Using a ΔV of 32 cm/s at the expense of 13.8 g of fuel, the aposelene was reduced by 52 km, changing the orbit period from 25.08 to 24.98 h. As a result, the total shadow duration was reduced to ~180 min, which was well within the probe's capabilities for survival.

In another case a special maneuver for probe P2 was designed to achieve three different goals at once, using a single tangential thruster: (a) adjust the spin rate of P2 to be closer to that of P1, (b) perform a small attitude precession, and (c) raise the periselene to avoid impact on the lunar surface on 2012/08/03. All goals were targeted with a multi-segment burn sequence on 2012/05/01 and 2012/05/06. The first segment was designed as a calibration burn to execute only 50 of the ~900 pulses required in total. The second segment included 820 pulses to achieve the majority of the goal, and the third segment was planned for fine-tuning at the end. Since this particular thrust maneuver had not been exercised before, the thrust calibration factors were not very well known. The first segment resulted in a 3.5% over-burn that was in turn used to calibrate and retarget the much larger second segment. In the end, all three maneuver goals were met with the first two segments already, so the third segment was not required: a spin rate reduction by 1.91 rpm, an attitude precession by ~1.7 deg towards the ecliptic south pole, and a semi-major axis reduction of ~100 km that increased the periselene altitude to a safe value of ~19 km at the time of the predicted impact. The amount of fuel expended, 82.4 g, was 45% less than if these goals had been targeted as single-purpose maneuvers. [23]

In total, 182 individual thrust maneuvers were executed since begin of the ARTEMIS mission – 76 on P1 and 106 on P2. Great care was taken to ensure that every single burn was reliably executed. Remaining fuel reserves, shown in Table A-1 in the Appendix, will be used to maintain the orbits of the two probes at safe periselene altitudes, and to perform deorbit burns at the end of the mission.

6. GROUND SYSTEMS

New Requirements

In preparation for ARTEMIS support, none of the existing ground systems were fundamentally changed, as all of the capabilities had to be retained to continue support of the THEMIS-Low mission. However, new capabilities were added to meet special ARTEMIS requirements. The most significant enhancements were related to expanding network communications to include the DSN, as mentioned earlier. In addition, navigation software tools were adapted to also handle support of non-Earth orbiting spacecraft.

Communications Networks Expansion

ARTEMIS required DSN 34-m Beam Waveguide (BWG) antenna support as the baseline, but also used the 34-m High Efficiency (HEF) antennas. Beginning in early 2012, JPL also offered the 70-m subnet as a measure to alleviate network resource contention. The much larger figure of merit (G/T) of the 70-m antennas allowed usage of the highest telemetry data rates (524.288 and 1048.576 kbps), which significantly reduced required support times. Throughout the ARTEMIS mission, UCB provided all acquisition data to DSN in Consultative Committee for

Space Data Systems (CCSDS) Orbit Ephemeris Message (OEM) format for both probes. Short-term ephemerides covered 30 days and were uploaded on a weekly basis for tracking support. Long-term ephemerides were uploaded once per month, covering six months for pass scheduling purposes. [6]

Software Tools

Starting with the integrated, operational software tools for THEMIS, additional capabilities needed to be implemented for ARTEMIS. New requirements were related to maneuver targeting, orbit and attitude determination, DSN network communications and range data processing, pass scheduling, sequencing, and 3D visualization. Capabilities to perform pass automation with lights-out operations during off-hours were retained, but had be expanded to also include the significantly more complex ground network telemetry and telecommand data flows with DSN, involving the CCSDS Space Link Extension (SLE) protocol. [3,6,11,12]

7. MISSION OPERATIONS

Constellation Operations

In many ways, ARTEMIS mission operations were a natural sequel to those of the THEMIS prime mission, and had to be performed in parallel with the THEMIS-Low mission extension that involved the remaining three probes, P3, P4, and P5. THEMIS-Low had its own set of requirements for navigation and science operations. However, all five probes were still treated as a single constellation to maintain continuity of operations. Consequently, the layout and functional organization of the MSOC, shown in Figure 6, was not changed.

Figure 6 – THEMIS and ARTEMIS operations consoles at the MSOC, located at UCB/SSL.

ARTEMIS Operations Preparation

Operations procedures, flight scripts, ground software, and interfaces were expanded, as required for ARTEMIS, but without disturbing existing functionality. New capabilities, such as more complex navigation tools, DSN network interfaces, and scheduling software were integrated and tested during the second year of the THEMIS prime mission without disrupting ongoing science operations.

In preparation for ARTEMIS, the multi-mission operations team at UCB needed to acquire extensive knowledge with deep space navigation and communications. Team members grew with the navigation challenges on hand, and benefited from frequent interactions with NASA experts at JPL and GSFC. Three team members were trained on the DSN scheduling process that is largely community based, and often involved extensive negotiations with other mission teams to resolve scheduling conflicts. [24]

A number of mission readiness tests were specifically designed to exercise key mission events prior to initiating the Earth departure, and in preparation for the critical flyby and LOI events. As a result of careful and extensive operations planning, implementation, and testing, the bifurcation from the THEMIS prime mission into the new ARTEMIS and THEMIS-Low missions was essentially seamless, and all mission goals to date were met.

8. SCIENCE OPERATIONS

Science Operations Planning

Much like with mission operations, the ARTEMIS science planning and operations concept also followed the constellation paradigm. Of particular scientific interest were crossings of probes P1 and P2 through the lunar wake region of the solar wind, and passages through low-periselene altitudes (below 300 km). In addition, the magnetospheric Regions of Interest (ROIs) defined for the THEMIS prime mission also applied to ARTEMIS, as the Moon carried the two probes through the Earth's distant magnetospheric tail once every month. Therefore, science data acquisition was often coordinated with THEMIS-Low. The planning cycle started typically 3-4 weeks in advance, using the MDT software mentioned earlier, as the primary planning tool. [3,24]

Science Data Acquisition

The ARTEMIS probes collected science data in four modes, as summarized in Table 2. These modes were essentially identical to those used during the THEMIS prime mission, except that the on-board memory allocation for survey and burst data was optimized to meet ARTEMIS requirements.

Table 2. ARTEMIS Science Data Collection Modes.

Mode	Utilization	Data Rate
Slow Survey (SS)	Low cadency routine data capture	~0.5 kbps
Fast Survey (FS)	High cadency routine data capture	~12 kbps
Particle Burst (PB)	High resolution capture of particle energy distributions and low frequency waveforms	~43 kbps
Wave Burst (WB)	High resolution capture of electric and magnetic field waveforms	~470 kbps

Slow Survey collection was the most basic data acquisition mode. Fast Survey data were recorded when the probes crossed specified regions of interest, such as the lunar wake region or the deep magnetospheric tail of the Earth. Special Fast Survey collections were also scheduled for the Earth and lunar flybys.

Burst data collection to capture high-resolution data for short periods of time occurred when either science trigger criteria based on sensor measurements were met, or during preprogrammed periods of time that coincided with predictable crossings of scientific regions of interest, or with simultaneous data collection periods on the other probes.

Science Instrument Configuration

Science instruments were configured for data acquisition out of on-board sequence tables that were uploaded on a weekly basis and in turn invoked flight software scripts loaded into the Instrument Data Processing Unit (IDPU). Special configurations and calibration table updates were performed via ground commanding.

Telemetry Requirements

When ARTEMIS was proposed, the maximum available telemetry data rate was predicted to be 65.536 kbps. With a downlink time of 3.5 h every other day, the expected data volume was ~380 Mbits per day. Actual results for the last two years are summarized in Table 3.

Pass Scheduling and Data Recovery

Communications passes were scheduled across multiple networks, as mentioned earlier. For DSN scheduling, JPL provided their standardized software tools to interface with the DSN scheduling system. Execution of multi-mission pass schedules at the MSOC was based on highly automated processes. [24]

Table 3. ARTEMIS Science Operations Metrics.

Parameter	2012	2013
P1 Instrument Efficiency	99.5%	97.9%
P1 Data Recovery Efficiency	99.0%	99.7%
P1 Average Recovered Daily Data Volume	417.6 Mbits	451.3 Mbits
P1 Recovered Data Volume above Requirements	10.0%	18.8%
P2 Instrument Efficiency	99.9%	98.8%
P2 Data Recovery Efficiency	98.8%	99.8%
P2 Average Recovered Daily Data Volume	424.5 Mbits	456.5 Mbits
P2 Recovered Data Volume above Requirements	11.7%	20.1%

ARTEMIS achieved excellent metrics for both mission instrument and data recovery efficiencies. Instrument efficiency metrics take into account mandatory instrument downtime during maneuver operations or long shadows, and effective downtimes due to on-board recorder saturation or due to anomalies. As shown in Table 3, expectations for the nominal daily data volume of 380 Mbits were significantly exceeded in both 2012 and 2013. Dynamic link calculations to predict the telemetry link margin and to maximize the data volume were constantly refined, and automated ground operations procedures were improved to obtain these results.

Ground Data Processing and Archiving

Ground processing and archiving of science and engineering data for THEMIS-Low and ARTEMIS was similar to the THEMIS prime mission. Software tools continued to allow data analysis across a single constellation, as well as with other missions.

9. EXPERIENCES AND LESSONS LEARNED

The ambitious and complex ARTEMIS mission extension provided opportunities to explore new navigation regimes. As a result, a number of interesting experiences were made and valuable lessons were learned. Some of these are noted here, while others are described in the referenced literature.

Team Coordination

Coordination and collaboration of the ARTEMIS team across multiple major organizations worked very well. UCB was the lead institution and conducted numerous telephone conferences, group meetings, and reviews of navigation plans.

Mission Readiness Testing

A mission readiness test campaign was planned and executed prior to the ARTEMIS mission start, and again in preparation for the critical LOI sequences. Activities needed to be interleaved with ongoing operations. The process worked very well, and the required procedures were successfully executed.

Navigation Operations

RCS designs should allow three different methods, namely fuel bookkeeping, PVT analysis, and thermal gauging to be used for determining the amount of liquid in a hydrazine propellant tank from the beginning of a mission. [13]

Also, spacecraft buses should be designed to better support propellant conditioning, such as providing control over tank heater turn-on/off functions, as opposed to solely relying on hardware thermostats.

Stationkeeping in Lunar Libration Point Orbits

Mission Constraints—Stationkeeping operations must take into account constraints, such as limitations on maneuver execution due to thruster locations and RCS performance.

Frequent Tracking—Libration point orbits are very sensitive to perturbations. Two-way Doppler and ranging tracks should therefore be scheduled frequently to discover orbit perturbations and spacecraft anomalies as early as possible, and with time to recover.

Propellant Usage—In EM libration point orbits the required ΔV for reliable stationkeeping with realistically modeled navigation errors only amounted to ~5 m/s per year which was an order of magnitude lower than previous studies had indicated. Part of the reason for this surprising result may be related to the fact that the optimization algorithm used for ARTEMIS stationkeeping maneuver planning always placed the maneuvers along a stable eigenmode of the multi-body environment. This technique favored continuation of a stable orbit rather than taking actions to avoid unstable conditions. Further analyses are still ongoing. [16]

Risk Management

Some of the on-board Fault Detection and Correction (FDC) mechanisms and telemetry-based limit monitors were purposely disabled on both probes to reduce risks of missing critical maneuvers due to a false trip.

Critical Event Coverage

For both LOI events the agreement with DSN was to schedule two 34-m antennas – one as primary and the second as a hot back-up – as Level 3 events (one level above routine operations, or Level 4) as opposed to scheduling a single DSN station at Level 2 or even Level 1. This approach was considered a less risky and more cost effective solution, and worked very well. It paid off during the continuous pre-LOI track for probe P1, when the prime antenna (DSS-54) lost its uplink due to a problem with the ground station transmitter. While telemetry monitoring continued via DSS-54, the back-up antenna (DSS-65) raised the uplink carrier and provided command support.

Pass Scheduling

ARTEMIS used network assets from five different networks. Pass scheduling functions were therefore complex, and were handled by the THEMIS/ARTEMIS operations team in collaboration with multiple remote scheduling offices. [24]

Tight constraints on the DSN due to resource contention were resolved in negotiations, particularly with NASA's other lunar missions, namely the Lunar Reconnaissance Orbiter (LRO), the Gravity Recovery and Interior Laboratory (GRAIL), and the Lunar Atmosphere and Dust Environment Explorer (LADEE) that operated in the same sector of space.

Spacecraft Anomalies

The two ARTEMIS probes experienced no radiation related anomalies since leaving Earth and its radiation belts behind. However, both probes saw anomalies in the SST detectors when passing through periselene at low lunar altitudes. The detectors drew more current, tripping the high current limits of the low-voltage power supplies. These problems subsided once the attenuators in front of the SST apertures were routinely closed during periselene passages.

An initial theory postulating the problem was caused by a large amount of stray light from the full moon entering the sensor apertures could not be confirmed by a correlation analysis. Another theory that still needs to be confirmed is that dust particles in the lunar vicinity were hitting the detectors and causing the electrical currents to rise.

Constellation Operations

In general terms, all five probes were always treated as members of a single constellation, although with different network interfaces and adjusted operations procedures. This approach worked very well, as the multi-mission team continued to operate the entire constellation from an integrated operations facility. ARTEMIS navigation and science operations had to be interleaved with those for the ongoing THEMIS mission. As shown in Table 4, the total thrust maneuver count executed to date stands at 631 for all five probes combined.

Table 4. THEMIS & ARTEMIS Maneuver Metrics.

Mission Phase	Maneuver Count
THEMIS Prime Mission	297
ARTEMIS	182
THEMIS-Low	152
Total	631

10. SUMMARY

To date, two of the original five THEMIS probes that became ARTEMIS spent more than four years outside of Earth orbits. Lunar transfer operations took two years from start to finish, and 2.5 additional years were spent to collect science data in lunar orbits. The joint ARTEMIS navigation and operations teams successfully planned and executed the complex navigation tasks without any flaws.

ARTEMIS represents the first ever operation of spacecraft in Earth-Moon libration point orbits, providing valuable experiences and lessons learned for future lunar and other solar system exploration missions that may use libration point orbits for staging points, or as transportation waypoints and safe haven for crews.

As part of NASA's Heliophysics Great Observatory, ARTEMIS delivered to the science community the first systematic, two-point observations of the Earth's distant magnetospheric tail, the solar wind, and the lunar space and planetary environment.

Joint investigations between ARTEMIS, LRO, and LADEE gave science teams unique opportunities to study the lunar atmosphere and the dynamics of the lunar exosphere and dust environment. The two ARTEMIS probes accurately measured the upstream and nearby solar wind relative to the Moon's location, and provided plasma conditions and magnetospheric tail drivers to the other two missions.

REFERENCES

[1] V. Angelopoulos, “The THEMIS Mission,” Space Science Reviews, Vol. 141, No. 1-4, 2008, pp. 5-34.

[2] S. Frey, V. Angelopoulos, M. Bester, J. Bonnell, T. Phan, and D. Rummel, “Orbit Design for the THEMIS Mission,” Space Science Reviews, Vol. 141, No. 1-4, 2008, pp. 61-89.

[3] M. Bester, M. Lewis, B. Roberts, J. McDonald, D. Pease, J. Thorsness, S. Frey, D. Cosgrove, and D. Rummel, “THEMIS Operations,” Space Science Reviews, Vol. 141, No. 1-4, 2008, pp. 91-115.

[4] V. Angelopoulos, “The ARTEMIS Mission,” Space Science Reviews, Vol. 165, No. 1-4, 2011, pp. 3-25.

[5] M. Bester, M. Lewis, B. Roberts, L. Croton, R. Dumlao, M. Eckert, J. McDonald, D. Pease, C. Smith, J. Thorsness, J. Wheelwright, S. Frey, D. Cosgrove, D. Rummel, M. Ludlam, H. Richard, T. Quinn, J. Loran, R. Boyd, C. Quan, and T. Clemons, “Ground Systems and Flight Operations of the THEMIS Constellation Mission,” Proceedings of the 2008 IEEE Aerospace Conference, Ed Bryan (ed.), Big Sky, MT, March 1-8, 2008, Paper 12.0502.

[6] B. Roberts, M. Lewis, J. Thorsness, G. Picard, G. Lemieux, J. Marchese, D. Cosgrove, G. Greer, and M. Bester, “THEMIS Mission Networks Expansion – Adding the Deep Space Network for the ARTEMIS Lunar Mission Phase,” Proceedings of the AIAA 2010 SpaceOps Conference, Huntsville, AL, April 25-30, 2010, Paper AIAA 2010-1934.

[7] M. Sholl, M. Leeds, and J. Holbrook, “THEMIS Reaction Control System – From I&T through Early Mission Operations,” Proceedings of the 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinnati, OH, July 8-11, 2007.

[8] S. B. Broschart, M.-K. J. Chung, S. J. Hatch, J. H. Ma, T. H. Sweetser, S. S. Weinstein-Weiss, and V. Angelopoulos, “Preliminary Trajectory Design for the ARTEMIS Lunar Mission,” Proceedings of the AAS/AIAA Astrodynamics Specialist Conference, Pittsburgh, PA, August 9-13, 2009, Paper AAS 09-382.

[9] D. Folta, M. Woodard, T. Sweetser, S. B. Broschart, and D. Cosgrove, “Design and Implementation of the ARTEMIS Lunar Transfer Trajectory Using Multi-Body Dynamics,” Proceedings of the AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, August 2, 2011, Paper AAS 11-511.

[10] G. J. Whiffen and T. H. Sweetser, “Earth Orbit Raise Design for the ARTEMIS Mission”, Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, Minneapolis, MN, August 13-16, 2012, Paper AIAA 2012-4427.

[11] D. Cosgrove, S. Frey, J. Marchese, B. Owens, S. Gandhi, M. Bester, D. Folta, M. Woodard, D. Woodfork, “Navigating THEMIS to the ARTEMIS Low-Energy Lunar Transfer Trajectory,” Proceedings of the AIAA 2010 SpaceOps Conference, Huntsville, AL, April 25-30, 2010, Paper AIAA 2010-2352.

[12] J. Hashmall, D. Felikson, and J. Sedlak, ”Use of Fuzzycones for Sun-only Attitude Determination: THEMIS Becomes ARTEMIS,” Proceedings of the 21st International Symposium on Space Flight Dynamics, Toulouse, France, September 28 – October 2, 2009.

[13] B. D. Owens, D. Cosgrove, M. Sholl, and M. Bester, “On-Orbit Propellant Estimation, Management, and Conditioning for the THEMIS Spacecraft Constellation,” Proceedings of the AIAA 2010 SpaceOps Conference, Huntsville, AL, April 25-30, 2010, Paper AIAA 2010-2329.

[14] J. E. Marchese, B. D. Owens, D. Cosgrove, S. Frey, and M. Bester, “Calibration of In-Flight Maneuver Performance for the THEMIS and ARTEMIS Mission Spacecraft,” Proceedings of the AIAA 2010 SpaceOps Conference, Huntsville, AL, April 25-30, 2010, Paper AIAA 2010-2120.

[15] D. C. Folta, T. A. Pavlak, K. C. Howell, M. A. Woodard, and D. W. Woodfork, “Stationkeeping of Lissajous Trajectories in the Earth-Moon System with Applications to ARTEMIS,” Spaceflight Mechanics 2010, Vol. 136, Part I, Advances in the Astronautical Sciences, pp. 193-208.

[16] D. Folta, M. Woodard, and D. Cosgrove, “Stationkeeping of the First Earth-Moon Libration Orbiters: The ARTEMIS Mission,” Proceedings of the AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, August 2, 2011, Paper AAS 11-515.

[17] B. D. Owens, J. E. Marchese, D. P. Cosgrove, S. Frey, and M. G. Bester, "Optimizing ARTEMIS Libration Point Orbit Stationkeeping Costs Through Maneuver Performance Calibration," Proceedings of the 22nd AAS/AIAA Space Flight Mechanics Meeting, Charleston, SC, January 29 – February 2, 2012, Paper AAS 12-182.

[18] M. Woodard, D. Cosgrove, P. Morinelli, J. Marchese, B. Owens, and D. Folta, “Orbit Determination of Spacecraft in Earth-Moon L1 and L2 Libration Point Orbits,” Proceedings of the AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, August 2, 2011, Paper AAS 11-514.

[19] J. E. Marchese, D. Cosgrove, M. Woodard, D. Folta, P. Morinelli, B. D. Owens, S. Frey, and M. Bester, "Optimizing Solar Radiation Coefficient as a Solve-for Parameter for the Orbit Determination Process during the Libration-Point Orbit Phase of the ARTEMIS Mission," Proceedings of the 22nd AAS/AIAA Space Flight Mechanics Meeting, Charleston, SC, January 29 - February 2, 2012, Paper AAS 12-183.

[20] B. Owens, D. Cosgrove, J. Marchese, J. Bonnell, D. Pankow, S. Frey, and M. Bester, "Mass Ejection Anomaly in Lissajous Orbit: Response and Implications for the ARTEMIS Mission," Proceedings of the 22nd AAS/AIAA Space Flight Mechanics Meeting, Charleston, SC, January 29 – February 2, 2012, Paper AAS 12-181.

[21] S. B. Broschart, T. H. Sweetser, V. Angelopoulos, D. C. Folta, and M. A. Woodard, "ARTEMIS Lunar Orbit Insertion and Science Orbit Design Through 2013," Proceedings of the AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, August 2, 2011, Paper AAS 11-509.

[22] D. Cosgrove, S. Frey, J. Marchese, B. Owens, and M. Bester, "ARTEMIS Operations from Earth-Moon Libration Orbits to Stable Lunar Orbits," Proceedings of the AIAA 2012 SpaceOps Conference, Stockholm, Sweden, June 11-15, 2012, Paper AIAA 2012-1296179.

[23] J. E. Marchese, D. Cosgrove, S. Frey, and M. Bester, "Planning and Execution of a Specialized Maneuver for the ARTEMIS Mission: Achieving Three Goals with One Sequence," Proceedings of the 23rd AAS/AIAA Space Flight Mechanics Meeting, Kauai, HI, February 10-14, 2013, Paper AAS 13-401.

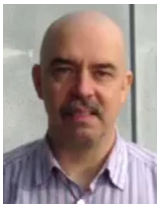
[24] M. Bester, G. Picard, B. Roberts, M. Lewis, and S. Frey, "Multi-Mission Scheduling Operations at UC Berkeley," Proceedings of the 2013 International Workshop on Planning & Scheduling for Space, Mountain View, CA, March 25-26, 2013.

BIOGRAPHY

Manfred Bester *received a doctorate in Physics from the University of Cologne, Germany, in 1984 with thesis work in millimeter-wave spectroscopy and radio astronomy. He joined UCB/SSL in 1986 and currently holds a position as Director of Operations, managing mission and science operations, navigation and ground systems functions. He also serves as Mission Operations Manager for THEMIS, ARTEMIS, NuSTAR, and ICON. He is a member of the AAS, ASP, OSA, and SPIE, a senior member of the AIAA, and a co-organizer of Track 12, Ground and Space Operations, at the IEEE Aerospace Conference.*

Daniel Cosgrove *received a BS in Physics from UC Santa Cruz in 2001. He worked at the Santa Cruz Institute for Particle Physics on subatomic particle detectors for the ATLAS experiment on the Large Hadron Collider at CERN. In 2004 he joined UCB/SSL, providing orbit and attitude determination analysis and support for the THEMIS mission. He became the THEMIS and ARTEMIS Navigation Lead in 2007.*

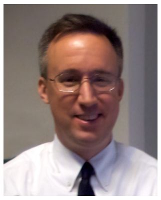
Sabine Frey *received her doctorate in Physics from the University of Leipzig, Germany in 1985. After a few years of employment at the university and in industry she started her space-physics career in 1993 at the Max-Planck-Institute for Extraterrestrial Physics (MPE) in Garching, Germany. In 1998 she joined UCB/SSL to work on the Cluster-II and Lunar Prospector projects, and developed software to analyze aurora and airglow observations. In 2004 she became the Mission Design Lead for THEMIS and worked since then on the THEMIS and ARTEMIS missions.*



Jeffrey Marchese *received his Ph.D. in Computational Physics from the Department of Applied Science at UC Davis in 2007. Since 2008, he worked as a member of the flight dynamics team at UCB/SSL, focusing on navigation, orbit, and attitude determination, mostly concerning the THEMIS and ARTEMIS missions.*

Aaron Burgart *received a MS in Aeronautical and Astronautical Engineering from Purdue University in 2011. In 2012 he joined UCB/SSL as a Flight Dynamics Analyst, providing attitude determination analysis and support for the THEMIS and ARTEMIS missions.*

Mark Lewis *is the Mission Operations Manager for the NASA RHESSI mission, and the Deputy Mission Operations Manager for the THEMIS, ARTEMIS, NuSTAR, and ICON missions at UCB/SSL. He studied Computer Engineering at Boston University and worked in mission operations and as Power & Thermal Engineer since the 1992 launch of the Extreme Ultraviolet Explorer (EUVE). He also was the Mission Operations Manager for the FAST and CHIPS missions.*



Bryce Roberts *received a BS in Mechanical Engineering from UCB in 1996. He got his start in space flight operations in 1996 when he joined the operations staff of UCB's Center for Extreme Ultraviolet Astrophysics (CEA) as* *a mission planner and software developer for NASA's EUVE mission. In 1998 he moved to the Johns Hopkins University as a software developer and mission planner for the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite, and was a key member of the team that developed ground-based software techniques to restore the satellite's attitude control after several reaction wheel failures. In 2005 he returned to UCB/SSL as a programmer and ground systems engineer, working on the THEMIS, ARTEMIS, FAST, RHESSI, NuSTAR, and ICON missions. He is a member of the AIAA.*

Jeremy Thorsness *studied Applied Physics at UC Davis and started working in space flight operations shortly after graduation in 1996. He began at UCB's Center for Extreme Ultraviolet Astrophysics (CEA) as a flight controller for the Extreme Ultraviolet Explorer (EUVE). In 1998 he moved to UCB/SSL to work as a flight controller and ITOS developer for the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) mission. While at SSL he worked on the CHIPS, THEMIS, ARTEMIS, CINEMA, NuSTAR, and ICON missions.*

John McDonald *received a BA in Physics from UC Santa Cruz in 1988. He went on to work at the Smithsonian Astrophysical Observatory (SAO), processing data from the International Ultraviolet Explorer (IUE). He joined UCB in 1991 to work on data processing during the pre-launch and early mission of the Extreme Ultraviolet Explorer (EUVE), and supported spacecraft operations and the guest observer program. After receiving his MS in Astronomy at San Diego State University in 1995, he worked for the SETI Institute on early laboratory studies for the Kepler mission. He was also a telescope operator for the Canada-France-Hawaii Telescope (CFHT) at Mauna Kea, Hawaii, before returning to Berkeley. At UCB/SSL he then worked in mission operations for CHIPS, THEMIS, NuSTAR, and ICON, as well as serving as Instrument Support Engineer for THEMIS and ARTEMIS.*

Deron Pease *received a BS in Physics from UC Santa Cruz in 1993, followed by a MS in Astronomy from San Diego State University in 1996. Later that year he went to work as part of the science instrument calibration team for NASA's Chandra X-ray Observatory, headquartered at the Harvard–Smithsonian Center for Astrophysics (CfA) in Cambridge, MA. In 2007 he joined UCB/SSL as a member of the multi-mission operations team, where he contributed space flight operations and instrument engineering support for the NASA missions THEMIS, ARTEMIS, FAST, NuSTAR, and ICON.*

Gregory Picard *received a BS in Geology from the University of Missouri at Columbia. He worked as mission planner at the Aerospace Corporation, supporting the Infrared Background Signature Survey (IBSS) payload on the STS-39 mission, and at JPL to support the TOPEX mission. He joined UCB in 1997 as a network scheduler for the EUVE mission. After working at Stanford University on Gravity Probe B (GP-B) from 2002, he then returned to UCB/SSL in 2008 as a scheduler for the RHESSI, NuSTAR, THEMIS, ARTEMIS, CINEMA, and ICON missions.*

Martha Eckert *received a BS in Computer Science with minors in Physics and Astronomy from Sonoma State University in 1990. She joined the operations staff of UCB's Center for Extreme Ultraviolet Astrophysics (CEA) in 1991 where she stayed until the EUVE mission ended in 2001. She has been at SSL ever since and worked in flight operations with FAST, RHESSI, THEMIS, ARTEMIS, NuSTAR, CINEMA, and ICON.*

Renee Dumlao *studied Space Systems Operations and started working as a Space Systems Operator and Active Duty member of the United States Air Force in 2000. In 2001 she began working in the Procedures Unit, developing and maintaining all Space Systems documentation for on-flight operations and mission ready personnel for the Defense Satellite Communications System (DSCS), NATO III and NATO IV/SKYNET 4 constellations. During this time, she was also an Instructor and Evaluator to validate training to ensure crew proficiency. She then went on to serve in the California Air National Guard as a Space Systems Operator for the MILSTAR satellite constellation. In 2006, she began at UCB/SSL to work as a flight controller for the Fast Auroral SnapshoT Explorer (FAST) mission. While at SSL she worked on the FAST, RHESSI, THEMIS, ARTEMIS, NuSTAR, CINEMA, and ICON missions.*

ACKNOWLEDGEMENTS

The authors wish to thank Prof. Vassilis Angelopoulos (UCLA, formerly UCB) for the opportunity to participate in this exciting mission. We also thank our colleagues at NASA/JPL (Drs. Theodore Sweetser, Stephen Broschart, and Gregory Whiffen) and at NASA/GSFC (David Folta, Mark Woodard, and Patrick Morinelli) for the excellent team collaboration with mission design and navigation operations support. The DSN team at JPL was instrumental in the ARTEMIS mission success. We also wish to thank our colleagues at UCB, namely Samuel Johnson, Thomas Clemons, James Lewis, Jonathan Loran, Gregory Paschall, Roberto Boyd, Clarina Quan, Bruce Satow, and James McCarthy for their support with IT systems, science data processing, and for maintenance of the operations infrastructure. Two former colleagues, Dr. Brandon Owens (now at NASA Ames Research Center) and Gregory Lemieux (now at Space Systems Loral), were instrumental in the success of the ARTEMIS mission by providing critical navigation and flight operations support.

THEMIS and ARTEMIS mission and science operations are conducted at the University of California, Berkeley under NASA contract NAS5-02099.

APPENDIX

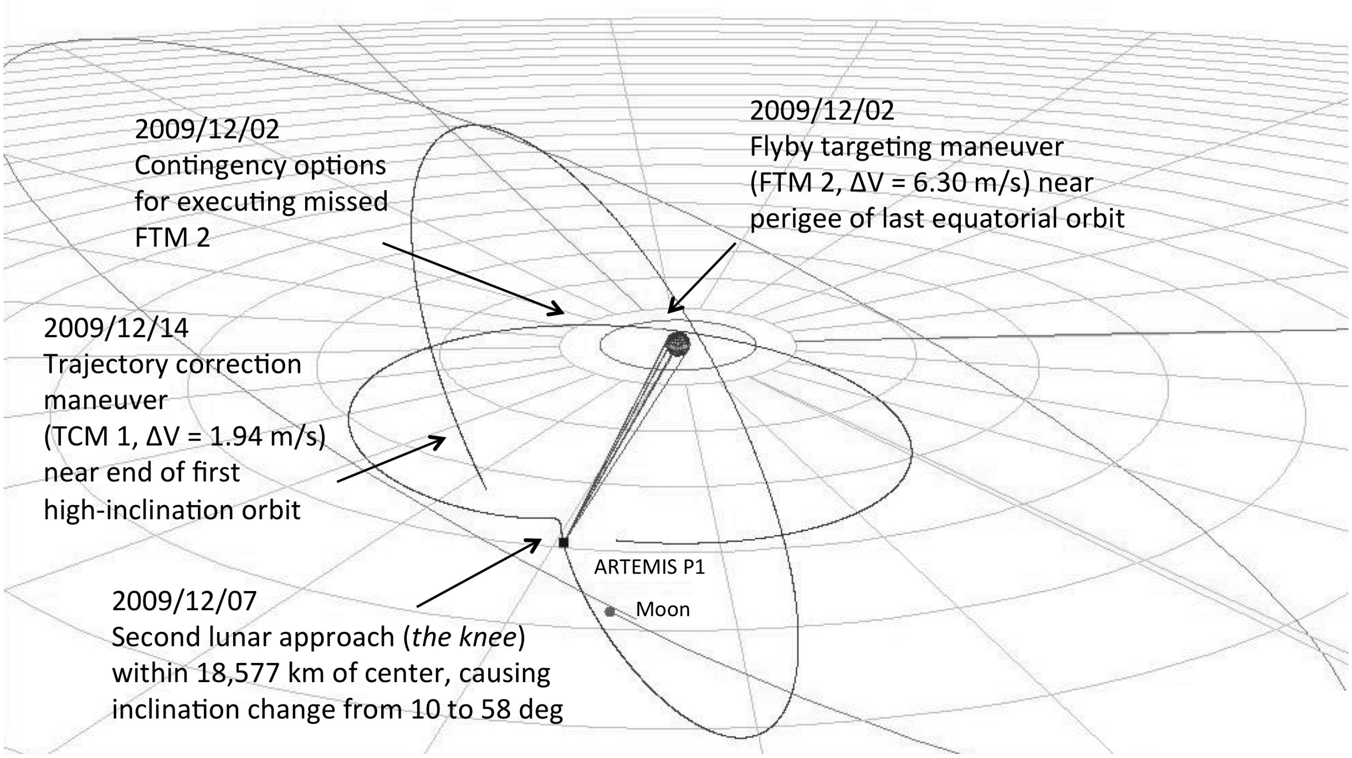


Figure A-1 – Illustration of ARTEMIS P1 (a.k.a. THEMIS B) lunar approach #2 (*the knee*) in Earth Centered Inertial (ECI) J2000 coordinates. The grid represents the equatorial plane.

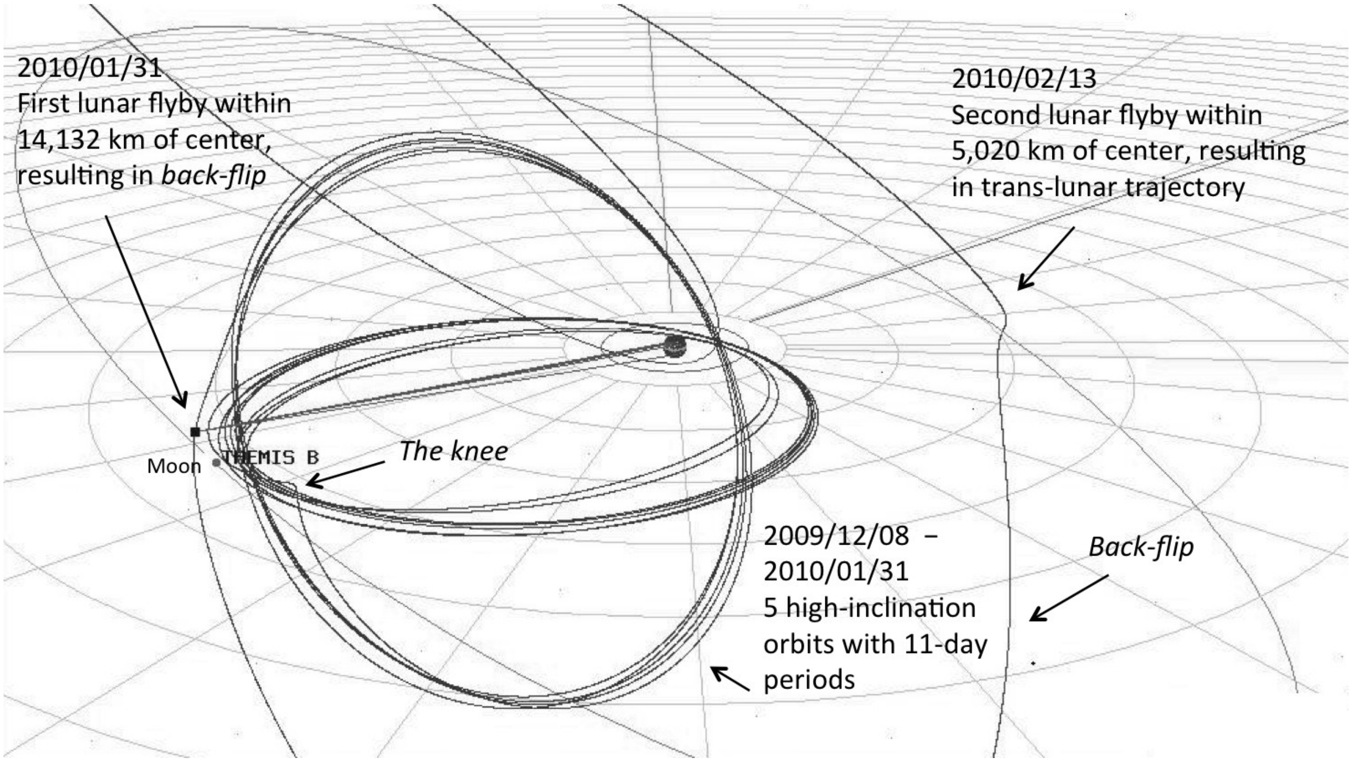


Figure A-2 – ARTEMIS P1 lunar flyby #1, back-flip, and lunar flyby #2 in ECI coordinates.

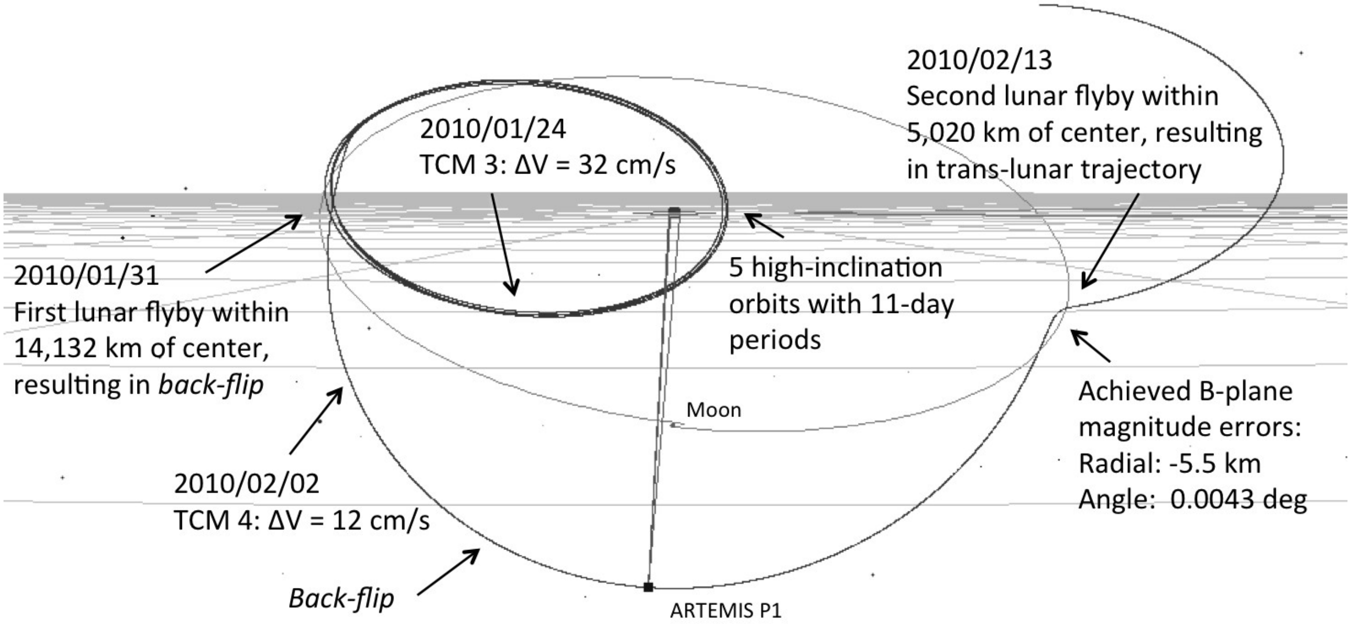


Figure A-3 – ARTEMIS P1 lunar flyby #1, back-flip, and lunar flyby #2 in more detail in ECI coordinates. Two TCMs were executed to accurately target the B-planes of the dual lunar flyby scenario. Tracking coverage during the back-flip was critical to monitor the second flyby. With the spacecraft antenna mounted on the southern side of the spacecraft body, communications coverage with the DSN 34-m stations had to be carefully analyzed.

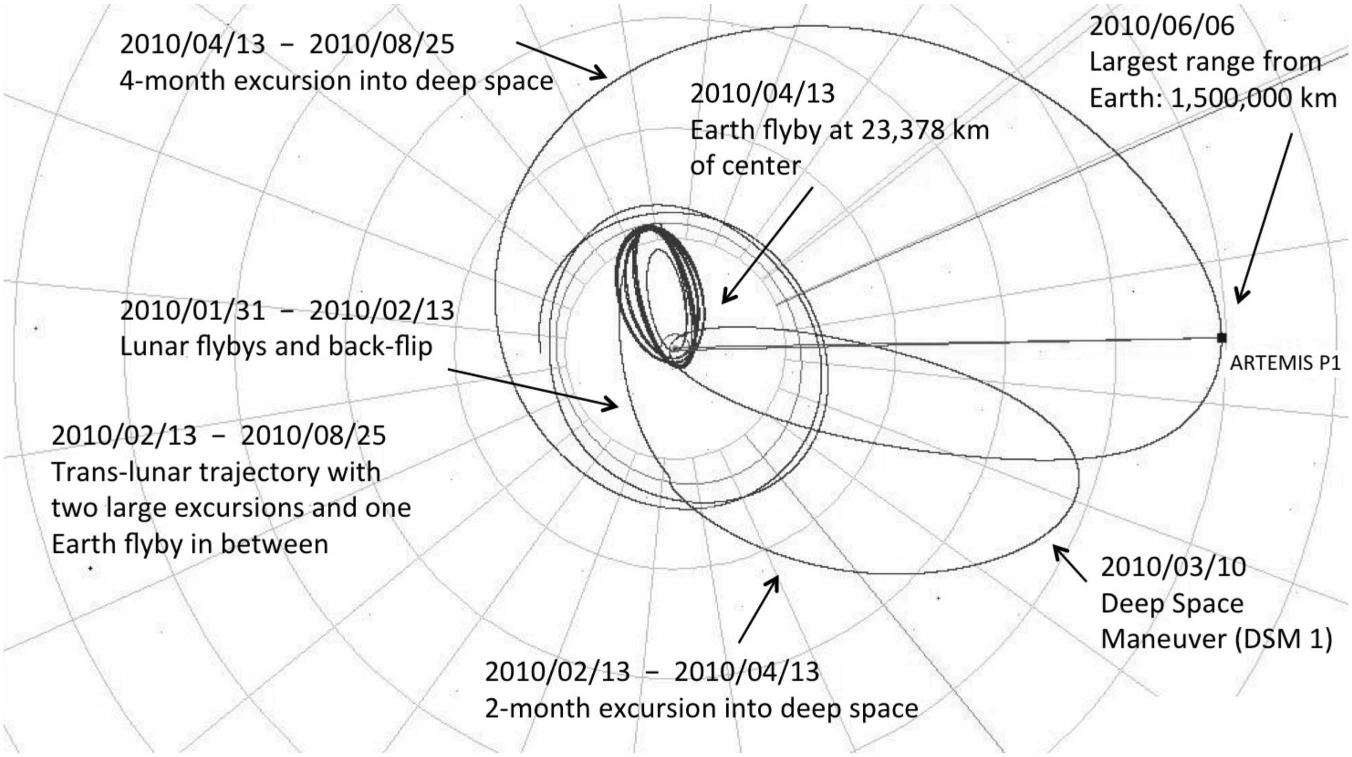


Figure A-4 – ARTEMIS P1 final Earth orbits, trans-lunar trajectory with two deep space excursions, one Earth flyby, and first revolution of EM L_2 libration point orbit in ECI coordinates.

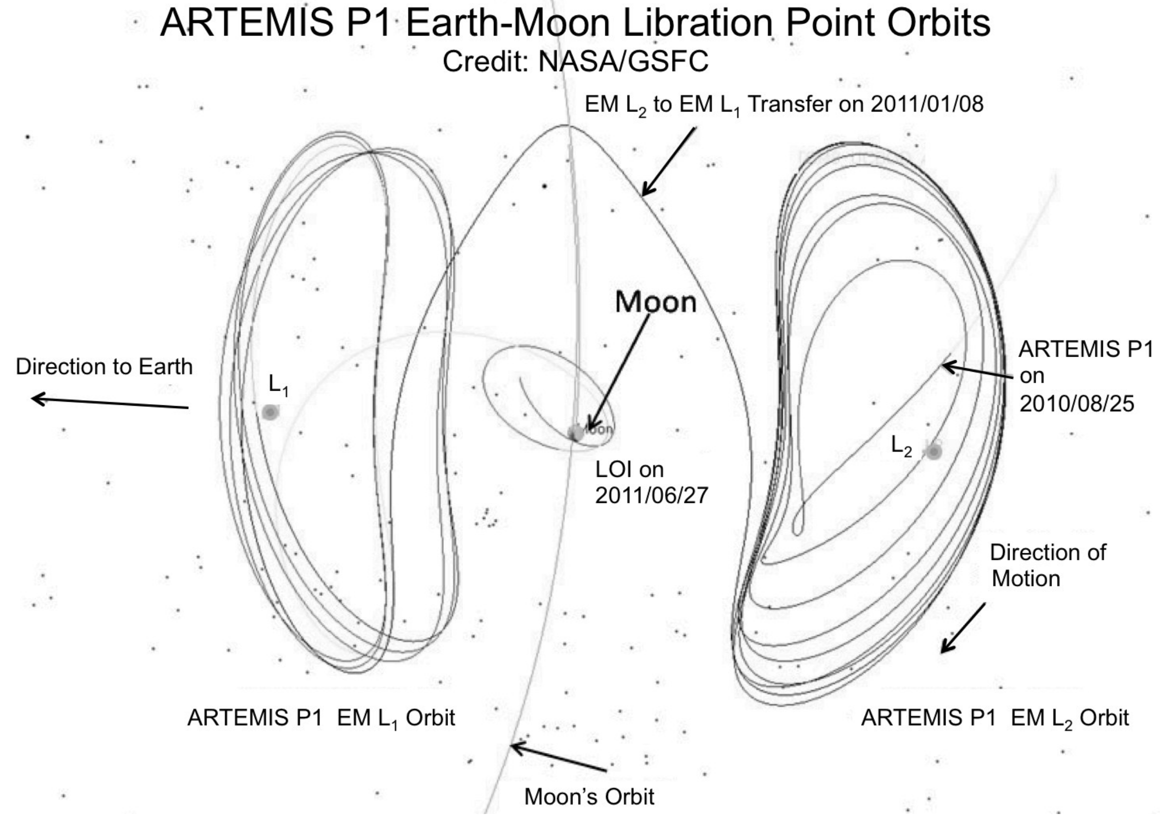


Figure A-5 – ARTEMIS P1 EM L_2 and EM L_1 libration point orbits with EM L_2 to EM L_1 transfer and insertion into a retrograde lunar orbit in rotating coordinates. View of the Earth-Moon plane from above.

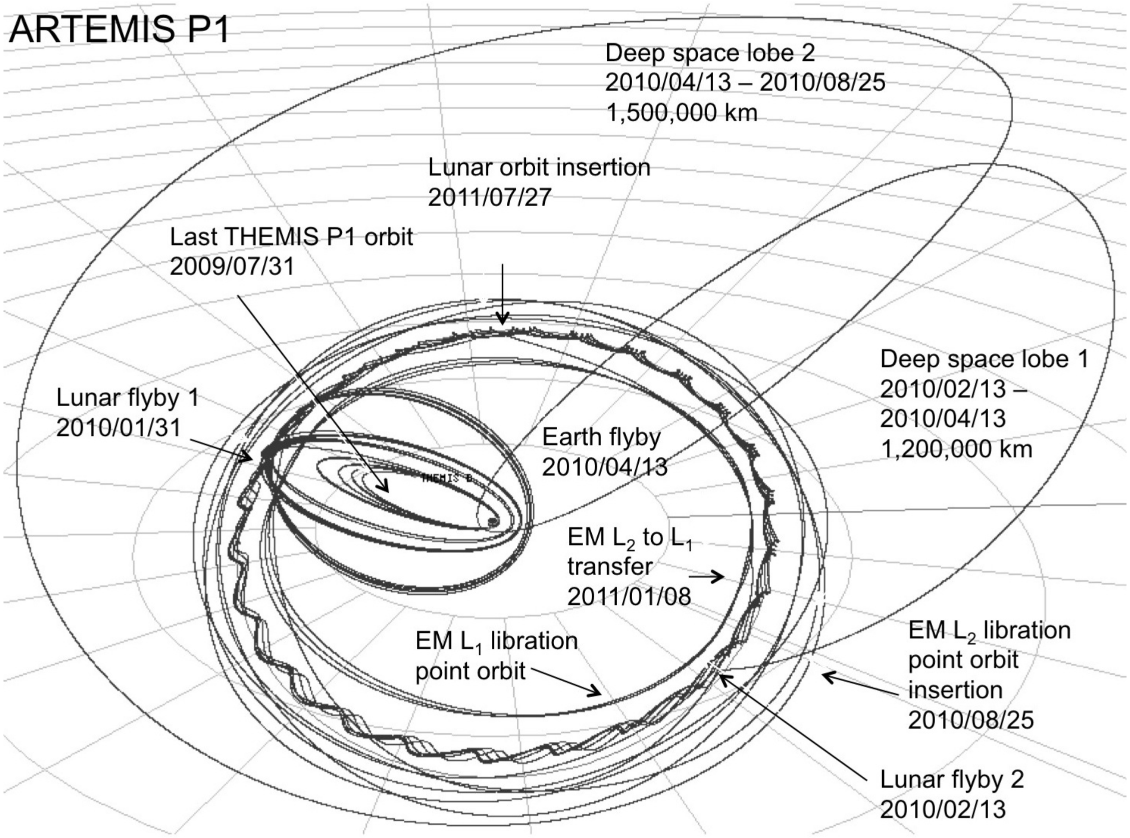
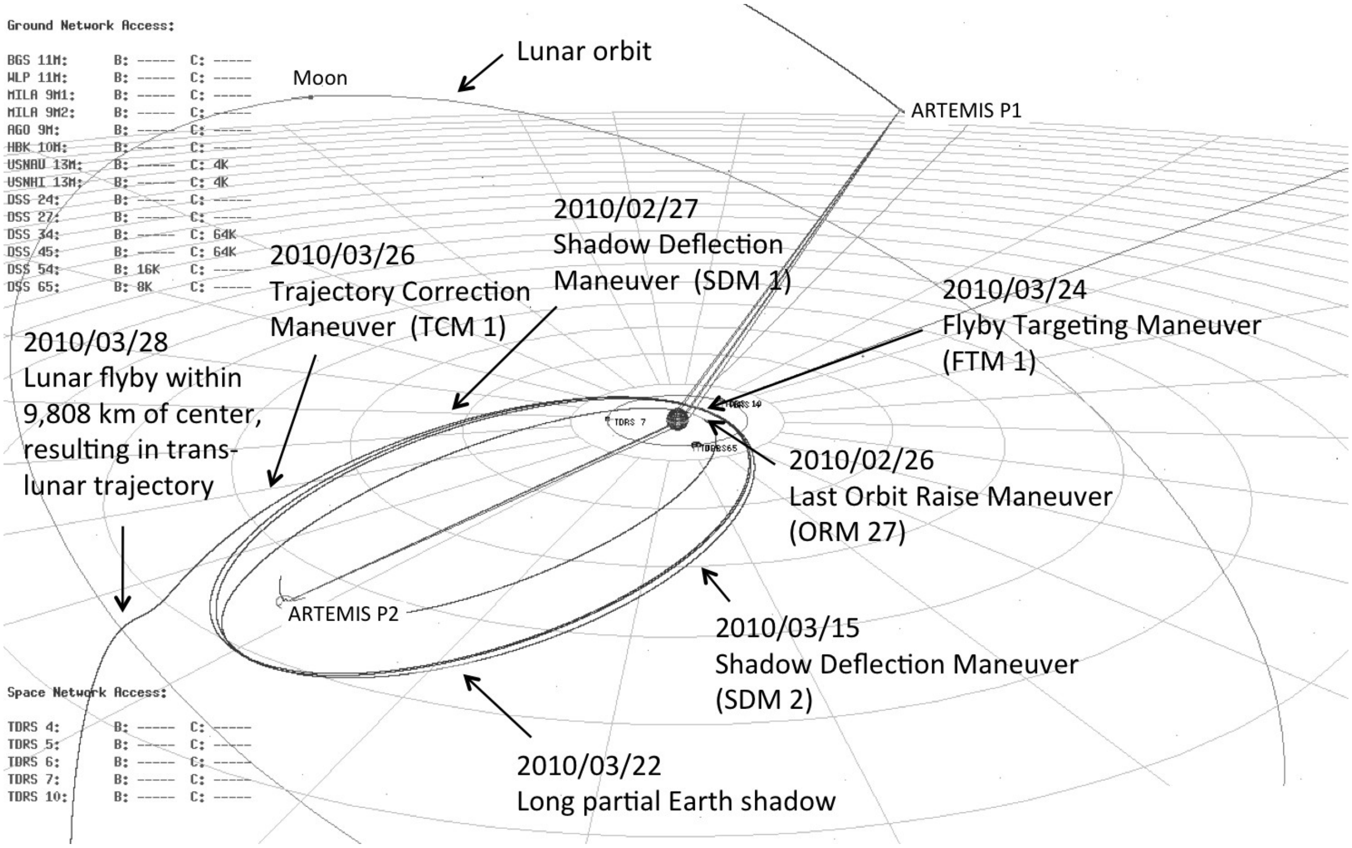


Figure A-6 – ARTEMIS P1 complete trajectory from Earth departure to lunar orbits in ECI coordinates.



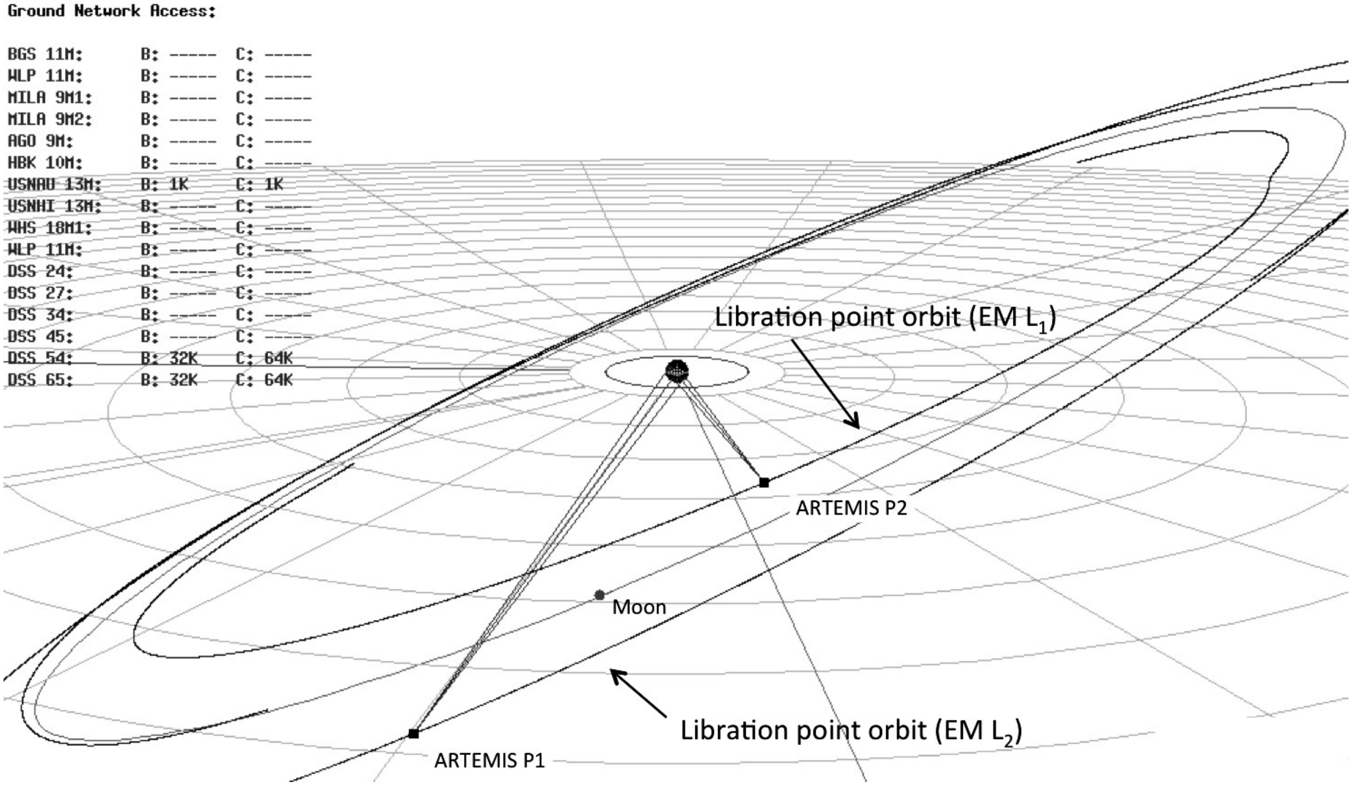
```
Ground Network Access:

BGS 11M:      B: -----  C: -----
WLP 11M:      B: -----  C: -----
MILA 9M1:     B: -----  C: -----
MILA 9M2:     B: -----  C: -----
AGO 9M:       B: -----  C: -----
HBK 10M:      B: -----  C: -----
USNAU 13M:    B: -----  C: 4K
USNHI 13M:    B: -----  C: 4K
DSS 24:       B: -----  C: -----
DSS 27:       B: -----  C: -----
DSS 34:       B: -----  C: 64K
DSS 45:       B: -----  C: 64K
DSS 54:       B: 16K    C: -----
DSS 65:       B: 8K     C: -----
```

```
Space Network Access:

TDRS 4:       B: -----  C: -----
TDRS 5:       B: -----  C: -----
TDRS 6:       B: -----  C: -----
TDRS 7:       B: -----  C: -----
TDRS 10:      B: -----  C: -----
```

Figure A-7 – ARTEMIS P2 (a.k.a. THEMIS C) Earth departure with the last Earth orbit and lunar flyby in ECI coordinates. The tables on the left side indicate availability of communications links with supporting network assets.



```
Ground Network Access:

BGS 11M:      B: -----  C: -----
WLP 11M:      B: -----  C: -----
MILA 9M1:     B: -----  C: -----
MILA 9M2:     B: -----  C: -----
AGO 9M:       B: -----  C: -----
HBK 10M:      B: -----  C: -----
USNAU 13M:    B: 1K     C: 1K
USNHI 13M:    B: -----  C: -----
WHS 18M1:     B: -----  C: -----
WLP 11M:      B: -----  C: -----
DSS 24:       B: -----  C: -----
DSS 27:       B: -----  C: -----
DSS 34:       B: -----  C: -----
DSS 45:       B: -----  C: -----
DSS 54:       B: 32K    C: 64K
DSS 65:       B: 32K    C: 64K
```

Figure A-8 – ARTEMIS P1 and P2 libration point obits in ECI coordinates.

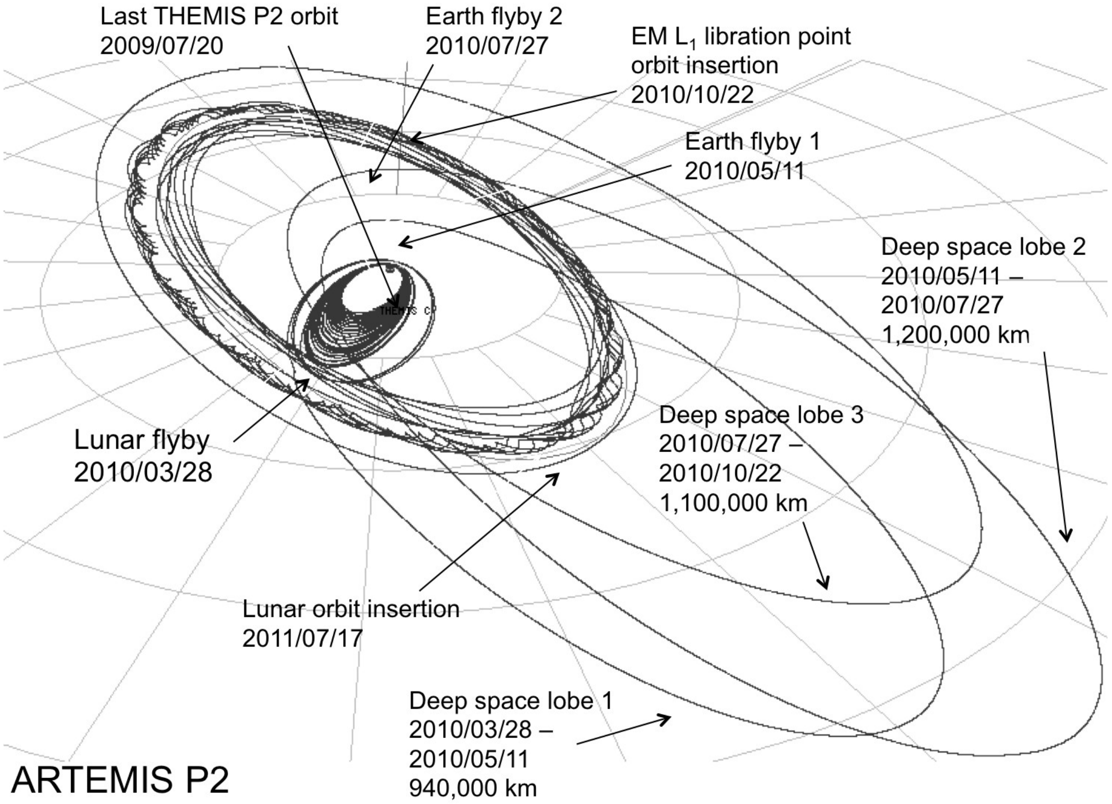


Figure A-9 – ARTEMIS P2 complete trajectory from Earth departure to lunar orbits in ECI coordinates.

Table A-1. Summary of ARTEMIS Maneuvers and Fuel Budgets.

Mission Phase	**Probe P1**				**Probe P2**			
	Maneuvers Executed in Mission Phase	Fuel Available at Begin of Phase [kg]	Fuel Expended by End of Phase [kg]	Total ΔV Achieved in Phase [m/s]	Maneuvers Executed in Mission Phase	Fuel Available at Begin of Phase [kg]	Fuel Expended by End of Phase [kg]	Total ΔV Achieved in Phase [m/s]
Earth Orbit	ORM 1 - 5 FTM 1 - 2 TCM 1 - 4	14.553	4.514	106.436	ORM 1 - 27 FTM 1 TCM 1 SDM 1 - 2	21.140	11.135	255.477
Trans-lunar	DSM 1 TCM 5 - 8	10.039	0.433	10.567	DSM 1 - 3 TCM 2 - 5	10.005	1.372	33.672
Libration Point Orbit	SKM 1 - 36	9.606	0.351	8.688	SKM 1 - 31	8.633	0.188	4.486
Lunar Orbit	LTI 1 LTI TCM 1 - 2 LOI PRM 1 - 5 OMM 1 - 4	9.255	4.427	102.629	LTI 1 - 2 LTI TCM 1 LOI PRM 1 - 5 OMM 1 - 4 ATT 1 SPIN 1 - 2	8.445	5.394	128.215
Current Status	—	4.828	—	—	—	3.051	—	—

Acronyms:

ATT	Attitude Precession Maneuver	ORM	Orbit Raise Maneuver
DSM	Deep Space Maneuver	PRM	Period Reduction Maneuver
FTM	Flyby Targeting Maneuver	SDM	Shadow Deflection Maneuver
LOI	Lunar Orbit Insertion Maneuver	SKM	Stationkeeping Maneuver
LTI	Lunar Transfer Initiation Maneuver	SPIN	Spin Rate Control Maneuver
OMM	Orbit Maintenance Maneuver	TCM	Trajectory Correction Maneuver