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The ARTEMIS Mission

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Abstract The Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission is a spin-off from NASA's Medium-class Explorer (MIDEX) mission THEMIS, a five identical micro-satellite (hereafter termed "probe") constellation in high altitude Earth-orbit since 17 February 2007. By repositioning two of the five THEMIS probes (P1 and P2) in coordinated, lunar equatorial orbits, at distances of ∼55–65 R_E geocentric (∼1.1–12 R_L selenocentric), ARTEMIS will perform the first systematic, two-point observations of the distant magnetotail, the solar wind, and the lunar space and planetary environment. The primary heliophysics science objectives of the mission are to study from such unprecedented vantage points and inter-probe separations how particles are accelerated at reconnection sites and shocks, and how turbulence develops and evolves in Earth's magnetotail and in the solar wind. Additionally, the mission will determine the structure, formation, refilling, and downstream evolution of the lunar wake and explore particle acceleration processes within it. ARTEMIS's orbits and instrumentation will also address key lunar planetary science objectives: the evolution of lunar exospheric and sputtered ions, the origin of electric fields contributing to dust charging and circulation, the structure of the lunar interior as inferred by electromagnetic sounding, and the lunar surface properties as revealed by studies of crustal magnetism. ARTEMIS is synergistic with concurrent NASA missions LRO and LADEE and the anticipated deployment of the International Lunar Network. It is expected to be a key element in the NASA Heliophysics Great Observatory and to play an important role in international plans for lunar exploration.

Keywords THEMIS · ARTEMIS · Magnetosphere · Reconnection · Solar wind · Turbulence · Lunar exosphere

1 Introduction

The "Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun" (ARTEMIS) mission is a two-spacecraft ("probe") complement that

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addresses key science questions related to both heliophysics science as observed from/at the lunar environment and the lunar exosphere, surface, and interior. The mission concept utilizes the two outermost satellites of the NASA MIDEX mission THEMIS (Angelopoulos 2008), a five identical satellite mission launched on 17 February 2007 to study the origin of the magnetospheric substorms, a fundamental space weather process (Sibeck and Angelopoulos 2008).

From distances hundreds of kilometers to 120,000 km (from the Moon and at variable inter-probe separations optimized for heliophysics science, the two ARTEMIS probes will study: (i) particle acceleration, reconnection, and turbulence in the magnetosphere and (ii) in the solar wind; and (iii) the electrodynamics of the lunar environment. With its unique, coordinated, two-point measurements, ARTEMIS will reveal the dynamics, scale size, and evolution of the distant tail, the 3-dimensional structure of solar wind shocks, and the structure, evolution and kinetic properties of the lunar wake. ARTEMIS builds on our understanding of the magnetotail and solar wind environment at lunar distances that was acquired from ISEE3 (Tsurutani and von Rosenvinge 1984), Geotail (Nishida 1994) and Wind (Acuña et al. 1995). ARTEMIS will also advance our understanding the Moon's wake going beyond the observations from Wind high altitude (10 R_L) wake crossings and the low ($\sim$100 km) altitude wake and exospheric observations by Lunar Prospector (LP, Hubbard et al. 1998; Binder 1998), Kaguya (e.g., Saito et al. 2010) and Chang'E. ARTEMIS's comprehensive plasma and fields observations over an extensive range of distances from low to high altitudes fill an observational gap in wake behavior and extend the measurement capability by including DC electric field observations and a two spacecraft complement. ARTEMIS's multi-point observations, orbits, and instrumentation are also ideally suited to advance our knowledge of several key topics raised in the 2003 National Research Council's (NRC) Decadal Survey for Solar System Exploration and several prioritized science concepts listed in the 2007 National Academy of Sciences (NAC) report, "The Scientific Context for Exploration of the Moon". With all its instruments operating flawlessly and from the achievable 100 km perigee altitude, $\sim$10° inclination orbit, ARTEMIS could contribute greatly to our understanding of the formation and evolution of the exosphere, dust levitation by electric fields, the crustal fields and regolith properties and the interior of the Moon. By optimizing periselene to obtain low-altitude passes below 100 km and inclinations as high as 20° to reach the outskirts of the South Pole—Aitken basin, the ARTEMIS team can further optimize the science return from the mission for planetary science in its prime or extended phase.

This paper describes the ARTEMIS mission concept. Following an overview of the mission history, instrument and spacecraft capabilities, and mission phases (Sect. 1), Sect. 2 presents the scientific objectives in relation to the mission design. Section 3 discusses the aspects of mission design that enabled optimal science within the capabilities of spacecraft already in orbit. Section 4 describes the unique features of the ARTEMIS operations that were critical in achieving the heliophysics and planetary aspects of the mission. This section also provides an overview of the data processing and data dissemination system as it has evolved through the successful THEMIS mission practices and is now applied on ARTEMIS. Detailed aspects of the scientific objectives, mission design, navigation, operations, and first results will be presented in future publications.

2 Overview

ARTEMIS arose well into the THEMIS mission's Phase-C development cycle, when it was recognized that Earth shadows exceeding the spacecraft bus thermal design limits would threaten THEMIS probes TH-B (P1) and TH-C (P2) during their third tail season. This was destined to happen on March 2010, about six months after the end of the prime mission (Fig. 1(a)). Additionally, at that time the angles between the lines of apsides for P1 and P2 would be 54° and 27° away from those of P3, P4, and P5, rendering the classic five-probe conjunctions of the prime THEMIS mission design non-optimal. Preliminary studies by NASA/JPL in 2005 indicated that by placing P1 and P2 into lunar orbits (Fig. 1(b)) using a low-thrust lunar capture mission design, the risk of freezing would be avoided as the shadow durations would become small and manageable. The potential of P1 and P2 for scientific discovery could be further maximized for heliophysics science by careful optimization of the mission design to result in variable inter-probe separation vectors relative to the Sun-Moon and Sun-Earth line. This optimization was the genesis of the ARTEMIS concept. An ARTEMIS science team was formed at that point to define the scientific goals of the mission and worked on science optimization. The mission was approved by the NASA Heliophysics Senior Review panel in May 2008 (http://wind.nasa.gov/docs/Senior_Review_2008_Report_Final.pdf), and ARTEMIS operations commenced on July 20th, 2009—coinciding with the 40th anniversary of NASA's first lunar landing.

With the prime THEMIS mission successfully completed by September 2009 and with fuel margins on P1 and P2 remaining robust, the ARTEMIS implementation is proceeding as planned. Three lunar flybys in January-March of 2010 resulting in translunar injections (TLI) will place the probes in orbits near the Earth-Sun Lagrange points. These flybys are also expected to provide a first glimpse into the type of ARTEMIS lunar wake data to be expected from the nominal mission. Following a series of Earth flybys in 2010, the two probes are expected to reach Lissajous orbits (the Lagrange points of the Earth-Moon system) in October 2010 and enter into lunar orbits in April 2011. Figure 2 shows the geometry of those orbits in a coordinate system centered at the Moon, with X-axis opposite Earth, Z axis perpendicular to the Earth-Moon orbit plane, positive North, and Y axis completing the right-hand coordinate system. Very little fuel is needed to move a probe from the Lunar Lagrange point 1 (LL1) on the Earth side, to the LL2, opposite to Earth. Very little fuel is required to maintain the spacecraft from one Lagrange point to the other, resulting in semi-periodic Lissajous orbits in this coordinate system.

The ARTEMIS team has been given the go-ahead to implement a 2 year mission. The probes' radiation safety margin, robust instrumentation, and stable orbits, however, make the mission capable of providing high quality measurements of the lunar environment during the next solar cycle. Table 1 outlines the mission phases, durations, and typical orbit separations in each phase and links them to the science objectives discussed above and in Sect. 2. The mission phases are as follows: The two probes, P1 and P2, arrive at the Lissajous orbits, on opposite sides of the Moon, on September 1, 2010 (P1, near-side) and October 19, 2010 (P2, far-side), respectively. The insertion of P2 is gradual, such that useful tail and solar wind two-probe conjunctions can commence as early as September 21, 2010. The probes stay in this configuration until January 8, 2011. In the Lissajous orbits, although the probes hover $\sim$60,000 km away from the Moon along the Earth-Moon line (on their respective sides of the Moon), they are librating along their orbit-tracks about Earth, ±60,000 km ahead of or behind the Moon. This strategy results in a variety of P1-P2 conjunctions with inter-probe separations of 60,000–120,000 km ($dR \sim 10$–$20\ R_E$, or 35–70 R_L) that are either along the Sun-Earth line or across it; those conjunctions can be either in the solar wind, or in the magnetotail and magnetosheath. This strategy also results in six long-range lunar wake crossings by either P1 or P2 from around 20 and 30 R_L. Figure 3(a) shows snapshots of two possible relative positions of P1 and P2 in the magnetosphere and the solar wind. Due

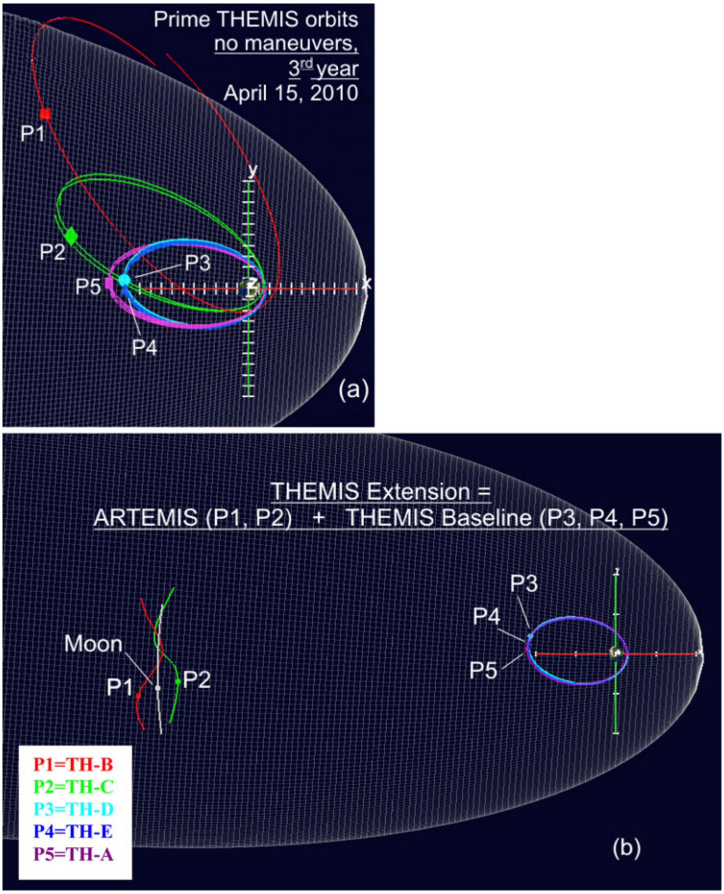


Fig. 1 (**a**) THEMIS orbits in X-Y Geocentric Solar Magnetospheric (GSM) coordinates during the 3$^{\text{rd}}$ year of the operations (2010) in the absence of orbitraising maneuvers for P1, P2. Differential precession of the line of apsides prevents conjunctions between probes along the Earth's magnetotail. In addition, long Earth shadows in March 2010 (not shown) would have presented a problem to mission safety. *Bottom*: The ARTEMIS mission raises the apogees of P1 and P2 such that they are captured into lunar orbits, resulting in new science from the lunar environment

to the sensitivity of the orbit profile to initial (capture) conditions and to orbit maintenance maneuvers, the exact times of those conjunctions may vary but their overall nature will remain qualitatively the same. This mission phase, which is denoted as Lunar Lagrange points 1 and 2 phase, or "LL1,2", lasts approximately 3 months.

In early January 2011, probe P1 will be commanded to leave its Lissajous orbit on the far side and enter orbit into the Lunar Lagrange point 1, or LL1, on the near-side of the Moon. At different phases of their Lissajous orbits, the two probes (P1 and P2) reside at inter-probe separation vectors of size 5–20 R_E, with longer ranges preferentially across the Earth-Moon line and shorter ranges along the Sun-Earth line. Figure 3(b) shows two snapshots of such possible configurations. Another six lunar crossings are also acquired in this phase, from distances around 10–30 R_L (most are around 15–20 R_L); those wake crossings occur typically far upstream of Earth's bow shock and are pristine, i.e., least affected by Earth

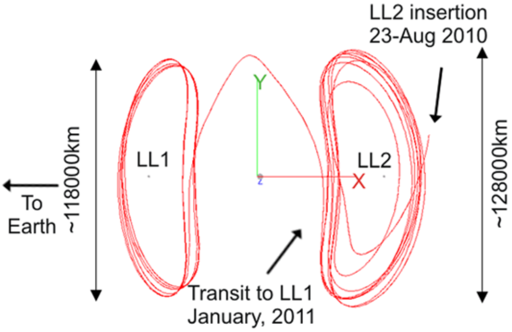


Fig. 2 ARTEMIS Lissajous orbits in the initial phase of the mission, shown here for the case of P1 (adapted from Broschart et al. 2009; also see Sweetser et al. 2010)

foreshock effects. This phase lasts another 3 months, until early April, 2011. It is denoted Lunar Lagrange point 1 phase, or "LL1" phase.

In early April 2011 P1 will be commanded to insert into lunar orbit by performing a series of periselene burn maneuvers; P2 will follow suit in late April. By May 2011 both P1 and P2 will be in stable equatorial, high-eccentricity orbits, of ~100 km × 19,000 km altitude. These are stable, 26 h period orbits with inter-probe separations 500 km–$5R_E$. One probe will be in a retrograde and the other in a pro-grade orbit, such that the precession rates of their line of apsides will walk relative to each other by 15–20 degrees per month; in ~2 years the lines of apsides will cover a full circle, resulting in a wide range of inter-probe vectors relative to the Sun-Earth line and lunar wake crossings from a wide range of altitudes. A subset of orbits resulting in simultaneous, two-probe crossings of the lunar wake is also possible during certain mission phases, when one of the two probes is at apoapsis along the Sun-Moon line behind the Moon (Fig. 3(c)).

The ARTEMIS spacecraft (probes) are identical. A probe in deployed configuration and the instrument field of views are shown pictorially in Fig. 4. The probes, which are spin-stabilized platforms (Harvey et al. 2008) with 3 s spin period, carry body-mounted particle instruments and tethered fields instruments. The spin axis is nominally maintained at an angle < 10 deg to the ecliptic South (unlike probes P3, 4, and 5, which have spin axes due close to ecliptic North). The probes are equipped with monopropellant hydrazine propulsion systems, capable of providing ~1.5 N of thrust at $I_{SP} \sim 210$ s near the end of mission. Maneuvers are typically side-thrusts. Axial thrusts provide, when necessary to combine with side-thrusts, a vector thrust off of the spin plane, when necessary to match precisely the specified ΔV vector. Attitude sensors include a Sun sensor, two backup rate gyros, and the science magnetometer (useful for attitude knowledge only near perigee). For ARTEMIS, away from Earth's strong field, the primary attitude sensor is thus the Sun sensor, used to derive full spin attitude information by modeling Sun motion as a function of time over a period of days to weeks. Attitude predicts from thrust and vehicle performance modeling are typically characterized well enough that the Sun sensor is used to check and re-set the absolute attitude whenever possible in-between thrust operations.

The particle instruments ESA and SST (fields of view shown in Fig. 4) measure thermal and super-thermal ions and electrons. Sun pulse information is used to sector data into 3D distribution functions over the period of one spin. The fields instruments, FGM, SCM, and EFI, measure with state-of-the-art cadence, offset stability and sensitivity the DC and AC magnetic and electric fields. Table 2 shows the main instruments and the reference in which more information about instrument characteristics can be obtained. Radiation dose margin of 2, latch-up protection circuitry and memory scrubbing have been implemented on the instruments and selectively on the spacecraft (Harvey et al. 2008). All instruments and

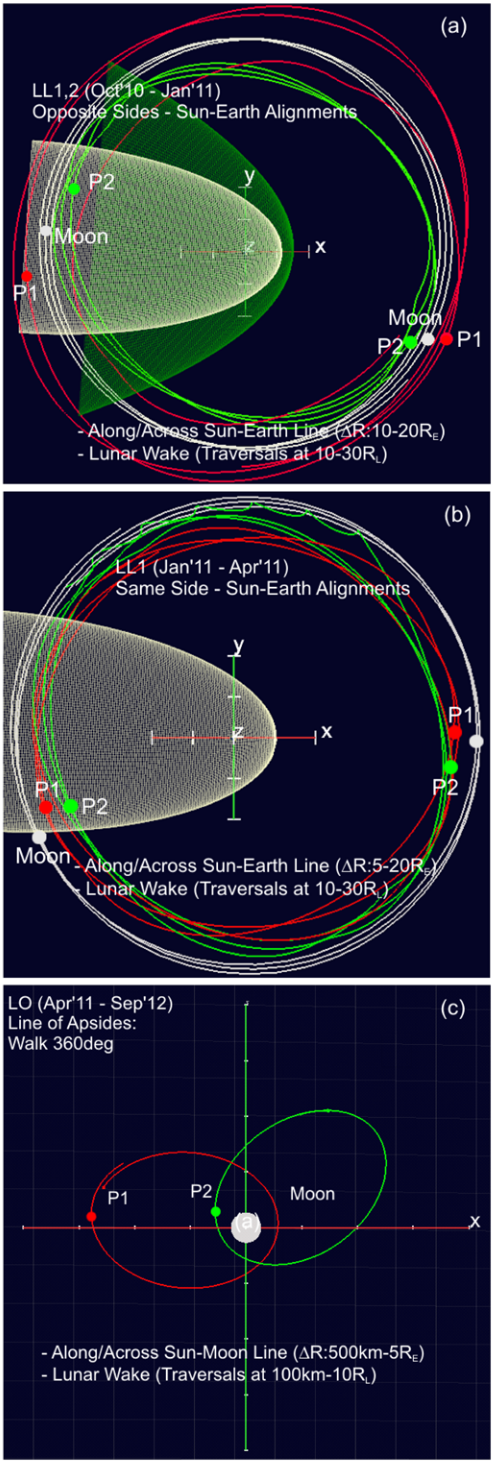


Fig. 3 (**a**) ARTEMIS orbits in the first 3 months of science operations: P1 and P2 are on Lunar Lagrange points 1 and 2, i.e., on opposite sides of the Moon, shown here in the GSM coordinate system (same as Fig. 1). Shown are two representative inter-probe separation conditions in the magnetosphere (*white mesh*) and in the solar wind (i.e., outside the shock region represented by the green mesh). (**b**) Same as in (**a**) but for the next 3 months of science operations.
(**c**) Representative ARTEMIS probe locations after lunar orbit insertion, shown in Selenocentric Solar Ecliptic coordinates, with *horizontal axis* towards the Sun (positive to the right) and *vertical axis* along the cross product of the ecliptic-normal and the Moon-Sun line (positive upwards)

Table 1 ARTEMIS orbits and mission phases relative to heliophysics and planetary objectives

Phase	Abbr	Interval	ARTEMIS: probes P1, P2	Heliophysics Objective	Planetary Objective
Translunar Injection	TLI	Oct. '09–Oct. '10	Translunar orbits to capture into LL1, LL2	Lunar flybys: Build tools, experience	Lunar flybys: Build tools, experience
P1 at LL2, P2 at LL1 ($D_L = 30$–$60\ R_L$)	LL1,2 Phase	Oct. '10–Jan. '11	$dR_{P1\text{-}P2} = 20\ R_E$ at Moon $dR_{P1\text{-}P2}$ along/across wake & Sun-Earth $dX^{GSE}_{P1\text{-}P2} \sim dY^{GSE}_{P1\text{-}P2}$ ~ 500 km–20 R_E	*In the Magnetotail* Rx, SW-magnetosphere interaction, tail turbulence *In the Solar Wind (SW)* Foreshock, shock acceleration, Rx, SW turbulence *In the Wake (SW or Tail)* Kinetics and dynamics of lunar wake in SW, sheath, tail	At solar wind (SW) wake or downstream: Pickup ions?
P1, P2 both at LL1 (each at $D_L = 30$–$60\ R_L$)	LL1 Phase	Jan. '11–Apr. '11	$dR_{P1\text{-}P2} = 5$–$20\ R_E$ at Moon $dR_{P1\text{-}P2}$ along/across wake & Sun-Earth $dX^{GSE}_{P1\text{-}P2} \sim dY^{GSE}_{P1\text{-}P2}$ ~ 500 km–20 R_E		At solar wind (SW) wake or downstream: Pickup ions?
In Lunar Orbit ($D_L = 1.1$– $12\ R_L$)	LO Phase	Apr. '11–Sep. '12	$dR_{P1\text{-}P2} = 500$ km–20 R_L at Moon $dR_{P1\text{-}P2}$ along/across wake & Sun-Earth Periselene = ∼100 km [trade TBD] Aposelene = ∼19000 km Inclination = ∼10 deg [trade TBD]		*In the Solar Wind (SW)* Wake/downstream: pickup ions Periselene wake: crust, core Periselene dayside: Dust *Magnetotail* Crust, mini-magnetospheres, core Periselene dayside only: Magnetotellurics, dust

Key: T = Tail; Rx = Reconnection; R_L = Lunar radii; R_E = Earth radii; D_L = Distance from Moon; $dR_{P1\text{-}P2}$ = Inter-probe separation vector; $dX^{GSE}_{P1\text{-}P2} = dR_{P1\text{-}P2}$ projection along X in Geocentric Solar Ecliptic coordinates—similar for $dY^{GSE}_{P1\text{-}P2}$, $dZ^{GSE}_{P1\text{-}P2}$

spacecraft are operating flawlessly, with no signs of performance degradation. Since the thermal and radiation design have been optimized for the worst-case environment, which is the one experienced by the inner THEMIS probes (on one-day period orbits, at 12 R_E apogee), the outer probes have seen significantly less cumulative thermal cycling and radiation (by approximately a factor of 2–4) relative to their design limit. Additionally, the outer probes were, by selection, the ones with more robust communication and power systems behavior. By virtue of the probes' stable lunar orbits, the relatively benign radiation environment at the Moon and the ARTEMIS operations (Sect. 3), it is expected that the ARTEMIS lifetime will be a good fraction of the upcoming solar cycle.

3 Science Objectives

This section is an outline of the ARTEMIS mission's key scientific objectives as they relate to mission requirements. Although ARTEMIS was designed to address heliophysics science objectives, moderate mission redesign enables it to optimize its observation strategy to address planetary objectives, as well.

3.1 Heliophysics Science Objectives

Figure 5 shows the three regimes to be visited by the ARTEMIS probes once the science operations phase has commenced, i.e., once both ARTEMIS probes are at the lunar environ-

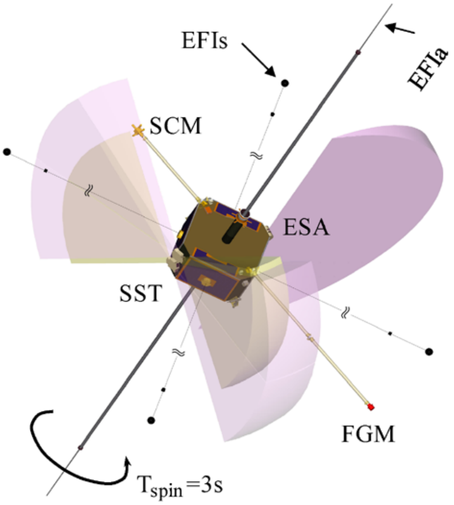


Fig. 4 Pictorial view of ARTEMIS probes and instrumentation. The spin-stabilized probes have a spin axis due ecliptic south, and a nominal spin period of 3 s. The fluxgate magnetometer (FGM) and Search Coil magnetometer (SCM) are on carbon epoxy, rigid, deployable booms of ~2 m and ~1 m length, respectively. The axial electric field (EFIa) whip sensors are at the tips of 3.5 m stacker booms and the spin plane electric field (EFIs) spherical sensors are on 20 and 25 m wire booms (truncated, not to scale in this picture). Ion and electron fields of view for the Solid State Telescope (SST) instrument are shown in different colors. The electrostatic analyzer (ESA) detector points radially outward and measures ions and electrons with identical fields of view

ment. ARTEMIS will address questions related to acceleration, reconnection, and turbulence in both regions visited by the Moon once per 28 days in its orbit about Earth: (i) the magnetosphere and (ii) the solar wind. Additionally, ARTEMIS will traverse the lunar wake routinely with one or both probes and will address questions related to (iii) the wake formation, refilling, structure, and evolution, as well as kinetic aspects of particle acceleration a the wake.

In the magnetosphere, brief passes by previous spacecraft, such as ISEE-3, Geotail, Galileo, and Wind, have demonstrated that the distant magnetotail at 55–65 R_E hosts a variety of fundamental plasma physics phenomena: quasi-steady reconnection resulting in heated plasma jets, beams of energized particles, twisted and/or unusually cold and dense plasma sheets, and turbulence. The distant reconnection line is thought to reside at 55–65 R_E from Earth, at times, making the lunar orbit particularly interesting for studies of global magnetotail circulation. The fundamental processes occurring there are common to other planetary and astrophysical systems. Additionally, the magnetotail at lunar distances is an ideal place to study the integrated output from the near-Earth processing of stored solar wind energy in the form of heated/accelerated flows and plasmoids. ARTEMIS will study these phenomena for the first time both comprehensively and systematically from the unique perspective afforded by its two identical probes. In the magnetosphere, ARTEMIS will address:

- How are particles accelerated up to hundreds of keV? Using simultaneous measurements in the lobe or mantle and in the plasma sheet, ARTEMIS will determine the mechanism of particle heating in the distant tail. The first-ever simultaneous measurements of energy inflow and particle heating will distinguish between competing particle acceleration

Table 2 ARTEMIS instruments and their capability. Survey data collection ensures plasma moments and spin fits of DC electric and magnetic fields, and nominal frequency spectra are transmitted throughout all orbits, whereas particle burst and embedded wave burst spectra ensure the highest cadence and spectral resolution fields and particles data during select intervals. Like on THEMIS, ARTEMIS bursts are selected using on-board triggers aimed at instances of high activity and include pre-burst buffers, or time-based triggers (e.g. periselenes)

Instrument	Specs	Reference
FGM: Fluxgate Magnetometer	DC magnetic field Sampling rate & resolution: DC-128 Samples/s & 3 pT Offset stability <0.2 nT/12 hr	Auster et al. (2008)
SCM: SearchCoil Magnetometer	AC Magnetic field Frequency: 1 Hz–4 kHz	Roux et al. (2008) Le Contel et al. (2008)
EFI: Electric Field Instrument	3D Electric field Frequency: DC—8 kHz	Bonnell et al. (2008) Cully et al. (2008)
ESA: Electrostatic Analyzer	Ions: 5 eV—25 keV; electrons: 5 eV–30 keV nominal g-factor/anode: ions: 0.875×10^{-3} cm^2 str electrons: 0.313×10^{-3} cm^2 str Nominal anode size: 11.25×22.5 deg minimum (solar wind ions): 5.625×5.625 deg	McFadden et al. (2008a) McFadden et al. (2008b)
SST: Solid State Telescope	Total ions: 25 keV–6 MeV Electrons: 25 keV–1 MeV	Angelopoulos (2008) for mounting and fields of view

mechanisms that have been proposed based on simulations and will determine the maximum energy obtainable under a variety of external conditions.

- What are the nature and effects of reconnection? In the absence of multipoint measurements, even the most basic characteristics of fast flows and plasmoid evolution in the tail remain poorly understood. Understanding these phenomena is important for determining how the distant tail reconnection process affects global flux and energy circulation, as well as the amount and extent of particle energization in the near-Earth environment. Radial separations of 1–10 R_E parallel to the Sun-Earth line will enable the two ARTEMIS probes and allied near-Earth spacecraft to track the evolution of high speed flows and plasmoids. Azimuthal probe separations will enable ARTEMIS to determine the cross-tail extent, orientation, shape, and topology of plasmoids. ARTEMIS will thus determine the characteristics and effects of reconnection in the distant magnetotail, from structural, magneto-hydrodynamic scales down to ion gyroradius and ion inertial length scales.
- What are the drivers and effects of turbulence? Turbulent dissipation is an effective mechanism for heating fluids and transferring mass, momentum, and energy. Characterizing the nature of these fluctuations and determining their origin and dissipation are therefore important for global circulation. Unlike the solar wind, for which time-series of near-constant velocity data can be interpreted as spatial fluctuations, tail flows are unsteady and the above simplification, enabling single spacecraft measurements of the turbulent flows, does not apply. To determine the drivers and effects of turbulence, the spatial and temporal variations of plasma and magnetic field measurements over a wide range of solar wind conditions and scale lengths must be measured. ARTEMIS's two-point measure-

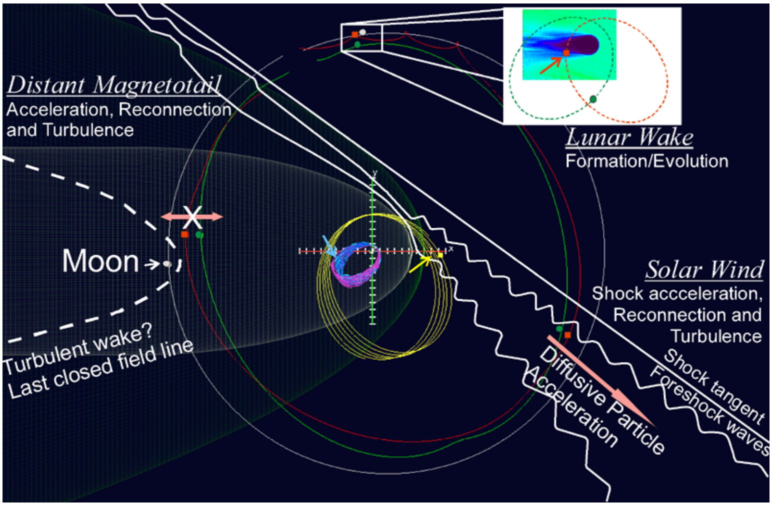


Fig. 5 ARTEMIS depicted by science region. Every 28 days probes P1 and P2 will traverse the magnetosphere, the solar wind and (multiple times) the lunar wake, addressing key questions in Heliophysics

ments at separations of a few hundred kilometers to several R_E in directions transverse to the Sun-Earth line, and in conjunction with upstream solar wind monitors, will pinpoint the origin of, establish the external conditions for, and characterize the nature of magnetotail turbulence.

In the solar wind, where ARTEMIS will spend more than 80% of its time, it will utilize its two-point measurement capability to address long-standing questions concerning the physics of solar wind particle acceleration in collisionless shocks and turbulence. Specifically, in the solar wind, ARTEMIS will address:

- How are particles accelerated at shocks? At interplanetary shocks, shock undulations are expected to host preliminary acceleration sites for solar energetic particle events and provide the seed population for particle acceleration for 10 to 100 MeV energies. Multiple spacecraft at appropriate scales are required to properly identify and study this 2D or even 3D phenomenon. Moreover, Earth's bow shock and foreshock are also excellent locations for studying the fundamental processes of particle acceleration. At lunar distances, where particles were first observed by the Apollo sub-satellites to have been diffusively accelerated at the bow shock, the acceleration process continues at rates that depend on spacecraft depth and distance to the point of tangency, as well as on upstream conditions. ARTEMIS orbits will sample the foreshock at various distances from the tangent line and at various solar wind conditions. ARTEMIS's direct inter-probe comparisons of upstream fluxes will provide a wealth of new information regarding the e-folding lengths of the diffusive acceleration process over key distances (0.1 to 20 R_E). ARTEMIS will accurately characterize the properties of interplanetary shock acceleration and diffusive particle acceleration at the Earth's bow shock and foreshock.
- What are the nature and extent of low-shear reconnection? Recent observations of reconnection "exhaust" regions have led to the identification of reconnection lines extending hundreds of Earth radii in the solar wind (Phan et al. 2006). Comprehensive examination of this phenomenon, and in particular the low-shear magnetic reconnection case, which

could be ubiquitous amongst stellar wind plasmas, is still lagging due to the scarcity of simultaneous high time resolution measurements on multiple nearby solar wind monitors. ARTEMIS's two probe high cadence plasma measurements, both alone and combined with other solar wind monitors, will enable fundamental studies of the most common, low-shear reconnection in the solar wind over scales ranging from tens to hundreds of R_E.
- What are the properties of the inertial range of turbulence? The solar wind is an excellent laboratory for the study of turbulence. Understanding the properties of the inertial range is important for modeling solar wind evolution through the heliosphere and for providing constraints on kinetic theories of energy cascade and dissipation in space plasmas in general. The crucial range, of the turbulent energy cascade at 1–20 R_E, however, has not been studied due to lack of appropriate satellite conjunctions. ARTEMIS's two-point measurements in the solar wind will fill an important gap in the study of the properties of solar wind turbulent cascade in the inertial regime and in determining how critical turbulence scale lengths vary under different solar wind conditions.

At the lunar wake, the interaction region between the solar wind and the Moon, ARTEMIS will have a unique opportunity to understand a wealth of basic physics phenomena pertaining to plasma expansion into a vacuum, applicable to many other astrophysical plasmas (voids in tori around Earth, Jupiter, and Saturn, the International space station, and Hubble). There ARTEMIS will answer:

- What are the three-dimensional structure and downstream extent of the lunar wake? Single-spacecraft wake observations cannot discern wake asymmetries arising from solar wind conditions or from crustal-solar wind interactions; this is due to either lack of pristine, nearby solar wind information or to lack of multipoint measurements. ARTEMIS's two probes will resolve spatio-temporal ambiguities at the wake. The well-instrumented probes will define the wake's extent and structure as function of downtail distance and characterize wake asymmetries.
- What are the plasma acceleration processes and energetics in and around the wake? ARTEMIS's comprehensive suite of field and plasma instruments will make possible a detailed study of the plasma physics occurring within the lunar wake that leads to acceleration and energization. The study will include the first DC electric field observations ever made in that region, direct observations of non-neutral plasma effects near the wake boundary, the extent of secondary electron beams, and their interaction with plasma refilling of the wake from the flanks.
- How do wake formation and refilling vary with solar wind and magnetospheric conditions? The wake structure varies in response to external drivers. Statistical studies provide tantalizing hints on how the wake responds to changing or transient solar wind conditions, but incomplete instrumentation and orbital coverage have limited our knowledge of this response. ARTEMIS will provide an unprecedented wealth of routine observations of the wake under a variety of solar wind conditions.

3.2 Planetary Science Objectives

The ARTEMIS team realized early on that significant benefits to planetary science could accrue from the two lunar probes with further, albeit small, orbit and instrument optimizations. ARTEMIS can address fundamental problems at the forefront of planetary science at the Moon (Fig. 6): sources and transport of exospheric and sputtered species; charging and circulation of dust by electric fields; structure and composition of the lunar interior by electromagnetic (EM) sounding; and surface properties and planetary history, as evidenced in

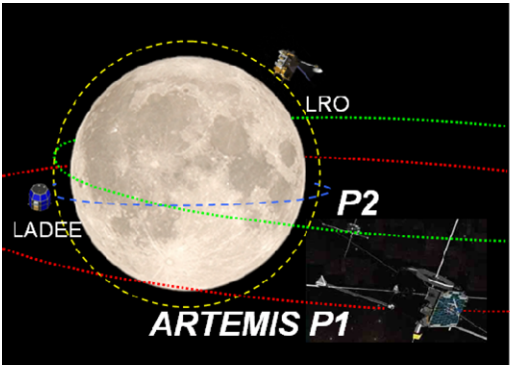


Fig. 6 ARTEMIS will study with two identical, cross-calibrated spacecraft lunar exospheric ions and dust, crustal magnetism, and the lunar interior. One probe will measure the pristine solar wind driver, while the other will study the lunar environment's response. ARTEMIS extends the SELENE/Kaguya results into the next decade, providing synergy with LRO, LADEE, and the International Lunar Network

crustal magnetism. Additionally, ARTEMIS's goals and instrumentation complement LRO's extended phase measurements of the lunar exosphere and of the lunar radiation environment by providing high fidelity local solar wind data. ARTEMIS's electric field and plasma data also support LADEE's prime goal of understanding exospheric neutral particle and dust particle generation and transport and will be in place for the deployment of the International Lunar Network (ILN), providing much needed solar wind information to ILN's studies of lunar deep electromagnetic sounding from the lunar surface.

Exosphere and sputtering. From lunar orbit, ARTEMIS will use its charged particle measurements obtained by the ESA and SST instruments as an extremely sensitive detection of ion species produced at the surface or in the exosphere and accelerated by solar wind electric fields. Newly created ions, produced by surface sputtering or ionization of exospheric gases, are generated at relatively low energies (0.01–10 eV), but immediately feel the effect of solar wind magnetic and electric fields (which ARTEMIS will also determine). Ions are then accelerated in cycloidal trajectories (i.e., "picked up"), as demonstrated by the Kaguya spacecraft (Nishino et al. 2009). Pickup ions have well-defined orbits, energy and direction as function of initial gyrophase; modeling of the observed fluxes can differentiate between surface and exospheric sources (Hartle and Killen 2006).

Lunar dust. The lunar surface electric field has been shown to respond closely to solar and magnetospheric plasma and energetic particles (Halekas et al. 2007) and also to vary with inclination with respect to the Sun. Electron reflectometry techniques have been used on Lunar Prospector (LP) to measure the potential drop between LP and the surface potential (Halekas et al. 2008a, 2009). The plasma and fields instrumentation on ARTEMIS is far more comprehensive than that flown on previous missions, enabling significant progress in our understanding of the origin and dynamics of lunar electric fields: LP measurements lacked direct knowledge of the spacecraft potential and ion measurements of any small positive potential. Although the LP potential has been modeled, ARTEMIS will be capable of actually measuring the spacecraft potential directly because it is equipped with electric field and ion analyzer instruments. Thus, ARTEMIS will go beyond the reflectometry measurements of LP with regards and measure a wide range of both positive and negative potentials.

Electromagnetic sounding. EM sounding exploits the fact that eddy currents are generated when a conductor is exposed to a changing external magnetic field. The eddy currents generate their own magnetic field, the induction field, which is readily measured by ground or space instruments. The depth to which a signal can penetrate depends on its frequency and the conductivity of the probed material. By using multiple frequencies, electromagnetic sounding has been used to probe the Earth's upper mantle (see Parkinson 1983; and references therein) and the deep lunar mantle, placing limits of ∼500 km on the radius of the lunar core (Dyal et al. 1974; Russell et al. 1974; Hood et al. 1982). More recently, EM induction was used to discover liquid water oceans in the icy Galilean satellites of Jupiter (Khurana et al. 1998; Kivelson et al. 1999; Kivelson et al. 2002).

Apollo and Lunar Prospector (LP) data have constrained the radius of a highly conducting lunar core to <400 km (Hood et al. 1999) and determined the deep mantle conductivity (Hood et al. 1982; Hood and Sonnett 1982) and its relation to the geothermal gradient and thermal evolution of the Moon. However, the transfer function is not very well constrained at depths less than 500 km from the surface or radial distances less than 500 km from the center, because at high frequencies the planar approximation breaks down and at low frequencies there are uncertainties in distinguishing the induction signal due to instrument offsets or noise. For example, Explorer 35 data, used to determine the driver in the Apollo era, had significant offset fluctuations, and the lack of simultaneous plasma measurements prohibited identification and removal of ambient space currents. Lunar Prospector studies did not have a nearby monitor of the driver signal.

ARTEMIS will measure the external, driving magnetic field with one probe and the response of the lunar interior to that field with the other probe when it is near periselene. Thus, in a manner analogous to planetary flybys (Khurana et al. 1998; Kivelson et al. 2002), ARTEMIS will determine the response of the conductive core to external field changes. Although the dipole response will be small (0.2–0.8 nT for a driver of dB = 5–20 nT), demonstrated offset stability (<0.1 nT/12 h), noise (<5 pT) and digitization (3 pT) on ARTEMIS/FGM (Auster et al. 2008) enable accurate measurements of the effect. Moreover, the presence of a nearby probe to measure the ambient field including its small variations enables, through subtraction from the total—induced plus external—field measured at periselene, extremely accurate determination of the induced response. Performing such measurements dozens of times over the course of the mission, a database of response as function of position and time relative to the driver impulse, will be assembled, and the core size and conductivity estimated. Differencing the highly sensitive magnetometer signals on the two spacecraft under various external driver frequencies is an ideal way to sound the interior conductivity of the Moon as function of frequency. For the first time the technique will be applied using nearby probes carrying identical sensors with very stable offsets that can be cross-calibrated just hours prior to each pass and can benefit from on-board plasma measurements to remove local space currents.

The ARTEMIS periselene altitude will be less than 100 km (exact altitude depends on results of orbit stability analysis optimizing for planetary goals). This altitude is ideal for making induction measurements from orbit, because with the exception of known, localized magnetic anomalies, all variances from the input signal can be attributed to induction effects. The technique can be applied both in the solar wind at the nightside and in the tail/magnetosheath/lobes on either side of the terminator.

Crustal magnetism. Crustal magnetism preserves ancient records of planetary and surface evolution. At Earth, study of crustal fields revealed polarity reversals of the core dynamo and established a chronology that ultimately confirmed the plate tectonics hypothesis. The origin of lunar magnetism is less clear because of the absence of a present day dynamo. The two strongest anomalies on the near side, Reiner Gamma and Descartes, and the strongest one on the far side, Crisium antipode, have surface fields that likely exceed 1000 nT. Minimagnetospheric interaction should result in solar wind density enhancements at the front and at the edges of the anomaly, as recently observed by the SELENE/Kaguya ion spectrometer (Saito et al. 2010). These anomalies also provide typical examples of the general correlation between crustal magnetic field regions and high albedo "swirl" features (Richmond et al. 2003; Nicholas 2007). ARTEMIS will measure lunar fields from 100 km or less, depending on the periapsis and longitudes that will be attained, at a 10° inclination or greater (goal $\sim 20°$), depending on the communications link budget and fuel margin available. It will study the interaction of near-equatorial magnetic anomalies with the solar wind and the magnetotail. These anomalies deflect and shock the solar wind plasma and cause electron heating and wave turbulence (Halekas et al. 2008b, 2008c). Even from 100 km altitude and inclination below 10°, the comprehensive instrumentation on ARTEMIS will measure the magnetic properties of Reiner Gamma and the interaction of this mini-magnetosphere with the solar wind and the Earth's magnetotail.

Thus while ARTEMIS cannot improve upon the geographic coverage of the crustal fields attained by LP and Apollo, the availability of comprehensive *in-situ* instrumentation will greatly expand upon the knowledge gained from prior studies of interactions of such anomalies with the solar wind. For example, ions (including reflected ions) will be measured, the waves from the ion-ion beam instabilities will be sensed in both electric and magnetic fields, and the spacecraft potential from the electric field instrument will be helpful in accurately determining the plasma moments. The high time resolution wave captures will be particularly important in the analysis of plasma waves and in further characterization of the mini-magnetosphere interaction with the solar wind.

Synergies with other missions. Because it overlaps with LRO's extended investigation in 2011 and 2012, the ARTEMIS mission is in a unique position to support LRO's prime and extended mission science objectives. LRO will study the lunar atmosphere and its variability with the LAMP instrument, and particle acceleration mechanisms and their radiation effects on tissue with the CRaTER instrument. ARTEMIS can support LAMP observations of the exosphere by providing accurate measurements of solar wind and magnetotail drivers. Observations during the overlap period between LADEE and ARTEMIS can be used as calibration points to relate the statistical studies that will be done independently by the two missions. CRaTER's objective to study Galactic Cosmic Ray (GCR) and Solar Energetic Particle (SEP) populations will be facilitated by the presence of ARTEMIS as a nearby solar wind monitor.

By measuring both upstream solar wind and local plasma conditions near the Moon, ARTEMIS is also in a unique position to support the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission, slated for a mid-2012 launch. LADEE carries instrumentation to study the dynamics of the lunar exosphere and dust environment, much of which will be tied directly to the ambient plasma conditions at the Moon and in the solar wind. Since LADEE lacks in-situ plasma instrumentation, the presence of ARTEMIS will enable a more direct linkage between specific ambient plasma processes and the resultant exospheric variability measured by LADEE. Moreover, ARTEMIS measurements of the surface potential in tandem with LADEE could revolutionize our understanding of charging processes related to lofted dust that would have gone unnoticed with LADEE measurements alone.

Finally, a major element of NASA's lunar flight projects is the International Lunar Network (ILN), comprised of small geophysical nodes on the lunar surface. These nodes are expected to be deployed in the next decade by NASA and international space agencies. One of the goals of the ILN is to perform lunar EM sounding from the surface with both electric and magnetic sensors. ARTEMIS in orbit will provide continuous magnetometer measurements of the driver signal to meet the needs of the measurement floor of the ILN network's EM sounding goal.

4 Mission Design

The ARTEMIS mission concept originated in 2005, well after the THEMIS Critical Design Review, when it was realized that optimizing the prime THEMIS mission orbit design would result in 8 h-long shadows for P1 and P2 (the outermost THEMIS probes), well beyond their thermal design limits. Since these would occur about six months after the end of the prime mission, alternate plans had to be devised early. Approaches for a mission extended phase were sought in collaboration with NASA/JPL in 2005, when it was realized that by increasing apogee and taking advantage of lunar perturbations, shadows could be avoided with minimal resources, about 100 $\mathrm{m\,s^{-1}}$, although with a complex operations scenario involving station-keeping in translunar orbits. After a re-design of the THEMIS launch vehicle target injection in 2006, which re-optimized the fuel margin on the five THEMIS probes, it was realized that sufficient margins would be available for P1 and P2 at end-of-mission to accommodate a lunar orbit insertion for P1 and P2, assuming a low-thrust injection at the Moon. The lunar orbits had to be highly eccentric, with periods from a few hours to 1.5 days, because there was insufficient fuel margin to accommodate a low-altitude circular orbit. In addition, such orbits were preferred because long periods resulted in infrequent shadows and battery cycling, consistent with the thermal design and verification program of the THEMIS probes. Additionally, the low thrust capability of the probes required that the Lunar Orbit Insertion (LOI) maneuver be split in multiple burns, of which the first was the most critical. Thus, residence in the Lagrange points to properly evaluate and adjust the LOI conditions was deemed necessary in order to reduce operations risk. Since the probes have axial thrusters thrusting only along (but not opposite to) the spin axis direction, and the probes have spin axis approximately along the ecliptic south, it was realized that lunar polar orbits would be less advantageous, as they would result in limited orbit control capability. Finally, lunar orbits had to avoid Earth and Moon shadows longer than 4 h, a revised requirement (relative to a 3 h limit at launch) stemming from the operation team's most recent assessment of the thermal design, based on analysis of in-flight performance data.

In 2007 internal studies at JPL resulted in an initial ARTEMIS trajectory subject to the above constraints that was of sufficient fidelity to be further optimized in collaboration with the science team. In 2008, NASA/HQ requested that the team consider ARTEMIS as part of its 2008 Senior Review process (rather than as a separate proposal) and recommended use of the Deep Space Network (DSN) for data relay, which enabled consideration of the 34 m antennas at a nominal contact frequency of 3.5 h/day. In a series of science working team meetings, the following science considerations were taken in the mission design: (1) The Lissajous orbits were deemed extremely useful scientifically, because they provide information on tail and solar wind spatial scales never measured before. The science team further requested that the Lissajous orbits be performed as two steps, at least 3-months long each: the LL1, 2 and LL1 step (explained in Sect. 1, in particular with Figs. 2 and 3 and Table 1) in order to maximize residence in the large inter-spacecraft separation regime. This was possible by inserting P1 at LL2 and P2 at LL1 for 3 months, followed by bringing P1 at LL1 to have both probes on the near-side of the Moon. (2) The differential precession of the line of apsides of the probes after lunar orbit insertion would be very small if the probes had similar lunar orbital elements. This could place restrictions on the insertion times and strategy and limit observation orientations. To avoid such restrictions and to maximize the inter-probe separation vectors, the science team requested that one of the probes be inserted into a retrograde orbit and the other into a pro-grade orbit to speed up the differential precession of the lines of apsides. P1 was selected for retrograde insertion, to help its fuel margin, since retrograde orbits require less orbit insertion velocity, but this choice may be reconsidered in 2010.

Table 3 Fuel margin available to execute ARTEMIS for heliophysics science goals; additional fuel may be required for modifications and maintenance corresponding to planetary objectives. DSM = Deep Space Maneuver. LOI = Lunar Orbit Injection. TCMs = Trajectory Correction Maneuvers

ARTEMIS Mission (P1, P2): ΔV overview				
Phase	Interval	Maneuver	dV P1	dV P2
TLI	Oct.09–	Orbit raise, Lunar fly-by	100.7	185.6
	Oct.10	Declination, Gravity Losses	20	28
LL1,2	Oct.10–Jan.11	DSM	0.9	17.3
LLI	Jan. 11	Maintenance	15	12
LO	Apr.11–	Lunar transfer initiation, LOI	86.6	108.7
	Sep.12	Decl., Gravity, Steering	7	12
all	all	TCMs	13	10
Total required for this ARTEMIS probe			243	374
Total available at end of prime mission			300	450
ΔV available ARTEMIS margin [m/s]			57	76
ΔV available for ARTEMIS margin (%)			23%	20%

(3) Equatorial, highly eccentric lunar orbits of ∼26 h period (100 km × 18,000 km altitude) were deemed most useful scientifically for the lunar orbit phase, as they enable separations of up to 5 R_E (18 R_L) at all orientations over the course of 2 years. Higher aposelenes would have caused increased Earth perturbations that would have resulted in early orbit insertion. Additionally, higher aposelenes would have also produced longer lunar shadows (beyond the 4 h limit requirement).

These science desires and mission operational constraints were worked into the final orbit scenario described in Sect. 1. In particular, the near-equatorial orbits, of period ∼1 day are easy to achieve with the side-thrusting capability (which allows thrusting at any vector orientation along the spin plane). Sufficient margin is available at the end of the nominal ARTEMIS mission design, as shown in Table 3. Since lunar and other perturbations also necessitate correction maneuvers that may be out of the spin plane, care must be taken to ensure that the return-to-nominal plan of the ARTEMIS operations team is achieved by the axial thrusters for reasonable (3 sigma) deviations of the trajectory from nominal. This is done by the ARTEMIS navigation team at GSFC, which analyzes and biases the nominal orbit such that achievable correction maneuvers can be inserted at specific points into the mission, if deemed necessary based on the actual maneuver execution and thruster performance in orbit. The resultant ARTEMIS lunar orbits are very similar, operationally, to the ones for the THEMIS mission at Earth, in terms of a thermal environment, power cycling, communications plan, and data collection strategy. These are dictated primarily by the properties of the equatorial, highly eccentric, nearly day-long period orbits, resulting in shadows that are below the four-hour flight-demonstrated extended survival limits of the probes during their Earth-orbit history. In addition to lunar shadows, care must be taken to predict and avoid ARTEMIS Earth shadows through mean anomaly phasing; this costs very little fuel if achieved far in advance, else it may result in shadows that can exceed the design limit. This combination of science and technical trades has resulted in a robust, low-risk mission design solution for ARTEMIS, and is expected to provide an unprecedented view of the lunar space environment in a very cost-effective way.

In late 2008 it was realized that significant planetary goals can also be achieved from ARTEMIS, with only small modifications to the mission design. These are a periselene altitude reduction and an inclination increase. With regards to the periselene altitude, the P1, P2 orbits are expected to be further optimized to "graze" the surface in the < 100 km domain once a month. By expending maintenance fuel on the order of a few $\mathrm{m\,s^{-1}}$ (see Table 3 for a perspective with regards to fuel margins), it is possible to maintain a stable orbit at low periselene. Considerations will be given to the fuel margins prior to orbit insertion and the operations complexity from periselene maintenance in the remainder of the mission. With regard to inclination adjustments, an inclined orbit results in additional opportunities of conjunctions with crustal anomalies near periapsis. But an inclined orbit increases the gravity gradient torque on the spin axis away from its optimal orientation of 3–13° (8° nominal). This affects communications as there are significant signal losses below 15° from the spin plane. Additional considerations include thermal effects, boom shadow effects on instrument performance, and station-keeping fuel. An inclination between 10–20° is expected to be achievable. The exact value will be determined closer to insertion time. These planetary science optimizations will be revisited in the summer of 2010, after translunar injection, and the results will be folded into the ARTEMIS mission design, assuming sufficient resources are available, in early 2011.

5 ARTEMIS Mission Operations Plans

The ARTEMIS mission is, by design, a natural evolution from THEMIS operations at Earth to operations in the lunar environment, in terms of spacecraft commanding and conditioning, instrument modes, instrument operations, and data relay/processing strategy. The ARTEMIS Mission Operations Systems is comprised of Mission Operations and Science Operations following the practices of THEMIS: ARTEMIS is operated by the Mission Operations Center (MOC) at the Space Sciences Laboratory, University of California, Berkeley (Bester et al. 2008). In addition, the JPL mission design team has developed and delivered the mission trajectory to the MOC for implementation; the GSFC flight dynamics team has developed for ARTEMIS Sun-Sensor—only attitude determination solutions; and the GSFC navigation group supports ARTEMIS in performing navigation error analysis, inserting orbit biases, and determining trajectory correction maneuvers that need to be inserted to compensate for a return-to-nominal mission design plan. The mission operations center performs: mission planning functions in accordance with science (instrument operation modes) requests; flight dynamics; orbit and attitude determination; maneuver planning; commanding and state-of-health monitoring of the five probes; recovery of science and engineering data; data trending and anomaly resolution. Science operations comprise the generation of instrument schedules, data processing and archiving, generation and maintenance of data analysis and display software, instrument trending, and science community support.

The main operations differences between ARTEMIS and THEMIS are: (i) the use of the Deep Space Network's (DSN) 34 m antennas for communications, and (ii) the instrument operations that will have to be adjusted to the new environment, reduced data volumes, and new science. Use of the DSN antennas necessitated new operational interfaces (ephemeris, scheduling, telemetry/command/tracking data, and file transfers) and processing/conversion tools. The integration of the DSN antennas into the existing MOC network is seamless, however. For example, range and range-rate data from the DSN are transmitted to the MOC, translated into the same format as the Berkeley Ground Station and the rest of the NASA ground network, and processed with the standard tools (GTDS) for orbit determination. The

Table 4 Typical mode of operations of ARTEMIS probes for Heliophysics and Planetary investigations, per 2 orbits. An orbit is ∼26 h. Bursts will be triggered either based on-board triggers, or based on time. FIT = E, B spin fits; MOM = ESA moments; RDFs = reduced particle distributions; FDFs = Full (angular) particle distributions; FBK = filterbank wave spectra; FFFs = Fourier wave spectra

Mode	Duration	Products
Slow Survey	2 orbits	FIT, MOM, RDFs, FBK
Fast Survey	3 h	FDFs, FFFs, Waveforms
PB (2/orbit)	40 min	Full cadence FDFs
WB(2 per PB)	2 × 6 s	Full cadence waveforms

main effect is that given the DSN link margin and contact duration, approximately $1/5$ of the amount of data that can be recorded on memory can be transmitted to the ground per contact (nominally once per two days, per probe). (The nominal instrument modes have been discussed in Angelopoulos (2008).) Because there is one contact per probe over the period of 2 days, careful planning and selection of the Fast Survey (FS), Particle Burst (PB), and Wave Burst (WB) intervals are required (Table 4). The downlink volumes are consistent with one FS interval of only ∼1.5 h per orbit (compared to 12 h per orbit at Earth) and the selection of one to two (max) PB per orbit with one or two (max) embedded WBs within it. The location of FS is time-based and will be one of the following: wake crossing, periselene, two probe wake/boundary alignment, nominal plasma sheet, or boundary layer crossing (magnetotail). Since not all of those can be achieved simultaneously, the operations plan involves mission phases to optimize data collection for specific science objectives at various parts of the mission. Alternative collection plans are also currently being considered.

The second difference is changes to instruments to best suit the proposed studies in the new environment and commanding of the instrument modes to obtain the optimal heliophysics and planetary science. ARTEMIS cares about instrument sensitivity far beyond the requirements of THEMIS, because it operates in a 10 nT typical ambient field and near-background particle fluxes, except for the solar wind beam population. With regard to the FGM and SCM instruments, cleanup methods have already been devised and disseminated (though not very widely used yet). Their operational use and efficacy and any changes in response to community feedback remain tasks for the future.

For the FGM instrument these include corrections to: ground processing of data around range changes, digital-to-analog differential non-linearity effects, offset drifts, and power system currents. Since it is anticipated that the magnetometer will be in a single range (likely range 8, ∼3 pT resolution, ∼100 nT maximum field, see Auster et al. 2008), and the non-linearity affects the data in high fields only, by far the most important corrections necessary in the lunar phase are the offset drift correction and the power system current noise removal. Routine offset determination using recently developed techniques in the solar wind (Leinweber et al. 2008) and calibration of L2 data to account for power system currents will be done by the science team in the operational phase of ARTEMIS. For the ESA instrument (McFadden et al. 2008a, 2008b), the solar wind mode routinely used on THEMIS is incompatible with the need to measure simultaneously the upstream ions, wake-accelerated or solar wind shock-accelerated ions, or lunar backscattered ions. The current plan is therefore to utilize the electron sensor for determining solar wind velocity, density, and electron temperature and ignore the ion saturation that occurs from the nominal magnetospheric mode operation of the ion sensor. The inter-calibration of ESA electron density and velocity with the other instruments (electric field, ion ESA) is currently under way. An alternative approach is to create a hybrid instrument operational mode with higher angle resolution in the solar wind direction, preserving the full energy resolution achievable in the magnetospheric mode. This approach will enable solar wind ion density and velocity measurements and provide reasonable total ion temperature measurements, as well.

Additional effects from shadows on all instruments are present. In the absence of a sunpulse the spin period is not known internally on the spacecraft, and particle instrument sectoring of distribution functions and on-board spin-fits of the magnetic and electric field data become suspect. As the spin period changes due to thermal effects (wire boom contraction causes probe to spin up), the above sectoring and spin-fit algorithm results in products with an apparent drift in sun-angle. The drift can result in several full rotations per hour, but since the spinup is a combination of several non-linear terms (as it depends on amount of partial sun illumination, wire/probe bus heat capacity, and moment of inertia), it can only be fitted to observed data. This has been done with good success using the FGM data, and routines for correcting the shadow data are now available. The spin-phase information will be included as a correction to the spin-phase files in the post-processing tools for all particles and fields quantities to produce accurately post-processed distributions and properly oriented spin-fits.

Science data processing, calibration, dissemination, and analysis tools development and maintenance follow the successful practices of THEMIS. Level-0 data are uncalibrated raw data, in day-file and raw packet format. Level-1 data are Common Data Format (CDF) files containing uncompressed, time-ordered, overlap-deleted data in raw instrument units (e.g., counts, 16 bit integers). They are efficiently packaged, and can be read by any platform that supports the NASA/GSFC-distributed CDF platform. L1 files are read automatically by IDL-based, freely and widely distributed analysis tools and are calibrated on-the-fly using the latest calibration parameters to take advantage of the most updated calibration done on the instrument without the need for any L1 file reprocessing. L2 files contain calibrated data of a subset of the dataset, representing the most important quantities from each instrument. L2 files are in physical units and also in CDF format and do not require further calibration; they can be read by any software that is able to access CDF files, such as Fortran, C, Matlab, and IDL. They are simple enough to be easily interpreted using standard documentation. Automated processing performs both standard calibration (using the latest parameters and orbit-predicts) and L2 file production within hours of data receipt at the MOC. Standard overview plots are also automatically produced to facilitate data quality evaluation and quick event selection, especially in conjunction with other missions. An example of an overview plot is shown in Fig. 7. Events such as calibration file changes or definitive orbit/attitude file updates trigger reprocessing of both L2 files and on-line plots.

Files are disseminated via project site and mirror site web pages by NASA/GSFC's Space Physics Data Facility and by Virtual Observatories. Plans for inclusion of ARTEMIS data into the Planetary Data System (PDS) are currently under way. The most useful and more prevailing means of data dissemination, however, is via the THEMIS and ARTEMIS data analysis software, an IDL-based suite of reading, analysis, and visualization routines offering both command-line and Graphical User Interface capability. This code, used by the science team, is freely available to the science community. Data ingestion is performed "on-the-fly", along with calibration, if L1 quantities are being introduced. The code interrogates the user's preferred http or ftp sites (the default is project site) and downloads only the data that has been reprocessed recently, based on the file creation date at the user's machine relative to the remote site. Batch downloads or bundled downloads are also possible but not required or needed. Once the data resides on a user's machine, analysis is possible off-line. Dozens of crib sheets, i.e., text files containing IDL code that demonstrates usage of certain routines, are available with the data distribution. Special-purpose crib sheets are also

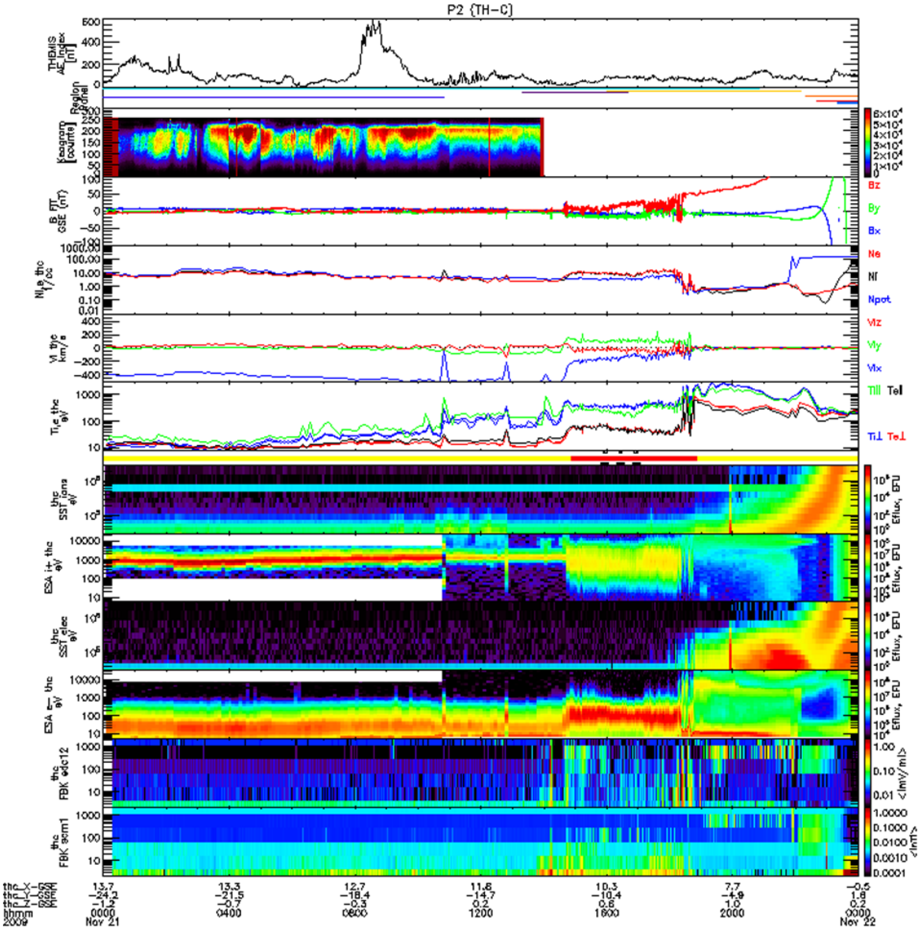
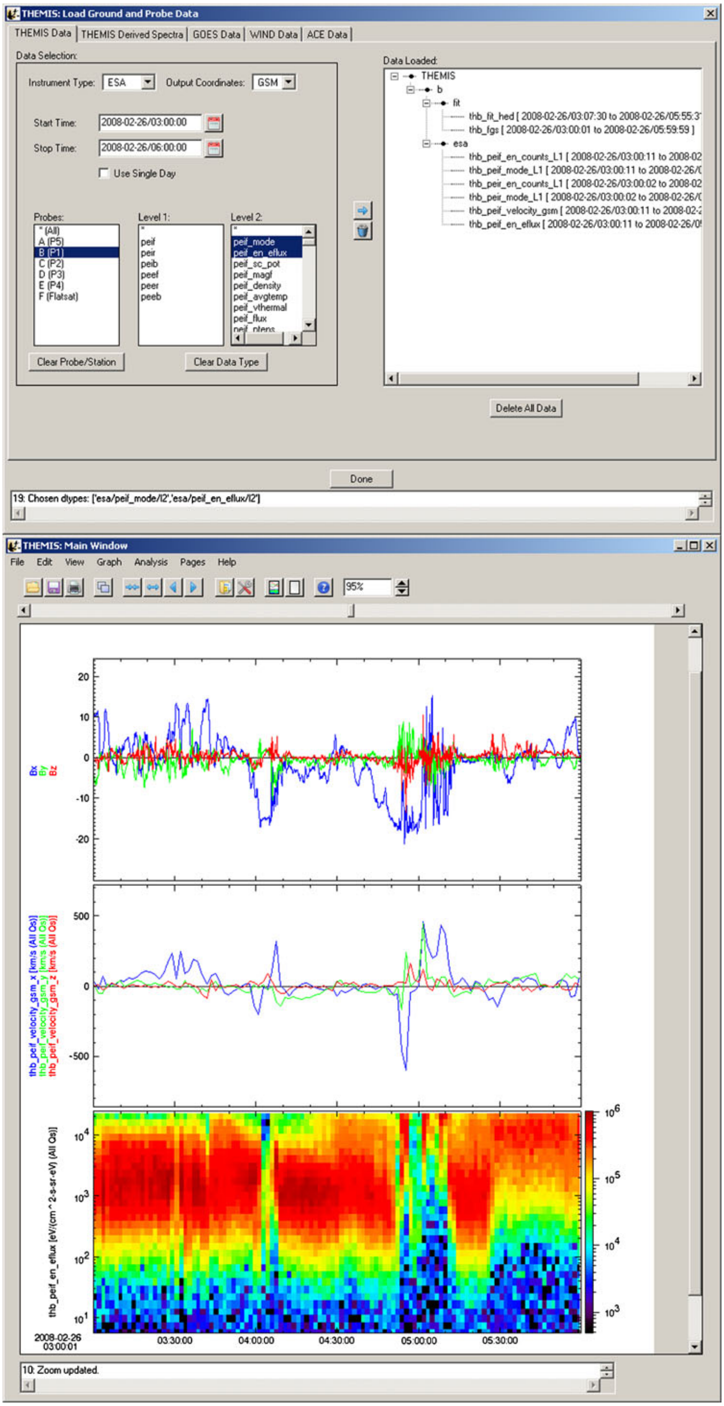


Fig. 7 Overview plot (routinely produced) from all instruments on ARTEMIS probe P2 during a perigee passes a few months prior to its translunar injection. Horizontal bar indicates mode (SS = yellow, FS = red, PB/WB = black bottom/top)

exchanged between users, enabling rapid, efficient communication and exchange of tools, experience, and ideas. The analysis code distributed also provides a Graphical User Interface (GUI) that allows users completely unfamiliar with command line IDL coding to have both quick access to the data and a fast introduction into the ARTEMIS analysis system (Fig. 8). The GUI is also accessible by IDL's product: "Virtual Machine", which is free of charge and also contains data manipulation capability by virtue of a "mini-language" operating on data structures or on arrays. Furthermore, the GUI allows easy plot manipulation capability (panning, zooming, line colors, symbol fonts, plotting), permitting publication-quality plots. The IDL calibration and analysis code is disseminated to the community via the THEMIS/ARTEMIS web sites; tutorials are routinely conducted at various institutions and during major international meetings.



Instrument Type: ESA
Output Coordinates: GSM

Start Time: 2008-02-26/03:00:00

Stop Time: 2008-02-26/06:00:00

Data Loaded:

- THEMIS
  - b
    - fit
      - thb_fit_hed [2008-02-26/03:07:30 to 2008-02-26/05:55:3
      - thb_fgs [2008-02-26/03:00:01 to 2008-02-26/05:59:59]
    - esa
      - thb_peif_en_counts_L1 [2008-02-26/03:00:11 to 2008-02
      - thb_peif_mode_L1 [2008-02-26/03:00:11 to 2008-02-26/
      - thb_peir_en_counts_L1 [2008-02-26/03:00:02 to 2008-02
      - thb_peir_mode_L1 [2008-02-26/03:00:02 to 2008-02-26/
      - thb_peif_velocity_gsm [2008-02-26/03:00:11 to 2008-02-
      - thb_peif_en_eflux [2008-02-26/03:00:11 to 2008-02-26/0

```
19: Chosen dtypes: ['esa/peif_mode/l2','esa/peif_en_eflux/l2']
```

```
10: Zoom updated.
```

Fig. 8 THEMIS/ARTEMIS Graphical User Interface showing Data Introduction panel and Plotting tool. The GUI benefits from the underlying command line software but provides tools for both plot manipulation and for easy manipulation of data quantities, seamlessly easing novice users into the data system

6 Summary

ARTEMIS, the first two micro-satellite mission to the Moon, is a cost-effective interdisciplinary mission addressing fundamental questions in NASA's Heliophysics and Planetary Disciplines. ARTEMIS will study space physics processes in the solar wind, magnetotail, and the lunar wake, and can also address important questions on the exospheric, surface, and subsurface lunar environment. With stable orbits, ARTEMIS can monitor both the solar wind and the lunar environment during the next solar cycle; it is therefore aligned with NAC/NRC's recommendations to characterize the lunar environment and predict space weather impacts on robotic and human productivity. Finally, being the first mission to use prolonged residence in lunar libration orbits, which are important for communications and as staging grounds for lunar landings, ARTEMIS represents a pathfinder for future lunar exploration missions.

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