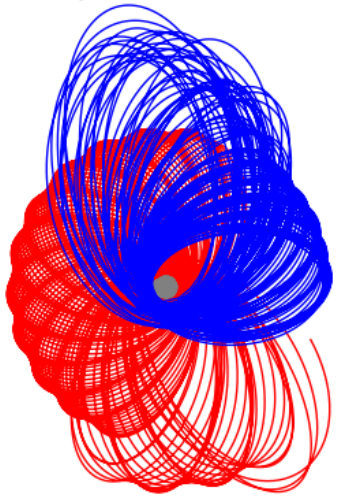
ARTEMIS Lunar Orbit Insertion and Science Orbit Design through 2013



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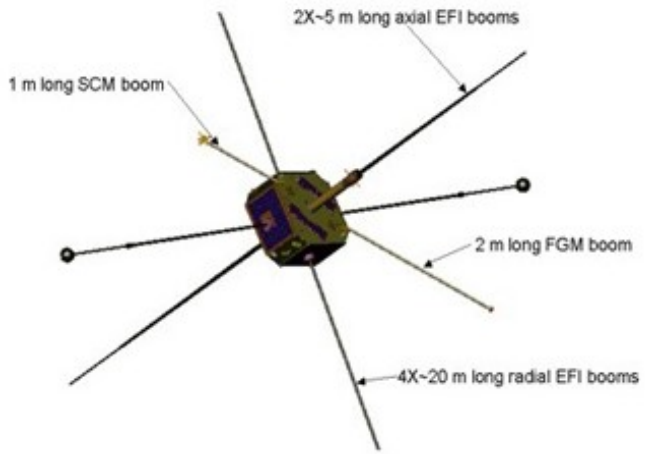
Introduction and Background

- The ARTEMIS mission has transferred two probes from Earth orbit to Lunar orbit
  - Probes named “P1” and “P2”
- ARTEMIS has been a collaboration between U-California at Berkeley, the ARTEMIS science team, Goddard Space Flight Center, and JPL.
- Probes were originally part of the THEMIS constellation
  - Built by Swales Aerospace (now ATK)
  - Equipped with instruments for measuring electro-magnetic fields and high-energy particles
  - Successful mission mapped interactions of the Earth’s magnetosphere with the solar wind using 5 probes.
- P1 and P2 began their voyage to the Moon in Summer 2009 and arrived in lunar orbit in June/July 2011
  - Two distinct low-energy transfers were follow using multiple lunar encounters to minimize fuel usage.
  - P1 and P2 resided in Lissajous orbits around the Earth-Moon Lagrange Points #1 and #2 (EML1, 2) for about 10 and 9 months respectively



JPL

SPACE SCIENCES LABORATORY
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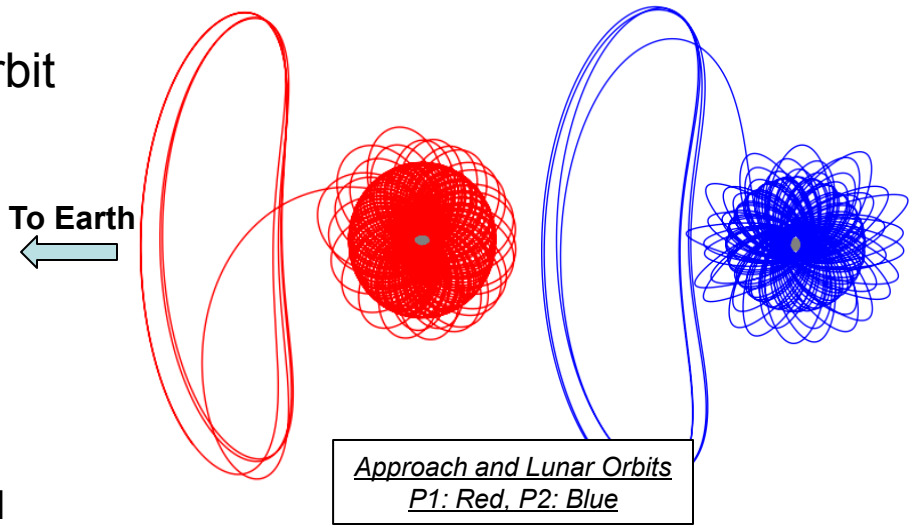
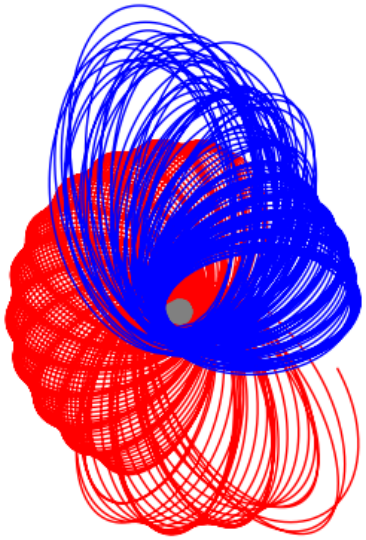
Lunar Orbit Design Introduction

- This talk focuses on the *baseline* trajectory design for the lunar science orbit portion of the mission.
  - Currently “in process”
- Interesting and novel design challenge:
  - Approach lunar orbit from Lissajous orbit
    - Approach geometries limited
    - Another ARTEMIS first
  - Highly-eccentric orbit (i.e., strong Earth and Sun perturbations)
    - Short-, medium-, and long-term orbit element oscillations
    - Most eccentric long-term lunar science orbit to date
  - Many science objectives drive orbit design
    - Heliophysics and Planetary Science objectives
    - More on next slide
  - Spacecraft maneuvering capabilities are restrictive
    - Effective thrust ~0.5 N
    - Limited ΔV, P1: ~180 m/s, P2: ~155 m/s



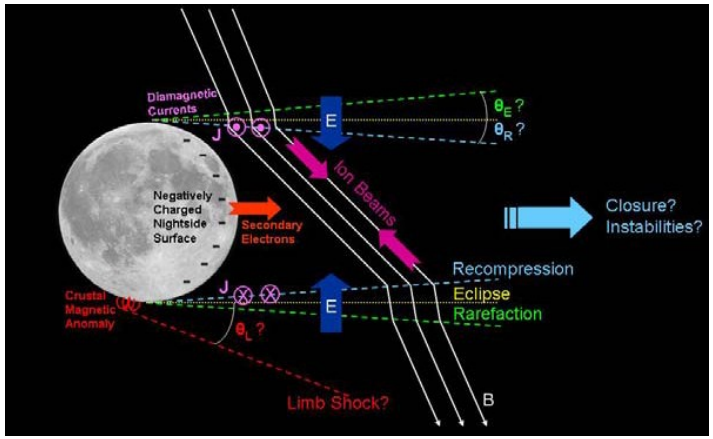
Approach and Lunar Orbits
P1: Red, P2: Blue



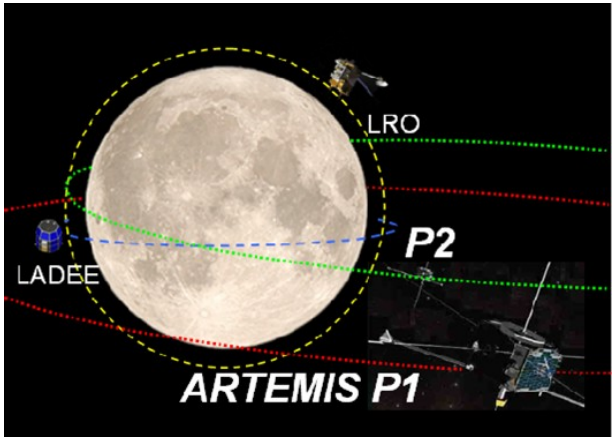
Relative Precession of Orbits
P1: Red, P2: Blue

Science Drivers

- ARTEMIS is jointed funded by NASA's Heliophysics and Planetary Science Divisions within the Science Mission Directorate
  - Many science goals!
  - Science drives the lunar orbit design
- 3-D mapping of the lunar wake induced by the solar wind
  - Range of downstream distances and relative probe orientations needed
- Crustal magnetic anomaly investigation
  - Requires <50 km passes over anomalies
- Lunar exosphere measurements
  - Range of altitudes from ~100 to thousands of km at variety of local solar angles needed
- Coordinated exosphere measurements with LADEE
  - At least one probe must have sub-200 km passes above the dawn terminator during the LADEE science phase (late 2013)
- Further, the orbit must be stable to maximize science and lifetime with the given propellant.



Lunar Wake Science Questions from :"THEMIS and ARTEMIS", a Proposal to the 2008 NASA Heliophysics Senior Review, V. Angelopoulos and D. Sibeck



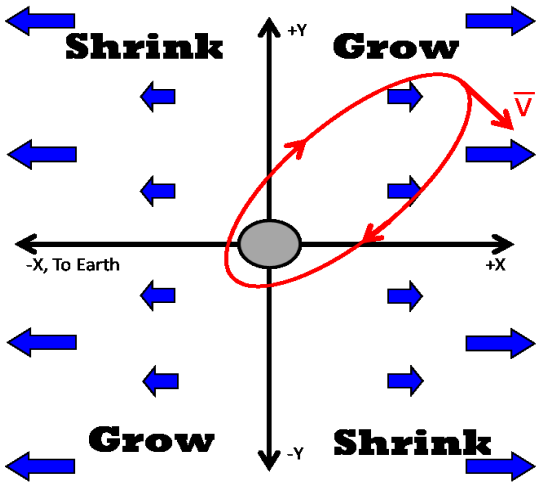
Coordinated Science with LADEE at the Dawn Terminator from :"The ARTEMIS Mission", V. Angelopoulos, Space Science Reviews

Dynamics

- 20x20 Lunar gravity, Earth pointmass, solar radiation pressure, and solar gravity included in the dynamic model

- Primary perturbation is Earth
  - Bi-weekly variation in periapsis altitude
    - Due to tidal forces
  - 4-5 month medium-term variation
    - Induced by secular change in the argument of periapsis
    - Understood using doubly-averaged equations

Influence of Earth in a rotating frame



Secular Lagrange Equations of Motion for the Hill 3BP (Scheeres et al., 2001)

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

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

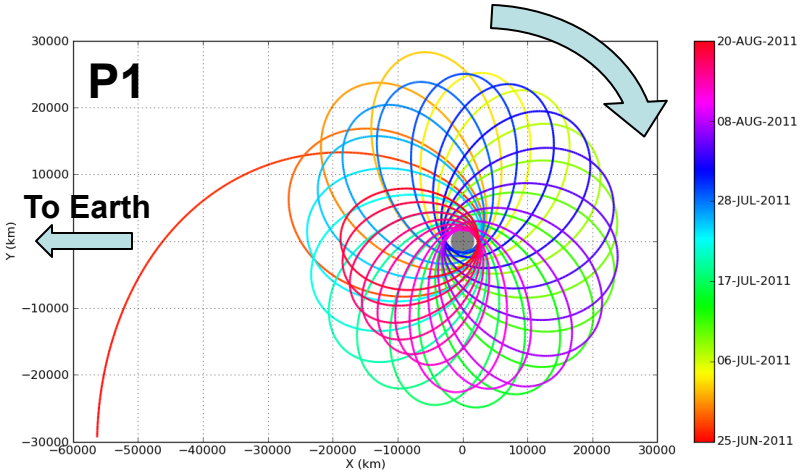
$$\frac{d\Omega}{dt} = -\frac{3}{8}\frac{N^2}{n}\frac{\cos i}{\sqrt{1-e^2}}\left(2+3e^2-5e^2\cos 2\omega\right)$$

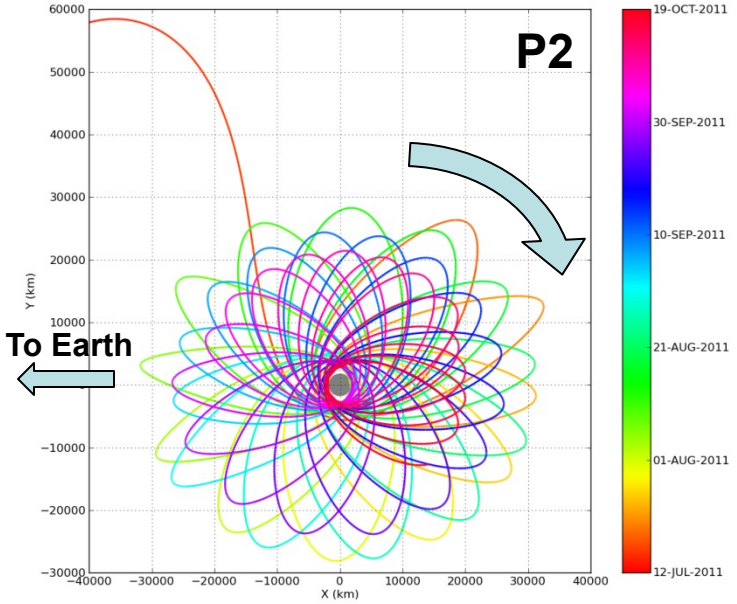
$$\frac{de}{dt} = \frac{15}{8}\frac{N^2}{n}e\sqrt{1-e^2}\sin^2 i \sin 2\omega$$

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

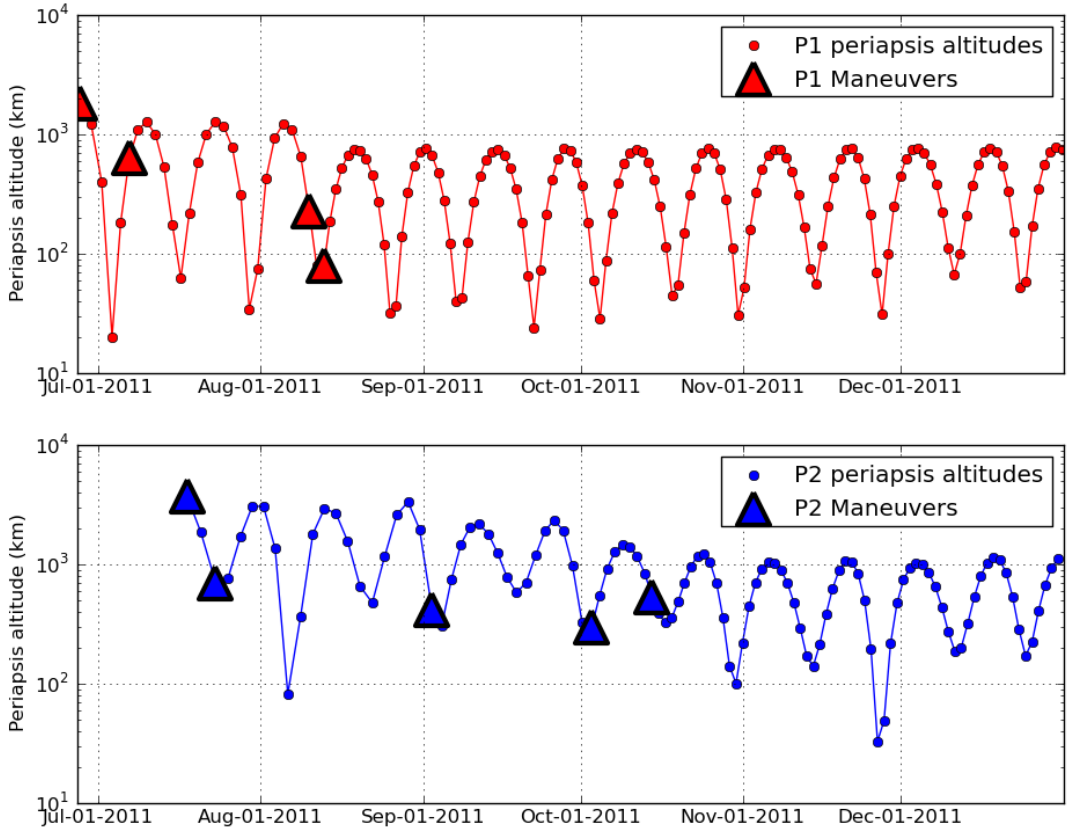
Approach and Orbit Geometry

- Both probes approach from EML1
  - Axial TCMs
  - Lunar Transfer Initiation (LTI)
  - Approach TCMs
  - Lunar orbit insertion (LOI)
  - 4x Period reduction maneuvers (PRMs)
    - In PROGRESS!!!
- Science orbit
  - P1 retrograde, P2 prograde
  - Inclination:
    - P1: 168-180 deg, P2: 0-17 deg
    - Maneuvers in Lissajous found to be very effective to change inclination
  - Periapsis: ~20-1000 km altitude
  - Apoapsis: ~19000 km range



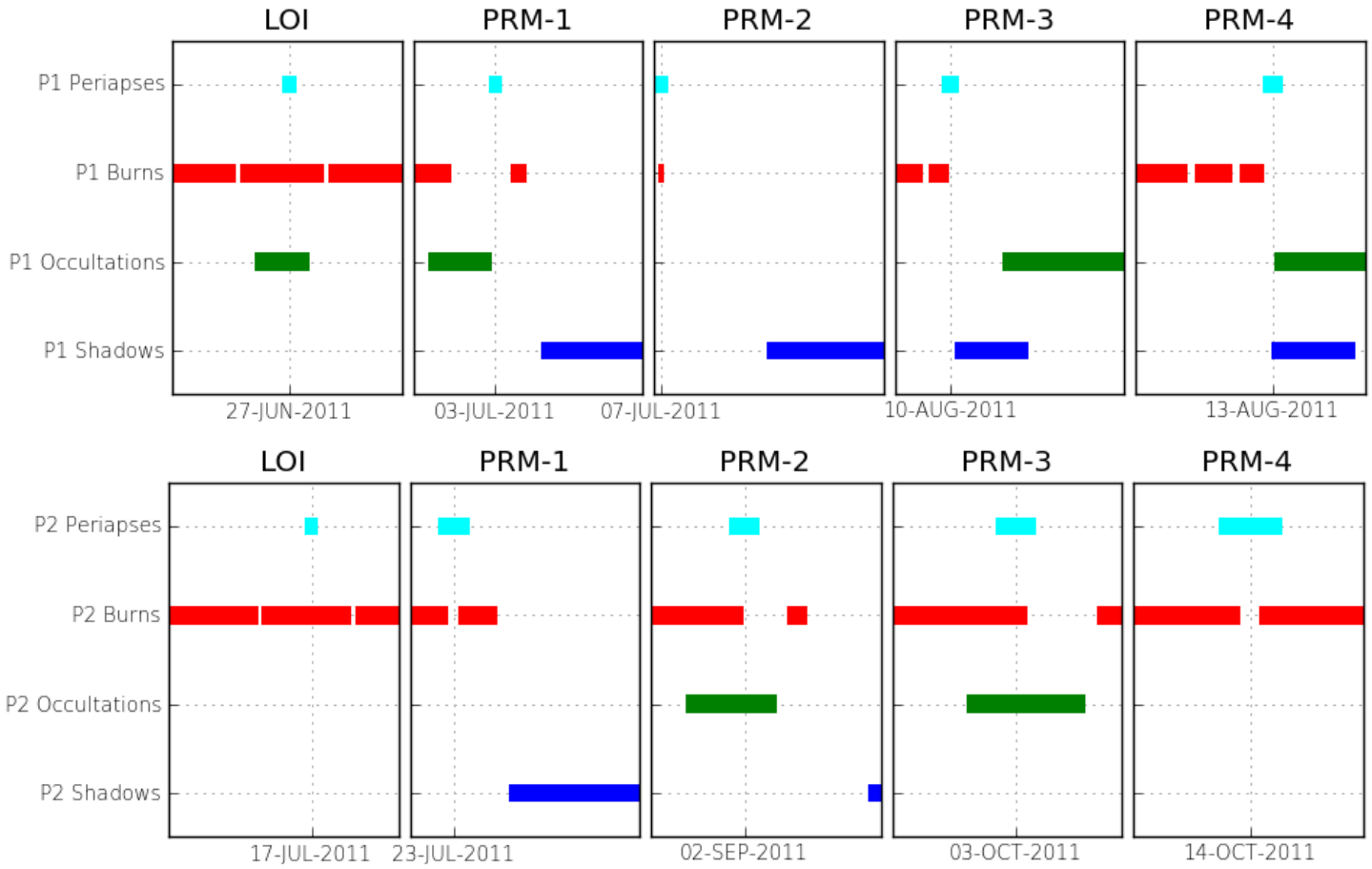


LOI and PRM Design



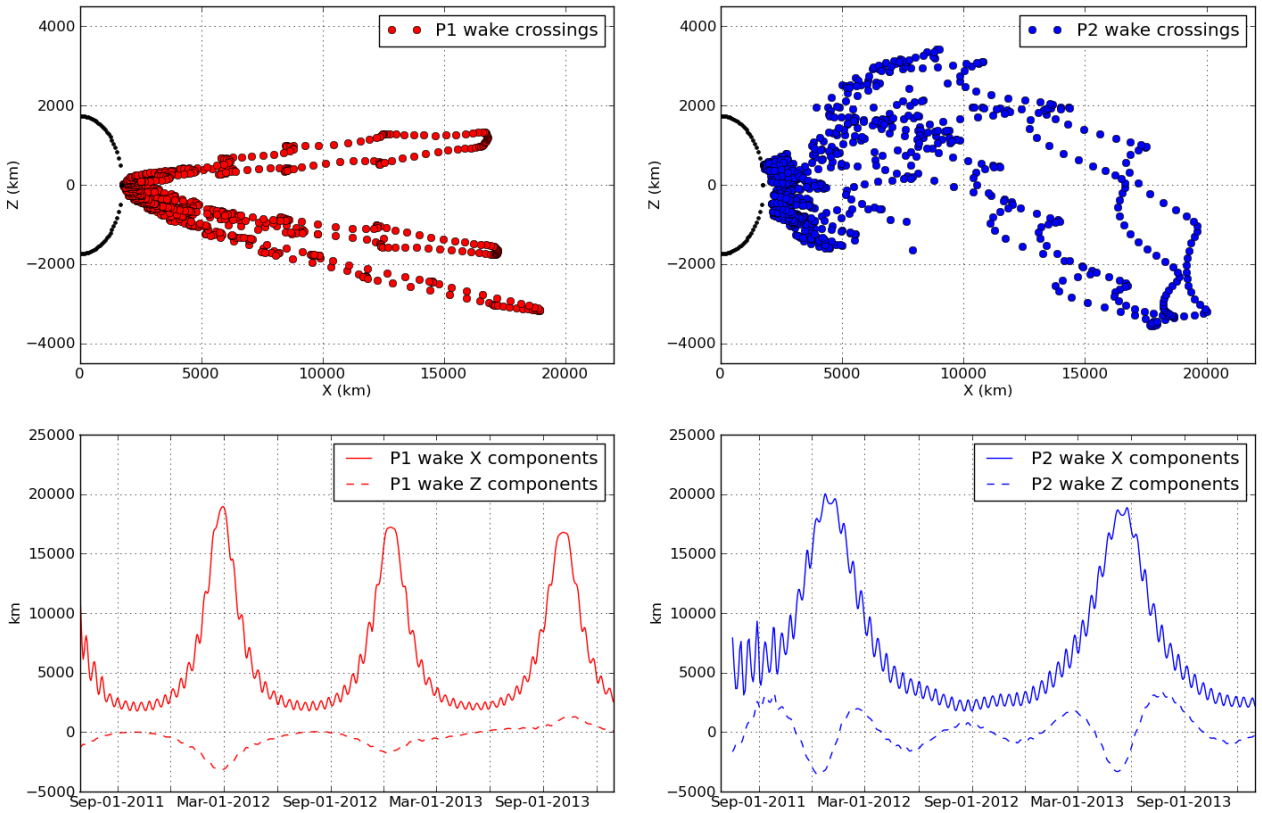
- The transfer to science orbit must be done over many maneuvers
  - LOI captures, PRMs guide to science orbit
- Fuel efficiency and operations manageability are top priorities
  - Total Delta-V: P1: 94.2 m/s, P2: 119.2 m/s

Maneuver Segmenting



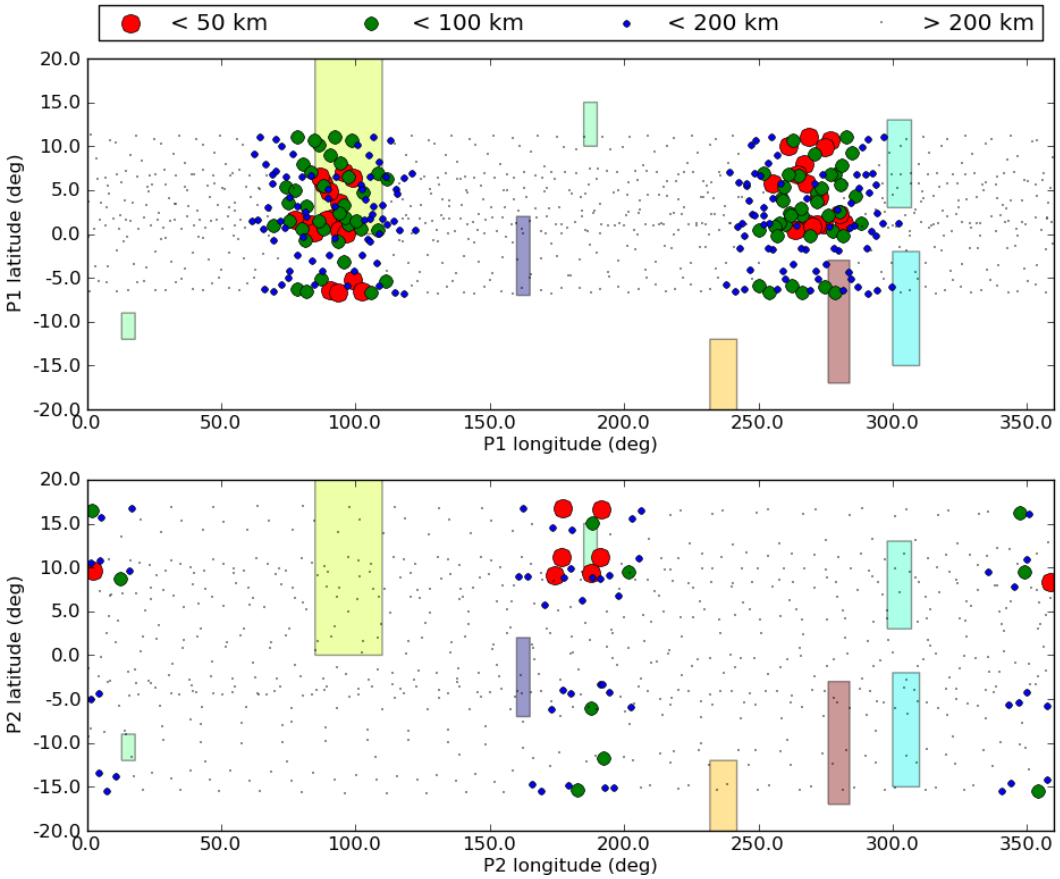
- Once burn periapsis, duration, and number of segments were selected, numerical optimization handled segment design

Science Opportunity: Wake Measurements



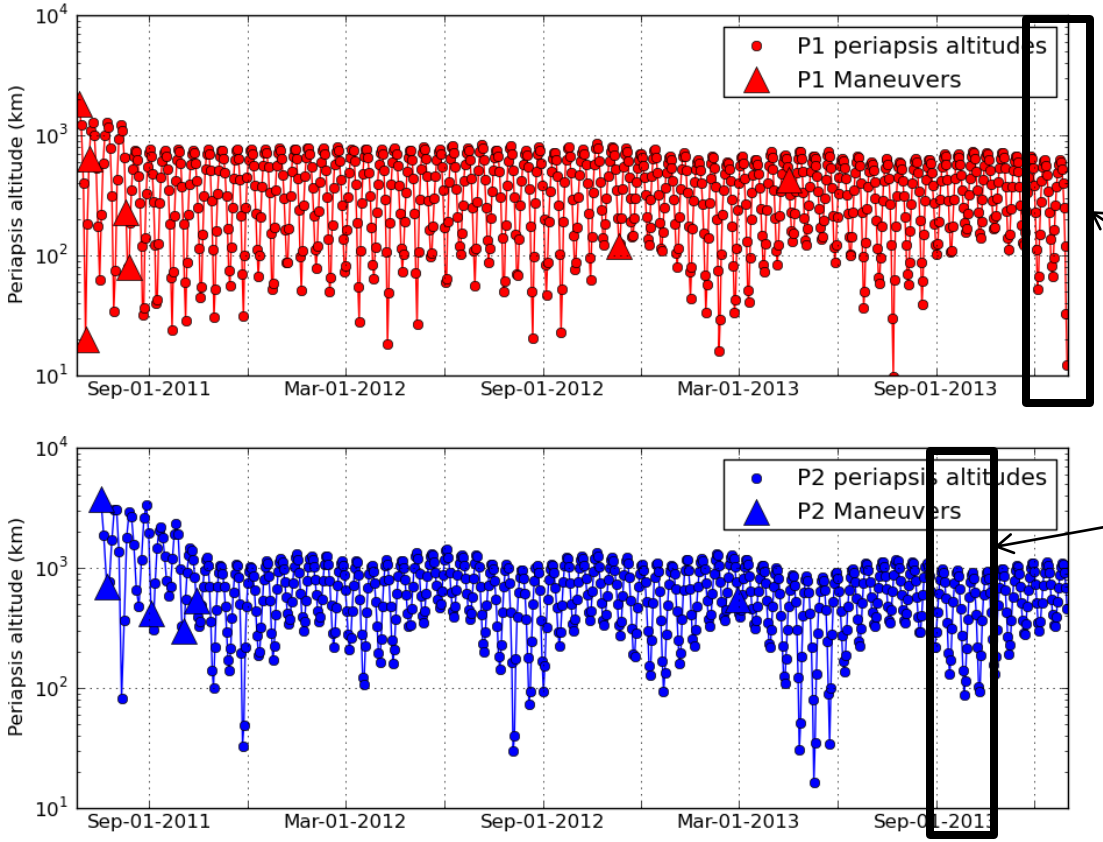
- Primary heliophysics measurement type
- Each point shows the X-Z plane crossing in the Sun-Moon rotating frame
  - Science actually conducted over an arc within and around the wake
- Wide variety of relative and absolute orientations

Science Opportunity: Magnetic Anomaly Characterization



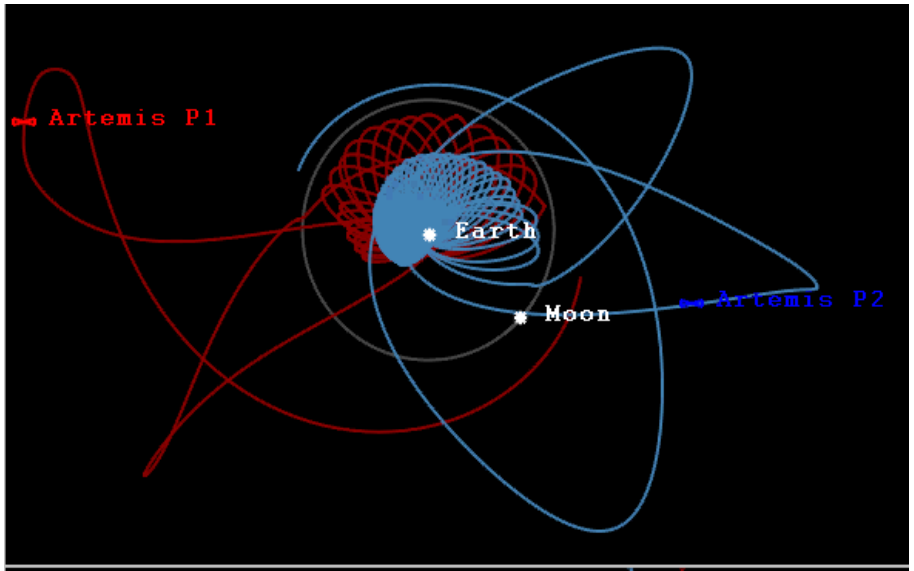
- Sub-50 km flyovers used to characterize lunar magnetic anomalies
- Dynamics restrict P1 to anomalies near 90, 270 deg longitude, P2 to near 0, 180 deg
  - P2 has fewer opportunities due to higher inclination and stronger solar perturbation

Science Opportunity: Exosphere Measurements and alignment with LADEE

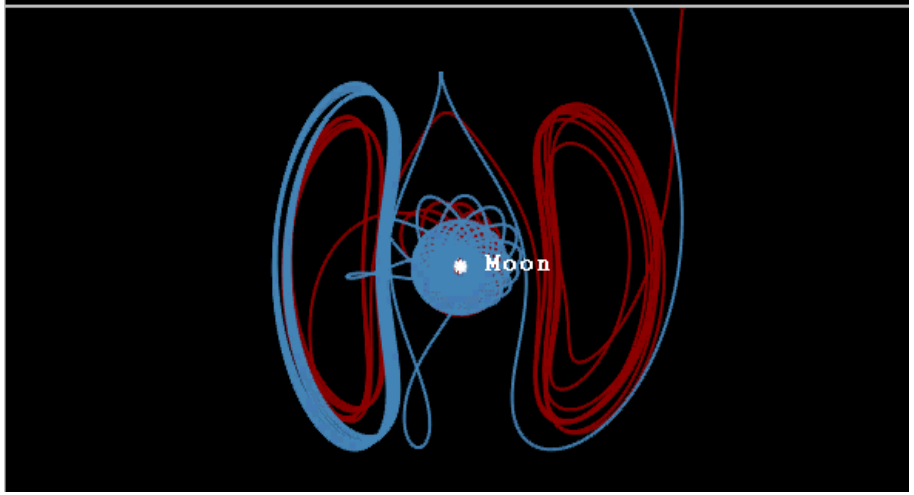


- Exosphere measurements are taken at a range of altitudes from 100 km and up at a range of local solar times
- To align ARTEMIS such that periapsis is near the dawn terminator during the LADEE mission was tricky
  - But done with correct approach from Lissajous and modification of the precession rate for P2

Current Status and Concluding Remarks



To Sun



To Earth

- Current Status:
  - P1: Successfully executed LOI, PRM-1, and PRM-2
    - 6% hot LOI execution errors necessitated PRM sequence redesign
    - PEB-1 scheduled for Aug. 3, PRM-3 scheduled for Aug. 12
  - P2: Successfully executed LOI and PRM-1
    - PRM-2 scheduled for Sept 2
- The ARTEMIS lunar orbit phase has the potential to deliver a wealth of science data
  - Already being collected, listen for results!
- BIG thanks to the ARTEMIS ops team at Berkeley for performing over 100(!) maneuvers over 2 years to get us here