LunarCube
Transfer Trajectory Options

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Introduction

- Numerous Earth-Moon (EM) trajectory and lunar orbit options are available for LunarCube missions
- Our investigation of potential trajectories highlights several transfer and lunar capture scenarios
  - Low Earth orbit (LEO); Geostationary transfer orbits (GTO); Higher energy direct lunar transfer orbits (EM-1)
  - Lunar elliptical and circular orbits with minimal capture requirements
  - Yield a wide range of transfer durations, fuel requirements, and final destinations including Sun-Earth and Earth-Moon libration orbits, and heliocentric designs
- Given the limited injection infrastructure, many designs are contingent upon the modification of an initial condition of the injected or deployed orbit
- Restricted by subsystems selection such as propulsion or communication
- Application Earth-Moon dynamical system design approach
  - Apply natural trajectory flow and take advantage of system perturbations
  - For missions with an intended lunar orbit, much of the design process is spent optimizing a ballistic capture
Introduction

• Trajectory - Propulsion trades drive many mission design options
  o Both low and high-thrust transfers are feasible assuming sufficient power or fuel mass
• For the EM-1 injected initial design, modify the lunar flyby distance to alter the system energy, matching that of a typical Sun-Earth system heteroclinic manifold
  o Option uses dynamics similar to the ARTEMIS mission design
  o Manifold and maneuvers raise perigee to that of a lunar orbit, adjust the timing wrt the Moon, rotate the line of apsides, and target a ballistic lunar encounter.
  o Orbital energy (C3) with respect to the Moon is targeted to < -0.1 km²/s²
• LEO or GTO design options use impulsive maneuvers to phase onto a local Earth-Moon manifold, which then transfers LunarCube to a lunar encounter
• Investigation concludes with several design options which provide estimated ΔV requirements, achieved lunar orbit parameters, and associated transfer trajectory information
• The use of Goddard’s dynamical systems mission design tool, Adaptive Trajectory Design (ATD), and operational software (GMAT, Astrogator) are utilized to generated results
Constraints

Low thrust and impulsive maneuvers concepts
- Low thrust level investigated vary from $\mu$N to mN,
  - Limits the control authority and trajectory modifications
  - Power limited, with power < 100W(?)
- Attitude control and pointing constraints may impede use or drive designs
- Impulsive designs drive fuel mass, deterministic $\Delta V$s, or timing

Launch vehicle and related primary trajectories
- Secondary payloads cannot drive primary mission goals but can provide a minimal cost approach
- Constrain the mission design wrt launch/ injection parameters
  - Injection energy can vary over launch period or window
  - Number of launch opportunities can be limited
- Three injection options limitations
  - LEO – launch dates, inclination and accelerations (Nodal precession and atmospheric drag)
  - GTO – launch dates and line of apsides alignment
  - EM-1 – launch dates, varying injection energy over window, unknown trajectory (apoapsis) direction
Dynamical Systems Theory

• Describes long-term qualitative behavior of complex dynamical systems
• Employs differential equations (continuous) / difference equations (discrete) to model system behavior
• Nonlinearity lead to complexity but not necessarily a loss of predictability.
• Focus not on precise solutions, but on general exploration of space (periodic orbits, quasi-periodic motion, chaos, …)

- Poincaré maps and invariant manifolds useful to locate long-term capture trajectories about the smaller primary in CR3BP
Circular Restricted Three-Body Problem

- Simplified model, autonomous system
- Provides useful information about fundamental solutions (libration point orbits, stable/unstable invariant manifolds, retrograde orbits, ...)
- Solutions from CR3BP transitioned to ephemeris model, generally, maintain orbit characteristics

The ARTEMIS Connection

- In 2009, two small spacecraft were transferred from low elliptical Earth orbits to lunar elliptical orbits
  - Use of a dynamical system (manifold) approach with numerical targeting
  - Lower thrust propulsion system (4N) with constrained thrust direction on a spinning spacecraft
  - Orbit-Raising maneuvers performed near periapsis to raise apoapsis to lunar distance
  - Lunar Gravity Assists (LGAs) to align trajectory for Earth-moon libration insertion and to raise periapsis
The ARTEMIS Connection - Manifolds

• In an ARTEMIS example, consider only the outbound arc of P1
• Follow the original outbound path to the location of a correction maneuver which shifted the spacecraft onto a different path, (orange) manifold
• Subsequent to and along the outbound trajectory two outbound manifold arcs emerge
• Represent potential outcomes from flow along the optimal path and the alternative that incorporates a possible correction maneuver
Deployment options

- The local Earth-Moon manifold has a particular geometry and design that is based on the Earth and moon dynamics (CRTB).
- This manifold as illustrated provides a background on the types of trajectories desired for a natural flow towards either the moon or the Earth-Moon libration point orbits, EML₁ or EML₂.
- The premise is that a spacecraft is inserted onto an intermediate orbit which asymptotically converges onto the manifold or intersects with the manifold.
- A manifold matching DV places the spacecraft onto one of the manifold trajectories which then flows to the region of lunar interest.

Figure 8. Example of Earth-Moon Local Manifold
• Initial orbit assumed 200 km LEO Final lunar orbit 1000 km,
• Trajectories designed using ATD©
GTO to the Moon

- Initial orbit assumed 200 km, 24 deg inclination, LEO Final lunar orbit 1000 km,
- Trajectories designed using ATD©
- Insertion from GTO Peripais and intermediate transfer reduces manifold matching DV cost

<table>
<thead>
<tr>
<th></th>
<th>Design-1 (figure 15)</th>
<th>Design-2 (figure 16)</th>
<th>Design-3 (figure 17)</th>
<th>Design-4 (figure 18)</th>
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<tbody>
<tr>
<td>DV 1 (m/s)</td>
<td>2507</td>
<td>676</td>
<td>719</td>
<td>679</td>
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<td>DV 2 (m/s)</td>
<td>0</td>
<td>0</td>
<td>824</td>
<td>421</td>
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<td>DV (m/s) (Lunar)</td>
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<td>731</td>
<td>517</td>
<td>598</td>
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<td>S/C DV total (m/s)</td>
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<td>1407</td>
<td>2060</td>
<td>1698</td>
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<tr>
<td>Transfer Duration (days)</td>
<td>5.4</td>
<td>4.7</td>
<td>20.3</td>
<td>16.2</td>
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</table>
Without altering the EM-1 injection energy, a LunarCube would perform a close lunar flyby and depart into heliocentric space.

Options to alter LGA energy include changing the flyby distance and orientation, permit trajectories to Sun-Earth L1/L2, Earth-moon L1/L2, and lunar orbits.

Slow down from EM-1 injection approaching lunar flyby
- Immediately after injection from EM1, thrust against velocity vector (relative to Earth) for several days.
- Option-1: Enter highly eccentric orbit around Earth and gradually raise perigee and lower apogee to approach Moon, in both orbit and phase.
- Option-2: Achieve LGA to enter onto Manifold to raise perigee and approach moon.
- Thrust against velocity vector (relative to Moon) to capture/spiral into a distant lunar orbit or change elliptical eccentricity.

Speed Up from EM-1 injection approaching lunar flyby
- Immediately after injection from EM1, thrust along velocity vector (relative to Earth).
- Achieve LGA to insert into a highly eccentric Earth orbit, with inclination close to Moon orbit.
- Raise perigee and lower apogee to approach Moon, in both orbit and phase.
- Thrust against velocity vector (relative to Moon) to capture/spiral into a distant lunar orbit or change elliptical eccentricity.
EM-1 to the Moon, A low Thrust Option

Transfer Trajectory with Low Thrust
(Sun-Earth Rotating Coordinate Frame)

- Launch Dec 15, 2017
- Lunar Capture in ~ 231 days
- Total DV of ~ 869 m/s
EM-1 to the Moon, A low Thrust Option

- Launch Dec 15, 2017
- Lunar Capture in ~ 171 days
- Total DV of ~ 1554 m/s
Other options to maintain apoapsis near lunar orbit distance and then raise periapsis for a minimal lunar orbit capture.
## Lunar Cube Transfer Trajectory Options
### Sample EM-1 Transfer Comparisons

<table>
<thead>
<tr>
<th>Related Fig</th>
<th>Decreased Velocity</th>
<th>Decreased Velocity</th>
<th>Decreased Velocity</th>
<th>Increased Velocity</th>
<th>Increased Velocity</th>
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<tbody>
<tr>
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<td>12</td>
<td>Need</td>
<td>12</td>
<td>Need</td>
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<td>Thrust Level (mN)</td>
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<td>Total DV (m/s)</td>
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<td>Transfer DV (m/s)</td>
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<td>190</td>
<td>1082</td>
<td>557</td>
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<td>Lunar Capture DV (m/s)</td>
<td>196</td>
<td>439</td>
<td>41</td>
<td>1038</td>
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<td>Lunar Flyby Radius (km)</td>
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<td>5025</td>
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<td>6318</td>
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<td>Max Transfer Range (Km)</td>
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<td>1,719,925</td>
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<td>Total Transfer Duration to Capture (days)</td>
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<td>250</td>
<td>41</td>
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<td>Lunar Capture Duration (days)</td>
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<td>Maximum Lunar Eclipse Duration (hrs)</td>
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<td>Lunar Orbit apoapsis x periapsis (km)</td>
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<td>tbd</td>
<td>350 x 50</td>
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<tr>
<td>Lunar Orbit Inclination (deg)</td>
<td>20</td>
<td>144</td>
<td>32</td>
<td>165</td>
<td>139</td>
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Lunar Missions

A variety of lunar science orbits can be achieved from any of these analyzed transfers

• Low thrust capture and insertion using a ballistically captured lunar orbit
• Perform an alignment of periapsis (apsides) with science goals
• Target a given periapsis altitude or periapsis decay over time
• Target various eccentricity, semi-major axis, inclinations
• Achieve various science parameters, e.g. Solar angles
Conclusions

• There are numerous Lunar Cube Transfer Trajectory Options available
• The deployment strategy, as a secondary payload, drives the available designs options
• Both low thrust and high performance propulsion systems can be used
  o High thrust can result in mass / volume considerations
  o Low thrust ranging from $\mu$-N to m-N can augment the trajectory given the proper initial conditions
  o Power level will drive low thrust capabilities and the ensuing trajectory design
• Transfer and lunar capture into science orbit durations can be time-consuming
• Use of dynamical systems, aka manifolds, can aid in the design and provide an intuitive approach in addition to optimization
• Combining dynamical systems techniques with high or low thrust propulsion systems provides versatile, efficient techniques for transfers to the Moon, especially for low-thrust options on high energy deployment trajectories.
• With a lower cost and many secondary payload opportunities, Lunar Cubes can be the next step for flexible trajectory designs, to the Moon and beyond