LunarCube
Transfer Trajectory Options

David Folta, NASA Goddard Space Flight Center
Donald Dichmann, NASA Goddard Space Flight Center
Pamela Clark, Catholic University
Amanda Haapala, Purdue University
Kathleen Howell, Purdue University
• 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
  o Low Earth orbit (LEO); Geostationary transfer orbits (GTO); Higher energy direct lunar transfer orbits (EM-1)
  o Lunar elliptical and circular orbits with minimal capture requirements
  o 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
  o Apply natural trajectory flow and take advantage of system perturbations
  o 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
  - 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
  - Option uses dynamics similar to the ARTEMIS mission design
  - 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.
  - Orbital energy (C3) with respect to the Moon is targeted to \(< -0.1 \text{ km}^2/\text{s}^2\)
- 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 \(\Delta V\) 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 $< 100$W

- 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

** Images from Haapala, Vaquero, Pavlak, Howell, and Folta, AAS/AIAA Astrodynamics Specialist Conference, 2013.**
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

P1 Planned Stable Sun-Earth

P1 Pre and Post TCM5 Stable Sun-Earth Manifold
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, EML$_1$ or EML$_2$.
- 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.

![Example of Earth-Moon Local Manifold](image_url)
LEO to the Moon

- Initial orbit assumed 200 km LEO Final lunar orbit 1000 km,
- Trajectories designed using ATD©

<table>
<thead>
<tr>
<th></th>
<th>Design-1 (figure 9)</th>
<th>Design-2 (figure 10)</th>
<th>Design-3 (figure 11)</th>
<th>Design-4 (figure 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion DV (m/s)</td>
<td>3137</td>
<td>3047</td>
<td>3046</td>
<td>3099</td>
</tr>
<tr>
<td>DV 1 (m/s)</td>
<td>500</td>
<td>553</td>
<td>1183</td>
<td>899</td>
</tr>
<tr>
<td>DV 2 (m/s)</td>
<td>192</td>
<td>192</td>
<td>507</td>
<td>524</td>
</tr>
<tr>
<td>S/C DV total (m/s)</td>
<td>692</td>
<td>745</td>
<td>1690</td>
<td>1423</td>
</tr>
<tr>
<td>Manifold duration (days)</td>
<td>10</td>
<td>27</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td>Transfer Duration (days)</td>
<td>13</td>
<td>30</td>
<td>27</td>
<td>36</td>
</tr>
</tbody>
</table>

25th AAS/AIAA Space Flight Mechanics Meeting, Jan 11-15, 2015, Williamsburg, VA
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>
</tr>
</thead>
<tbody>
<tr>
<td>DV 1 (m/s)</td>
<td>2507</td>
<td>676</td>
<td>719</td>
<td>679</td>
</tr>
<tr>
<td>DV 2 (m/s)</td>
<td>0</td>
<td>0</td>
<td>824</td>
<td>421</td>
</tr>
<tr>
<td>DV (m/s) (Lunar)</td>
<td>593</td>
<td>731</td>
<td>517</td>
<td>498</td>
</tr>
<tr>
<td>S/C DV total (m/s)</td>
<td>3100</td>
<td>1407</td>
<td>2060</td>
<td>1698</td>
</tr>
<tr>
<td>Transfer Duration (days)</td>
<td>5.4</td>
<td>4.7</td>
<td>20.3</td>
<td>16.2</td>
</tr>
</tbody>
</table>
EM-1 to the Moon

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

• Speed Up from EM-1 injection approaching lunar flyby
  o Immediately after injection from EM1, thrust along velocity vector (relative to Earth)
  o Achieve LGA to insert into a highly eccentric Earth orbit, with inclination close to Moon orbit.
  o Raise perigee and lower apogee to approach Moon, in both orbit and phase
  o Thrust against velocity vector (relative to Moon) to capture / spiral into a distant lunar orbit
  o 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></th>
<th>Decreased Velocity</th>
<th>Decreased Velocity</th>
<th>Decreased Velocity</th>
<th>Increased Velocity</th>
<th>Increased Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Related Fig</strong></td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td><strong>Initial Mass (kg)</strong></td>
<td>9</td>
<td>12</td>
<td>Need</td>
<td>12</td>
<td>Need</td>
</tr>
<tr>
<td><strong>Thrust Level (mN)</strong></td>
<td>0.5</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total DV (m/s)</strong></td>
<td>869</td>
<td>629</td>
<td>1314</td>
<td>1595</td>
<td>1141</td>
</tr>
<tr>
<td><strong>Transfer DV (m/s)</strong></td>
<td>673</td>
<td>190</td>
<td>1082</td>
<td>557</td>
<td>860</td>
</tr>
<tr>
<td><strong>Lunar Capture DV (m/s)</strong></td>
<td>196</td>
<td>439</td>
<td>41</td>
<td>1038</td>
<td>25</td>
</tr>
<tr>
<td><strong>Lunar Flyby Radius (km)</strong></td>
<td>6763</td>
<td>5025</td>
<td>4696</td>
<td>2510</td>
<td>6318</td>
</tr>
<tr>
<td><strong>Max Transfer Range (Km)</strong></td>
<td>1,524,000</td>
<td>1,719,925</td>
<td>447,959</td>
<td>1,154,950</td>
<td>467,698</td>
</tr>
<tr>
<td><strong>Total Transfer Duration to Capture (days)</strong></td>
<td>231</td>
<td>250</td>
<td>41</td>
<td>171</td>
<td>214</td>
</tr>
<tr>
<td><strong>Lunar Capture Duration (days)</strong></td>
<td>60</td>
<td>27</td>
<td>11</td>
<td>65</td>
<td>15</td>
</tr>
<tr>
<td><strong>Maximum Lunar Eclipse Duration (hrs)</strong></td>
<td>1.0</td>
<td>4.6</td>
<td>0.9</td>
<td>4.0</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Lunar Orbit apoapsis x periapsis (km)</strong></td>
<td>6800 x 100</td>
<td>9993 x 1545</td>
<td>tbd</td>
<td>350 x 50</td>
<td>tbd</td>
</tr>
<tr>
<td><strong>Lunar Orbit Inclination (deg)</strong></td>
<td>20</td>
<td>144</td>
<td>32</td>
<td>165</td>
<td>139</td>
</tr>
</tbody>
</table>
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
  - High thrust can result in mass / volume considerations
  - Low thrust ranging from μ-N to m-N can augment the trajectory given the proper initial conditions
  - 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