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
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
  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
  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 $< 100$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)
• Deterministic system, yet nonlinearity leads to loss of predictability
• Focus not on precise solutions, but on general exploration of space (periodic orbits, quasi-periodic motion, chaos, …)

Dynamical Systems Theory

• 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

4th International Workshop on LunarCubes, October 7-10, 2014 Sunnyvale, CA.
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

4th International Workshop on LunarCubes, October 7-10, 2014 Sunnyvale, CA.
LEO to the Moon

LEO to EML2 via manifold

LEO to moon via manifold

<table>
<thead>
<tr>
<th>Maneuvers</th>
<th>Stable Manifold (41.6 days)</th>
<th>Direct w/ Lunar Assist (18.27 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Vehicle $\Delta v$</td>
<td>3.047 km/s</td>
<td>3.137 km/s</td>
</tr>
<tr>
<td>$\Delta v_1$</td>
<td>552.9 m/s</td>
<td>500.0 m/s</td>
</tr>
<tr>
<td>$\Delta v_2$</td>
<td>0.192 m/s</td>
<td>587.7 m/s</td>
</tr>
<tr>
<td>$\Delta v$ Required</td>
<td>553.092 m/s</td>
<td>1087.7 m/s</td>
</tr>
</tbody>
</table>

Initial orbit assumed 200 km LEO
Final lunar orbit 1000 km

Trajectories designed using ATD©

4th International Workshop on LunarCubes, October 7-10, 2014 Sunnyvale, CA.
GTO to the Moon

Initial orbit assumed 200 km perigee GTO
Final lunar orbit 1000 km

Maneuvers  Transfer from GTO (18.85 days)
\( \Delta v_1 \) 2.503 km/s
\( \Delta v_2 \) 80.81 m/s
\( \Delta v_3 \) 565.95 m/s
\( \Delta V \text{ Required} \) 3.150 km/s

4th International Workshop on LunarCubes, October 7-10, 2014 Sunnyvale, CA.
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
  - 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

4th International Workshop on LunarCubes, October 7-10, 2014 Sunnyvale, CA.
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.

<table>
<thead>
<tr>
<th></th>
<th>Slow down</th>
<th>Speed up</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injection date</strong></td>
<td>15-Dec-2017</td>
<td>15-Dec-2017</td>
</tr>
<tr>
<td><strong>Science orbit insertion</strong></td>
<td>6-Aug-2018</td>
<td>31-Jul-2018</td>
</tr>
<tr>
<td><strong>Transfer time (days)</strong></td>
<td>234</td>
<td>228</td>
</tr>
<tr>
<td><strong>Delta-V (m/sec)</strong></td>
<td>1142</td>
<td>1315</td>
</tr>
</tbody>
</table>
### Lunar Cube Transfer Trajectory Options

#### Sample EM-1 Transfer Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Example-1</th>
<th>Example-2</th>
<th>Example-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Mass (Kg)</td>
<td>9</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Thrust Level (mN)</td>
<td>0.4</td>
<td>0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Total DV (m/s)</td>
<td>869</td>
<td>665</td>
<td>1595</td>
</tr>
<tr>
<td>Transfer DV (m/s)</td>
<td>673</td>
<td>305</td>
<td>557</td>
</tr>
<tr>
<td>Lunar Cap DV (m/s) over 180 days</td>
<td>196</td>
<td>360</td>
<td>1038</td>
</tr>
<tr>
<td>Lunar Flyby Radius (km) (EM1 nominal = 3065)</td>
<td>6763</td>
<td>6911</td>
<td>2510</td>
</tr>
<tr>
<td>Max Transfer Range (km)</td>
<td>1,524,000</td>
<td>1,525,250</td>
<td>1,154,950</td>
</tr>
<tr>
<td>Total Transfer Duration (days) to Capture</td>
<td>231</td>
<td>257</td>
<td>171</td>
</tr>
<tr>
<td>Transfer Duration from Return Lunar Encounter to Capture (days)</td>
<td>60</td>
<td>66</td>
<td>65</td>
</tr>
<tr>
<td>Total # of Low Thrust Maneuvers</td>
<td>6</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>Duration of Transfer Trajectory Low Thrust Arcs (days)</td>
<td>131</td>
<td>71*</td>
<td>112</td>
</tr>
<tr>
<td>Maximum Eclipse Duration (hrs) (Lunar Eclipse)</td>
<td>1</td>
<td>2.7</td>
<td>4</td>
</tr>
<tr>
<td>Lunar Orbit (Km) after 180 Days of Thrusting (Apoapsis x Periapsis)</td>
<td>6800 x 100</td>
<td>12000 x 1300</td>
<td>350 x 50</td>
</tr>
<tr>
<td>Lunar Orbit Inclination (deg)</td>
<td>20</td>
<td>25 (155)</td>
<td>165</td>
</tr>
</tbody>
</table>
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 low thrust propulsion systems versatile, efficient techniques for low-energy transfer to the Moon are achieved

Lunar Cubes are the Next Step for Flexible Trajectory Designs, to the Moon and Beyond

4th International Workshop on Lunar Cubes, October 7-10, 2014 Sunnyvale, CA.