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
  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 \( \mu \text{N} \) to \( \text{mN} \),
  - 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)
- 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, …)

**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
  o Use of a dynamical system (manifold) approach with numerical targeting
  o Lower thrust propulsion system (4N) with constrained thrust direction on a spinning spacecraft
  o Orbit-Raising maneuvers performed near periapsis to raise apoapsis to lunar distance
  o Lunar Gravity Assists (LGAs) to align trajectory for Earth-moon libration insertion and to raise periapsis

P1 Design

P2 Design

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
LEO to the Moon

LEO to EML2 via manifold

\[ \Delta v_1 = 552.9 \text{ m/s} \]

\[ \Delta v = 3.047 \text{ km/s} \]

\[ \Delta v_2 = 0.192 \text{ m/s} \]

LEO to moon via manifold

\[ \Delta v_2 = 587.7 \text{ m/s} \]

\[ \Delta v_1 = 500.0 \text{ m/s} \]

\[ \Delta v = 3.137 \text{ km/s} \]

Trajectories designed using ATD©

<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>1087.7m/s</td>
</tr>
</tbody>
</table>

Initial orbit assumed 200 km LEO
Final lunar orbit 1000 km

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

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

4.40 days
14.45 days

Maneuvers

<table>
<thead>
<tr>
<th>Maneuvers</th>
<th>Transfer from GTO (18.85 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta v_1$</td>
<td>2.503 km/s</td>
</tr>
<tr>
<td>$\Delta v_2$</td>
<td>80.81 m/s</td>
</tr>
<tr>
<td>$\Delta v_3$</td>
<td>565.95 m/s</td>
</tr>
<tr>
<td>$\Delta V$ Required</td>
<td>3.150 km/s</td>
</tr>
</tbody>
</table>

$\Delta v_1 = 2.503$ km/s
$\Delta v_2 = 80.81$ m/s
$\Delta v_3 = 565.95$ m/s

$\Delta V$ Required

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

Lunar Capture with Low Thrust
(Lunar Inertial Coordinate Frame)

Final Science Orbit (Red)
Coast arc (Blue)
Low Thrust Periapsis arc (green)
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>Injection date</td>
<td>15-Dec-2017</td>
<td>15-Dec-2017</td>
</tr>
<tr>
<td>Science orbit insertion</td>
<td>6-Aug-2018</td>
<td>31-Jul-2018</td>
</tr>
<tr>
<td>Transfer time (days)</td>
<td>234</td>
<td>228</td>
</tr>
<tr>
<td>Delta-V (m/sec)</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 $\mu$-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