Orbital Operations for Phobos and Deimos Exploration

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Phobos Orbital Environment

• Dominated by Martian Tides
  – Clohessy-Wiltshire (CW) equations
  – Circular-Restricted Three-Body Problem (CR3BP)

• Perturbations
  – Non-spherical gravity field of Phobos
  – Non-circular Phobos orbit about Mars
  – Solar radiation pressure
  – “3rd body” gravity (Sun, Jupiter)
  – Orbit Determination errors
  – Maneuver execution errors

• Full-dynamic integrations
Leading/Trailing Hover

• Place a spacecraft directly behind Phobos.
• Phobos gravity increases the spacecraft orbital velocity, raising semi-major axis (relative to Mars), causing the spacecraft to fall back.
• Two maneuvers required to bring the spacecraft back the original station.

<table>
<thead>
<tr>
<th>Duration</th>
<th>Fuel Used</th>
<th>Min Alt</th>
<th>Max Alt</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 day</td>
<td>59 m/s/day</td>
<td>15.3 km</td>
<td>27 km</td>
</tr>
<tr>
<td>0.4 day</td>
<td>39 m/s/day</td>
<td>10.3 km</td>
<td>122 km</td>
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<tr>
<td>0.6 day</td>
<td>27 m/s/day</td>
<td>9.6 km</td>
<td>570 km</td>
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</table>
Other Hovers

Pole Hover

- In CW equations, a spacecraft above the pole of Phobos will experience harmonic motion into and out of the plane.
- Must essentially move the longitude of the node ahead and behind Phobos in its orbital track.
- 86 m/s/day required to hover 20 km above the pole, neglecting Phobos’s gravity, which only make it worse.

Sub-Mars Hover

- In CW equations, a spacecraft between Phobos and Mars will drift ahead of Phobos before rising above it and falling back. (the 2x1 ellipse).
- To remain at the sub-Mars point, the spacecraft must accelerate continuously to effectively reduce Mars’s gravity so that the orbital rate matches that of Phobos.
- 315 m/s/day to hover at 20 km altitude, neglecting Phobos gravity.
- Closer? Use the CR3BP
CR3BP Solutions

Periodic Orbits in “Ideal” Model
(Circular Restricted 3-Body Problem)

Lyapunov Orbits \textit{unstable}

Halo Orbits \textit{unstable}

Vertical Orbits \textit{unstable}

“Distant” Retrograde Orbits \textit{stable}
Stability vs. Altitude

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13 August 2012
Full Propagations (1)

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Lyapunov Orbit

Height above Phobos over Time

View from Above

View toward Mars

View from Side
Full Propagations (2)
Full Propagations (3)

Height above Phobos over Time

Halo Orbit

View from Above

View toward Mars

View from Side

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Halo Orbit Stability

- 1 mm/s disturbance causes the spacecraft to depart on the unstable manifold.
- This could be used to go to the surface for very little fuel.
Vertical Orbit Maintenance Requirements

- Lagrange-Point orbits require precision navigation and frequent, precise maneuvering.

- Navigation:
  - 100 m is comparable to radiometric-only data
  - 0.1 m to 1.0 m are achievable with optical navigation

- Maneuvering:
  - On-board maneuver design and execution (autonomy or astronaut control) is probably required for these frequencies.

<table>
<thead>
<tr>
<th>m/s/day for Vertical orbit maintenance</th>
<th>0.5 hours</th>
<th>1.0 hour</th>
<th>1.5 hours</th>
<th>2.0 hours</th>
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<tbody>
<tr>
<td>Position Error: 0.1 m</td>
<td>0.22</td>
<td>0.17</td>
<td>0.29</td>
<td>0.73</td>
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<tr>
<td>Position Error: 1.0 m</td>
<td>0.25</td>
<td>0.22</td>
<td>0.35</td>
<td>1.0</td>
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<tr>
<td>Position Error: 10 m</td>
<td>1.3</td>
<td>1.0</td>
<td>1.9</td>
<td>N/A</td>
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<tr>
<td>Position Error: 100 m</td>
<td>13.8</td>
<td>9.8</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Orbiting

- Direct orbits do not exist.
  - Phobos sphere of influence is below the surface!
- Distant Retrograde Orbits (DRO) or Quasi-Satellite Orbits (QSO) exist and are very stable.
Potential Concepts of Operations

DRO + Halo

- DRO staging/home orbit
- Transition to Halo: 10-20 m/s
- Excursion craft descends to surface near sub-Mars point on unstable manifold
- “Mothership” remains in Halo orbit for constant communication: 0.08 m/s every two hours to remain within 8 km of surface.

DRO + Leading Hover

- DRO staging/home orbit
- Transition to leading-face hover: 13 m/s
- Excursion craft descends to surface near leading face
- “Mothership” remains on leading-face hover for constant communication: 6 m/s every two hours to remain within 30 km of surface.
Conclusions

• Lagrange-Point orbits exist in Mars-Phobos and Mars-Deimos systems
  – Frequent, precise navigation and control required to maintain
  – Within current state-of-the-art
• DRO/QSO orbits are stable
  – Can get very close to the surface
  – Offer options for staging
• Transitioning between these orbit types is possible for modest propellant cost
Any Questions?