Identifying Accessible Near-Earth Objects for Crewed Missions with Solar Electric Propulsion

Stijn De Smet
Jeffrey S. Parker
Jonathan F.C. Herman
Jonathan Aziz

Colorado Center for Astrodynamics Research
University of Colorado at Boulder

Brent W. Barbee
Jacob A. Englander

NASA Goddard Space Flight Center
Motivation

- Growing interest in human exploration of Near-Earth Objects (NEOs)
- Crucial step in designing crewed missions to NEOs is identification of good targets
- Near-earth object Human space flight Accessible Targets Study (NHATS)
  - Only for chemical trajectories
  - Low thrust options were not considered because of computational cost
- This research lays some of the foundation for expanding the NHATS study with solar electric propulsion

Source: http://neo.ssa.esa.int/
NHATS background

- Identify all feasible trajectories to NEAs to all asteroids in time frame 2015-2040

- Requirements:
  - Total mission $\Delta V \leq 12 \text{ km/s}$
  - Mission duration $\leq 450 \text{ days}$
  - Stay time $\geq 8 \text{ days}$
  - Re-entry velocity $\leq 12 \text{ km/s at 125 km}$

- Trajectory design: Lambert solver

- Highly automated system: automatically re-computes trajectories for asteroid when ephemeris of asteroid is updated, as well as automatically computing trajectories for newly discovered asteroids
Goal

- To identify attractive rendezvous missions with NEAs using solar electric propulsion

- Compare those attractive SEP rendezvous trajectories with the chemical trajectories
  - Comparison is complicated by different nature of chemical and SEP trajectories
Chemical trajectories are ranked based on total mission $\Delta V$
- SEP operates on longer time scales $\rightarrow$ also at kinematically inefficient points (gravity losses) $\rightarrow$ higher $\Delta V$
- SEP has higher $I_{sp}$ $\rightarrow$ less propellant mass for same $\Delta V$

→ Unfair to only compare on total mission $\Delta V$

Comparison will be made based on initial mass in low-Earth orbit (IMLEO)

For same payload mass, increasing IMLEO for chemical systems leads to higher achievable $\Delta V$, increasing mission opportunities
- SEP systems can only expel certain amount of propellant in certain time frame dependent on power of system
- Increasing IMLEO / propellant mass does not always result in more mission opportunities

→ Power largely influences the comparisons
Method

- Use chemical trajectories to estimate lower bound on required power for each SEP trajectory
  - Use this information as filter for SEP trajectories to avoid running clearly infeasible trajectories

- Implement SEP & optimize trajectories
  - Using chemical trajectory design variables as initial guess

- Compute IMLEO for both SEP and chemical trajectories and compute their difference
Method – filtering of 2000 SG344
- Sims-Flanagan based modeling
- Model low-thrust by small impulsive burns
- Control nodes at planetary / NEO encounters
- Matchpoint constraints for continuous trajectory
- Solved using SNOPT

Adapted from Sims et al., 2006
Assumptions for SEP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass-to-power ratio</td>
<td>30 kg/kW</td>
</tr>
<tr>
<td>Jet efficiency</td>
<td>60%</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>90%</td>
</tr>
<tr>
<td>Chemical specific impulse</td>
<td>450 s</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>2000 s</td>
</tr>
</tbody>
</table>

Derived from NHATS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum re-entry velocity</td>
<td>12 km/s</td>
</tr>
<tr>
<td>Maximum total mission duration</td>
<td>450 days</td>
</tr>
</tbody>
</table>
Trajectory example

- Earth orbit
- Asteroid orbit

Thrust [N] vs Flight time [days]

Leg 1
Leg 2
Asteroid: 2000 SG344
Power: 50 kW

Chemical, 120 tons for 370 days
SEP, 115.1 tons for 370 days
5-40 tons of savings
Asteroid: 2015 BM510
Power: 150 kW

Results

Chemical, 236 tons for 386 days
180-270 tons of savings
SEP, 151.1 tons for 450 days
2 SLS 4xRL LEO capability
3 SLS 4xRL LEO capability
2004 VJ1 - 150 kW: similar to 2015 BM510: could be launched with 2 SLS 4xRL10, its chemical counterpart needs at least 3 SLS 4xRL10

Also scenarios with 300 kW have been investigated

- Launch window for 3 SLS 4xRL10 with SEP allows for smaller TOF’s than chemical
Conclusion on research

- SEP can be used to significantly enhance crewed NEO rendezvous missions
  - Initial mass in LEO can be reduced
  - Launch periods can be extended
  - Additional mission opportunities become available
  - TOFs can be reduced

- These benefits are not achievable with traditional impulsive maneuvers

- Results presented here suggest that many other targets in the asteroid population would enjoy similar performance improvements through the use of SEP
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Extra slides
Rough guess for required spacecraft power is

\[ P_0 = \frac{\Delta V \cdot m_{\text{avg}} \cdot I_{\text{sp}} \cdot g_0}{2\Delta t \cdot \eta_{\text{jet}} \cdot \varepsilon_T} \]

Average mass is the average of the mass after the chemical departure burn and the mass at Earth return

\[ m_{\text{avg}} = \frac{m_{0,\text{SEP}} + M_{\text{Earth return}}}{2} = \frac{M_{\text{Earth return}}}{2} \cdot \left(1 + \exp \left(\frac{\Delta V}{I_{\text{sp}} \cdot g_0}\right)\right) \]

This gives

\[ P_0 = \frac{\Delta V \cdot m_{\text{PL}} \cdot \left(1 + \exp \left(\frac{\Delta V}{I_{\text{sp}} \cdot g_0}\right)\right) \cdot I_{\text{sp}} \cdot g_0}{4\Delta t \cdot \eta_{\text{jet}} \cdot \varepsilon_T - kP_0 \cdot \Delta V \cdot I_{\text{sp}} \cdot g_0 \left(1 + \exp \left(\frac{\Delta V}{I_{\text{sp}} \cdot g_0}\right)\right)} \]
Chemical

IMLEO = \( M_{PL} + M_{\text{chem prop}} + M_{\text{chem prop, esc}} + M_{\text{kick stage}} \)

= \( M_{PL} + M_{\text{chem prop}} + (1 + k_{KS}) \cdot M_{\text{chem prop, esc}} \)

= \( M_{PL} \cdot \exp\left( \frac{\Delta V_{\text{tot}} - \Delta V_{\text{esc}}}{I_{sp,2} \cdot g_0} \right) \cdot \left( 1 + k_{KS} \right) \cdot \exp\left( \frac{\Delta V_{\text{esc}}}{I_{sp,1} \cdot g_0} \right) - k_{KS} \)

SEP

IMLEO = \( M_{\text{Earth ret}} + M_{\text{SEP prop}} + M_{\text{chem prop, esc}} + M_{\text{kick stage}} \)

= \( M_{\text{Earth ret}} + M_{\text{SEP prop}} + (1 + k_{KS}) \cdot M_{\text{chem prop, esc}} \)

= \( \left( M_{\text{Earth ret}} + M_{\text{SEP prop}} \right) \cdot \left( 1 + k_{KS} \right) \cdot \exp\left( \frac{\Delta V_{\text{esc}}}{I_{sp,1} \cdot g_0} \right) - k_{KS} \)
Results

Asteroid: 2015 BM510
Power: 300 kW

ΔIMLEO [tons]

- Chemical, 236 tons for 386 days
- 80-500 tons of savings
- SEP, 152.1 tons for 402 days
Asteroid: 2004 VJ1
Power: 150 kW

Results

Chemical, 247 tons for 450 days
100-350 tons of savings
SEP, 156.3 tons for 450 days
Asteroid: 2004 VJ1
Power: 300 kW

Results

- Chemical, 247 tons for 450 days
- 100-550 tons of savings
- SEP, 157.6 tons for 450 days
## Summary results

### Table 3: Minimal IMLEO for the different scenarios

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Case</th>
<th>Minimal IMLEO [tons]</th>
<th>Launch date [mm-dd-yyyy]</th>
<th>TOF [days]</th>
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<tbody>
<tr>
<td>2000 SG344</td>
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<td>115.1</td>
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<td>2015 BM510</td>
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<td>151.1</td>
<td>12-18-2025</td>
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<td></td>
<td>300 kW</td>
<td>152.1</td>
<td>06-25-2025</td>
<td>402</td>
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<tr>
<td></td>
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<td>09-05-2025</td>
<td>386</td>
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<td>2004 VJ1</td>
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<td>05-16-2025</td>
<td>450</td>
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## Summary results

**Table 4: Launcher analysis**

<table>
<thead>
<tr>
<th>Launchers required</th>
<th>Asteroid</th>
<th>Case</th>
<th>Launch season [days]</th>
<th>Minimal TOF [days]</th>
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<tbody>
<tr>
<td>2 SLS 1xRL (140 tons)</td>
<td>2000 SG344</td>
<td>50 kW</td>
<td>568</td>
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<td>2015 BM510</td>
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<tr>
<td></td>
<td>2004 VJ1</td>
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<td>N.A.</td>
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</table>
Summary results

Table 4: Launcher analysis

<table>
<thead>
<tr>
<th>Launchers required</th>
<th>Asteroid</th>
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<th>Launch season [days]</th>
<th>Minimal TOF [days]</th>
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<tbody>
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<td>2 SLS 4xRL (186.2 tons)</td>
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<td>N.A.</td>
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<table>
<thead>
<tr>
<th>Launchers required</th>
<th>Asteroid</th>
<th>Case</th>
<th>Launch season [days]</th>
<th>Minimal TOF [days]</th>
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<td>3 SLS 4xRL (279.3 tons)</td>
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