Survey of Ballistic Lunar Transfers to Near Rectilinear Halo Orbit

Nathan L. Parrish, Ethan Kayser, Shreya Udupa, Jeffrey S. Parker, Bradley W. Cheetham, and Diane C. Davis
Goal: Evaluate and understand the trade space for ballistic lunar transfers from Earth launch to arrival in a near rectilinear halo orbit (NRHO).

Several favorable families were identified and studied.

Over 70,000 optimal trajectories were designed in order to understand the trade space.
Why Ballistic Lunar Transfer (BLT)?

- Assume spacecraft Isp = 300 s

- Benefits:
  - Reduced spacecraft $\Delta V$
  - Reduced operational cadence (more time between maneuvers)
  - Increased launch window
  - Secondary payloads to anywhere in cislunar space

- Trade-offs:
  - Increased time of flight (12-20 weeks)
  - Greater maximum distance from Earth can challenge comms
  - Increased operations duration
  - Potentially higher $C_3$

Bottom line: Increased mass delivered to NRHO

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### SLS Block 1 Performance

<table>
<thead>
<tr>
<th>$\Delta V$ (m/s)</th>
<th>Mass delivered to NRHO (mT)</th>
</tr>
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<tbody>
<tr>
<td>BLT</td>
<td>~25.7 mT</td>
</tr>
<tr>
<td>BLT w/ lunar flyby</td>
<td>~26.3 mT</td>
</tr>
<tr>
<td>Direct transfer</td>
<td>~23.6 mT</td>
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Introduction & Background
Background - BLTs

• Sun’s gravity causes plane change and perigee raise, taking the spacecraft from TLI to NRHO for “free”
• Deterministic ΔV opens up launch period and permits rendezvous with target
• Transfer relies on dynamics of four-body problem (Earth, Sun, Moon, spacecraft)
Background - BLTs

- Sun’s gravity perturbation affects the radius of perigee
- Effect determined by which quadrant apogee is in:
  - Quadrants II or IV raise perigee
  - Quadrants I or III lower perigee
Dynamics and Assumptions — Phase-Fixed (Gateway Rendezvous)

- Simulation engine: Copernicus Trajectory Design and Optimization System
- Force model:
  - Sun, Earth and Moon point masses, states from DE430
  - 14,000 kg spacecraft
  - SRP Area: 23 m², CR: 2.0, spherical model
  - Impulsive maneuvers
- Launch not considered — start in parking orbit at Earth
  - 100 km circular
  - 28° inclination
  - Node orientation optimized
- NRHO: 9:2 patch point from CR3BP
- Maneuvers:
  - Trans Lunar Injection (TLI): Velocity direction
  - Up to 3 Deep Space Maneuvers (DSMs)
  - NRHO Insertion near perilune with 0-rev “wind on”
- Objective: Minimize weighted sum of spacecraft ΔV and TLI ΔV (TLI ΔV included for lunar flyby cases only)
Dynamics and Assumptions — Phase-Fixed (Gateway Rendezvous)

- Simulation engine: Copernicus Trajectory Design and Optimization System
- Force model:
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  - Moon 8x8 gravity field, GRGM660PRIM model
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- Launch not considered — start in parking orbit at Earth
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- NRHO: rendezvous with reference NRHO
- Maneuvers:
  - Trans Lunar Injection (TLI): Velocity direction
  - Up to 3 Deep Space Maneuvers (DSMs)
  - Several options examined for NRHO insertion and rendezvous
- Objective: Minimize weighted sum of spacecraft ΔV and TLI ΔV
  (TLI ΔV included for lunar flyby cases only)
Results
### Analysis Overview

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<td></td>
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</table>
Many families of transfers exist.

This is a partial taxonomy.

Each of these “families” has numerous “sub-families”, many of which are practically equivalent.

See reference:

<table>
<thead>
<tr>
<th>#</th>
<th>Lunar flyby</th>
<th>Apogee quadrant</th>
<th>TLI approx. location</th>
<th># of Moon orbits between flyby &amp; insertion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>II (towards Sun)</td>
<td>Ascending node</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>II (towards Sun)</td>
<td>Descending node</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>IV (away from Sun)</td>
<td>Ascending node</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>IV (away from Sun)</td>
<td>Descending node</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Yes</td>
<td>II (towards Sun)</td>
<td>Ascending node</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>II (towards Sun)</td>
<td>Ascending node</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>Yes</td>
<td>II (towards Sun)</td>
<td>Ascending node</td>
<td>5-6</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>IV (away from Sun)</td>
<td>Ascending node</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>Yes</td>
<td>IV (away from Sun)</td>
<td>Ascending node</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>Yes</td>
<td>IV (away from Sun)</td>
<td>Ascending node</td>
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<td>11</td>
<td>Yes</td>
<td>II (towards Sun)</td>
<td>Descending node</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>Yes</td>
<td>II (towards Sun)</td>
<td>Descending node</td>
<td>5</td>
</tr>
<tr>
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<td>Yes</td>
<td>IV (away from Sun)</td>
<td>Descending node</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>Yes</td>
<td>IV (away from Sun)</td>
<td>Descending node</td>
<td>5</td>
</tr>
<tr>
<td>16</td>
<td>Yes</td>
<td>IV (away from Sun)</td>
<td>Descending node</td>
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Phase-Free BLTs - TLI near Ascending Node

Launch away from the Sun
Launch towards the Sun

Earth Departure Epoch
Phase-Free BLTs

Launch into quadrant IV  
(away from Sun)

Launch dates: 
March 30, 2024 – May 9, 2024

Family repeats every synodic month

Transfer time 85-125 days
Phase-Free BLTs

Launch into quadrant II (towards Sun)

Launch dates:
March 30, 2024 – April 27, 2024

Family repeats every synodic month

Transfer time 85-125 days
### Analysis Overview

| No lunar flyby | Phase-Free  
| (NRHO perilune can occur at any epoch) | Phase-Fixed  
| (Rendezvous with reference NRHO) |
|---|---|
| For 4 families of transfers, studied:  
  ● Day-to-day variation  
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  ● Month-to-month variation | For 6 families of transfers, studied:  
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Phase-Fixed BLTs (Gateway Rendezvous)

Questions:
- How does deterministic spacecraft $\Delta V$ change as a function of launch date and arrival date?
- When considering rendezvous with reference Gateway orbit, how are launch periods affected?

Notes:
- Assume insertion into NRHO always occurs at perilune
- For phase-free cases, perilune insertion can take place at any epoch
- For phase-fixed cases, perilune insertion must take place at $\sim$same epoch as Gateway perilune
Phase-Fixed BLTs (Gateway Rendezvous)

Launch away from Sun

Launch towards Sun

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Phase-Fixed BLTs (Gateway Rendezvous)

| Launch away from Sun | Launch towards Sun |

Arrival dates in Reference Orbit

Earth Departure Epoch

Determine Spacecraft ΔV (m/s)

Increasing the number of revolutions of “wind-on” reduces deterministic insertion ΔV at the expense of time of flight.
Most $\Delta V$ is in the DSMs

- 0-rev wind-on
- 1-rev wind-on
- 2-rev wind-on

- 1 NRHO period
Most $\Delta V$ is in the DSMs

Launch period can be extended by 4-5 days by choosing different wind-on durations

### Insertion & Rendezvous Study

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<tr>
<th>Example launch period</th>
<th>0-rev wind-on</th>
<th>1-rev wind-on</th>
<th>2-rev wind-on</th>
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<tr>
<td>Total Spacecraft $\Delta V$ (m/s)</td>
<td>Earth Departure Epoch (Days Since June 1, 2024)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 NRHO period</td>
<td>0</td>
<td>-3</td>
<td>15</td>
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In the graph:

- **ITR 0 rev**
- **ITR 1 rev**
- **ITR 2 rev**
- **0 rev**
- **1 rev**
- **2 rev**
In general, adding revolutions to the arrival wind-on reduces the insertion $\Delta V$. 

![Graph showing insertion $\Delta V$ vs. Earth Departure Epoch (Days Since June 1, 2024)]
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Phase-Free BLTs with Lunar Flyby

- Outbound lunar flyby reduces launch vehicle C3 requirement
- Additional geometry constraint introduced — reduces launch period
- Transfer options come in pairs every month
Phase-Free BLTs with Lunar Flyby

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Phase-Free BLTs with Lunar Flyby

- Families characterized by:
  - “Short”, “Medium”, or “Long” time of flight
    - “Short” transfers: 114-122 days
    - “Medium” transfers: 135-150 days
    - “Long” transfers: 165-173 days
  - Towards or away from the Sun

- Developed 78 seed solutions based on these families
  - Each family, every month for a year
  - Then studied launch period of each family
Phase-Free BLTs with Lunar Flyby

Short Transfers (TOF 114-122 days)

- Transfer Time (days)
- Flyby Altitude (km)
- TLI C3 (km²/s²)
- DSM ΔV (m/s)
- Insertion ΔV (m/s)
- Total SC ΔV (m/s)

Earth Departure Epoch
Each of the “seed” solutions used to study the nearby solutions for every family.
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Phase-Fixed BLTs with Lunar Flyby

One Year's Worth of Solutions from 6 families
Phase-Fixed BLTs with Lunar Flyby

One Year’s Worth of Solutions from 6 families

Arrival Epoch

Mar 2025 -
Jan 2025 -
Nov 2024 -
Sep 2024 -

Earth Departure Epoch

Sep 2024 -
May 2024 -
Jul 2024 -
Sep 2024 -
Nov 2024 -
Jan 2025 -
Mar 2025 -

Seed solutions

Total SC ΔV (m/s)

300
250
200
150
100
50
Phase-Fixed BLTs with Lunar Flyby

One Year’s Worth of Solutions from 6 families

Zoom in here
Phase-Fixed BLTs with Lunar Flyby
Phase-Fixed BLTs with Lunar Flyby

Spacecraft $\Delta V$ for 2 Months

- Long
- Medium
- Short

Earth Departure Epoch

Total SC $\Delta V$ (m/s)

May 18
May 4
Apr 20
Apr 6
Mar 23
Mar 9
Feb 23
Feb 9 2025
Sep 22 2024
Oct 6
Oct 20
Nov 3
Nov 17
Phase-Fixed BLTs with Lunar Flyby

Spacecraft $\Delta V$ for 2 Months

Arrival dates in Reference Orbit
Phase-Fixed BLTs with Lunar Flyby

Launch Vehicle C3 for 2 Months

Arrival Epoch

May 18 -
May 4 -
Apr 20 -
Apr 6 -
Mar 23 -
Mar 9 -
Feb 23 -
Feb 9 2025

Earth Departure Epoch

Sep 22 2024
Oct 6
Oct 20
Nov 3
Nov 17

TLI C3 km²/s²

-2.2
-2
-1.8
-1.6
-1.4
-1.2
-1

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Phase-Fixed BLTs with Lunar Flyby

- Longest interval of no available launch: 12.5 days
- Longest interval of launch available: 15.5 days
- Average interval of launch available: 4.96 days
Recommendations / Conclusions
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Summary

- BLT increases payload delivered to NRHO and reduces spacecraft $\Delta V$ compared to direct transfer
- Many launch opportunities exist
- Deterministic $\Delta V$:
  - Insertion & rendezvous is <20 m/s
  - Launch and spacecraft performance determine deep space maneuvers (DSMs) and launch period availability
- Statistical $\Delta V$ not analyzed yet, but consists of:
  - Launch vehicle cleanup
  - Trajectory correction maneuvers
  - Rendezvous, proximity operations, and docking
- Time of flight:
  - Without lunar flyby: 12 to 18 weeks
  - With lunar flyby: 16 to 25 weeks
- Launch vehicle C3:
  - BLT without lunar flyby: -0.7 to -0.3 km$^2$/s$^2$
  - BLT with lunar flyby: -2.2 to -1.5 km$^2$/s$^2$

Note: These summary values are based on the results to-date with assumptions described.
This study was funded by NASA under contract 80NSSC19C0001
Thank you

Contact:
Dr. Nathan Parrish
parrish@advanced-space.com

Additional resources available at
https://advancedspace.com/blt/

2100 Central Avenue, Suite 102
Boulder, CO 80301
720-545-9191
Backup
Phase-Fixed BLTs - Example Simultaneous Options

TLI Epoch: 2024 May 20 12:00

- Without Distant Lunar Flyby
- Total $\Delta V$: 223.5 m/s

TLI Epoch: 2024 May 21 00:00

- With Distant Lunar Flyby
- Total $\Delta V$: 26.1 m/s
Summary - Representative Case

Characteristics:
- Lunar flyby launch opportunity: March 27 - April 4, 2024
- Launch vehicle C3 requirement: -1.4 km²/s²
- Spacecraft ΔV budget (DSMs & insertion): 60 m/s
- Time of flight: 127-115 days
- Flyby altitude: 200-11,000 km

Caveats:
- Launch period is based on phase-free case. Constraining final rendezvous will reduce the launch period and/or increase ΔV required.
- Simplified spacecraft model.
- Additional analysis required to evaluate statistical ΔV.
Insertion & Rendezvous Study

Logistics module location during insertion maneuver

Gateway Location during logistics module perilune insertion maneuver

"Insert then rendezvous" (ITR) strategy

Coming in from BLT

Heading towards apolune, where 3 m/s rendezvous maneuver will be performed

~3500 km separation from 3 m/s apolune maneuver propagated backward