Survey of Ballistic Lunar Transfers to Near Rectilinear Halo Orbit

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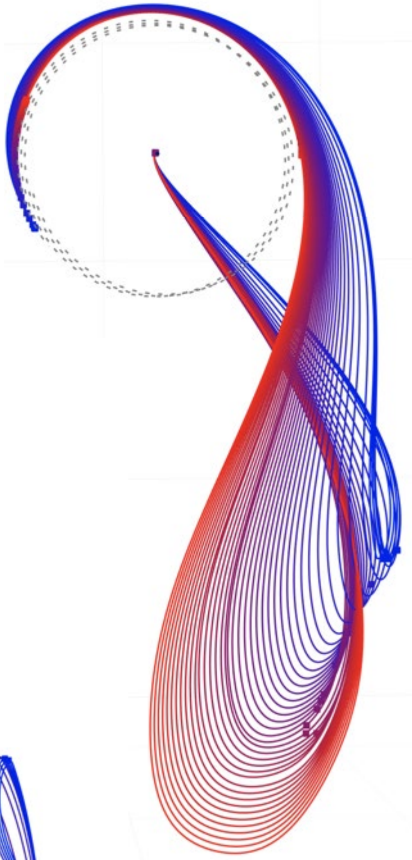
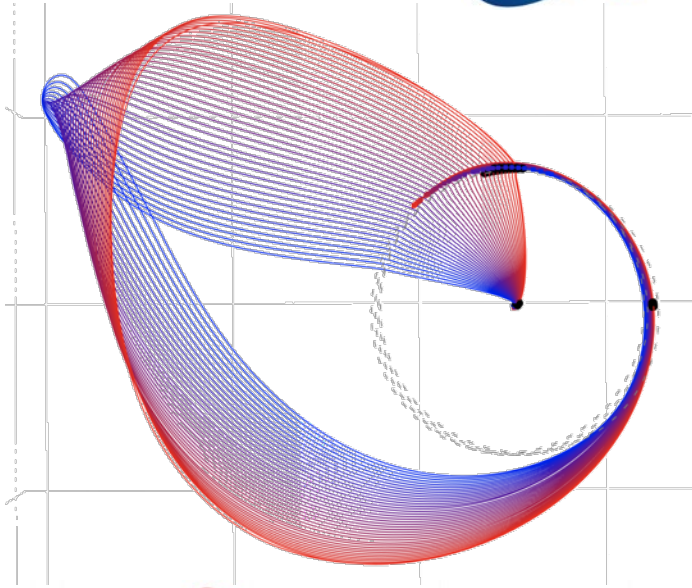
a.i. solutions

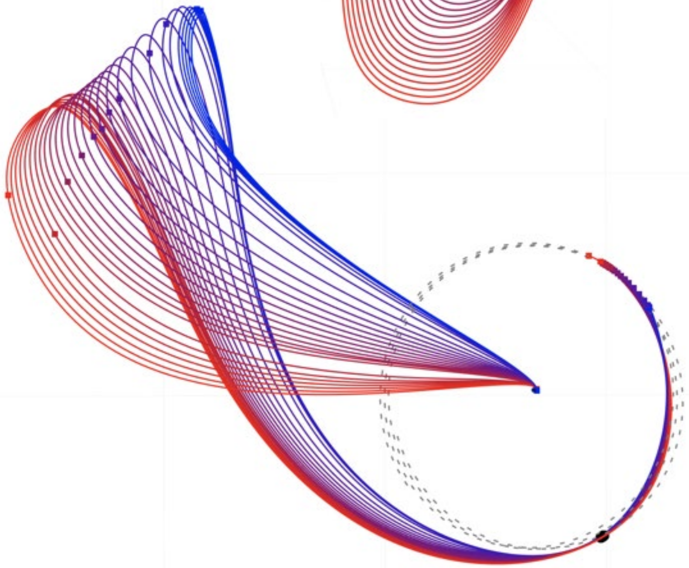


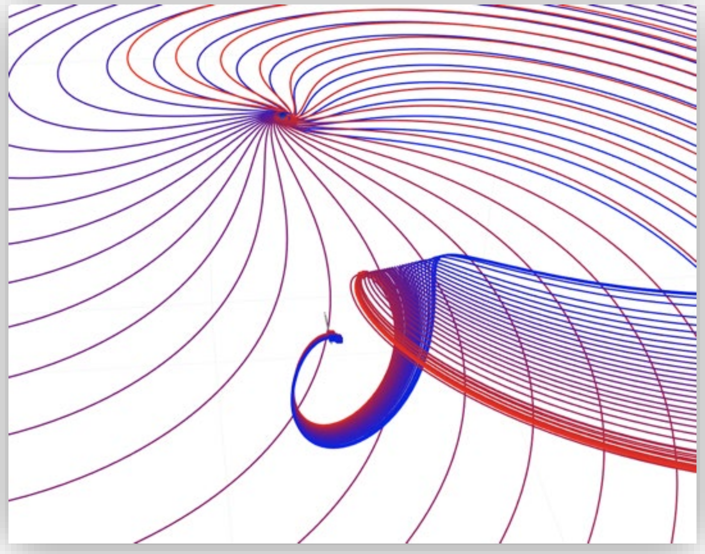
Goal: Evaluate and understand the trade space for ballistic lunar transfers from Earth launch to arrival in a near rectilinear halo orbit (NRHO).

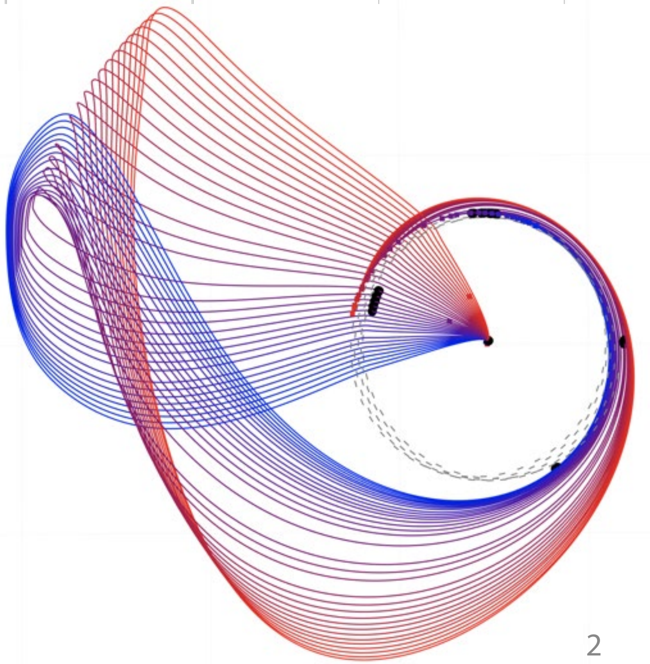


Several favorable families were identified and studied.

Over 70,000 optimal trajectories were designed in order to understand the trade space.



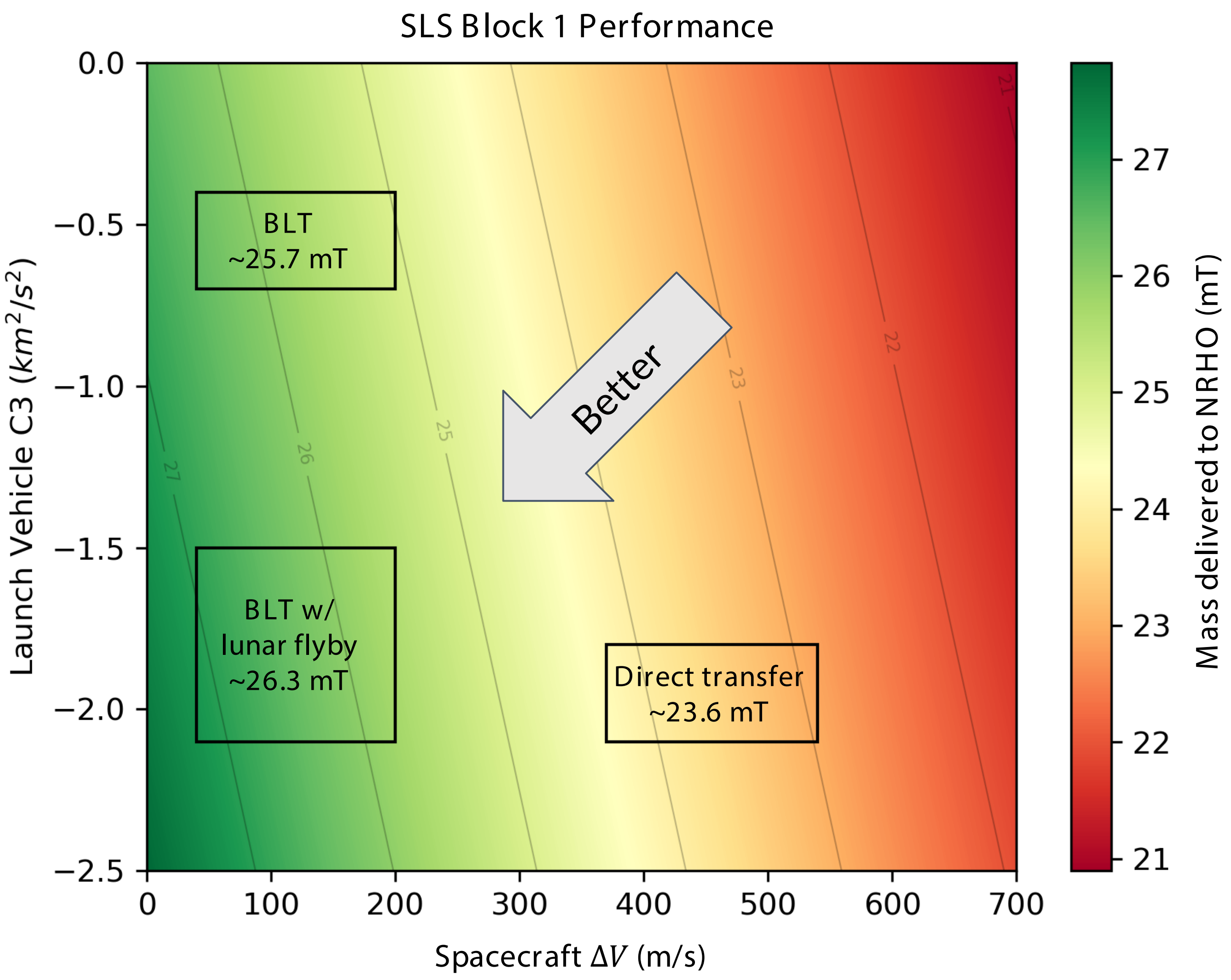




Why Ballistic Lunar Transfer (BLT)?

- Assume spacecraft Isp = 300 s
- Benefits:
  - Reduced spacecraft ΔV
  - 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

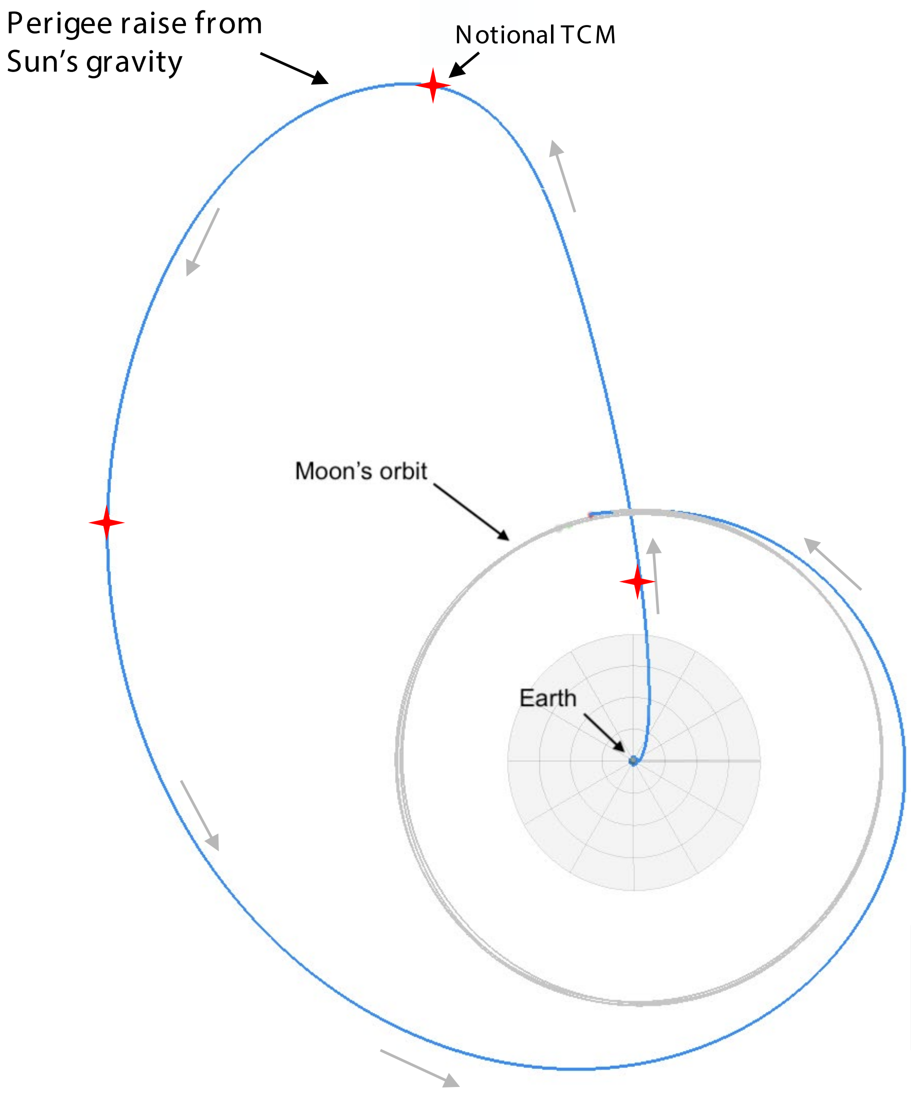
Bottom line:
Increased mass delivered to NRHO



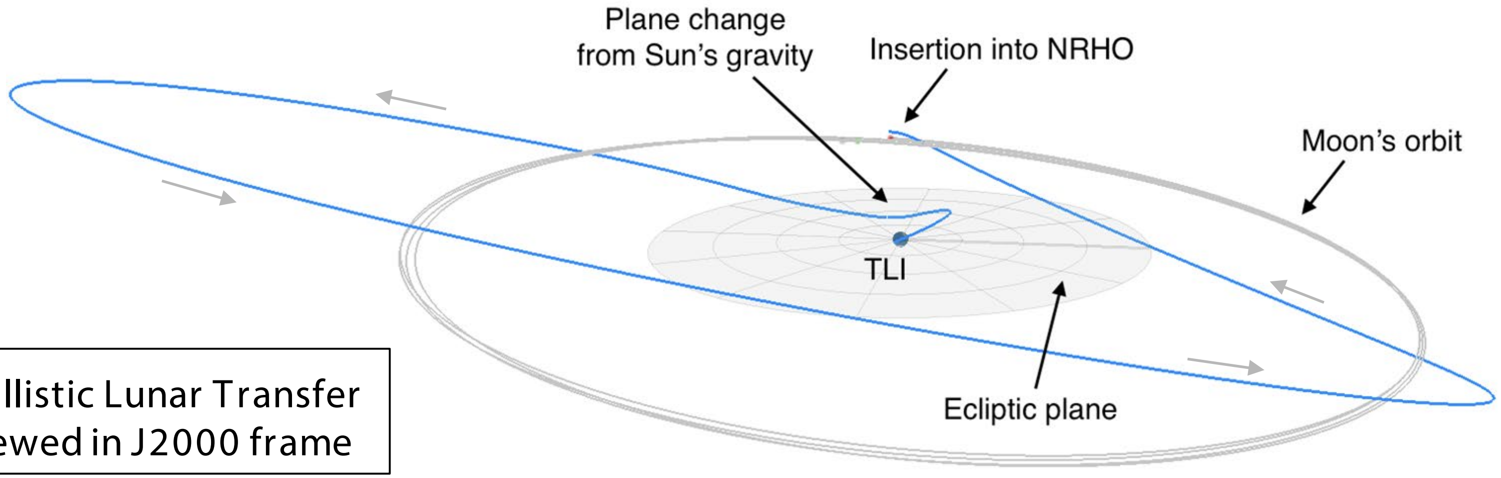
Introduction & Background

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)

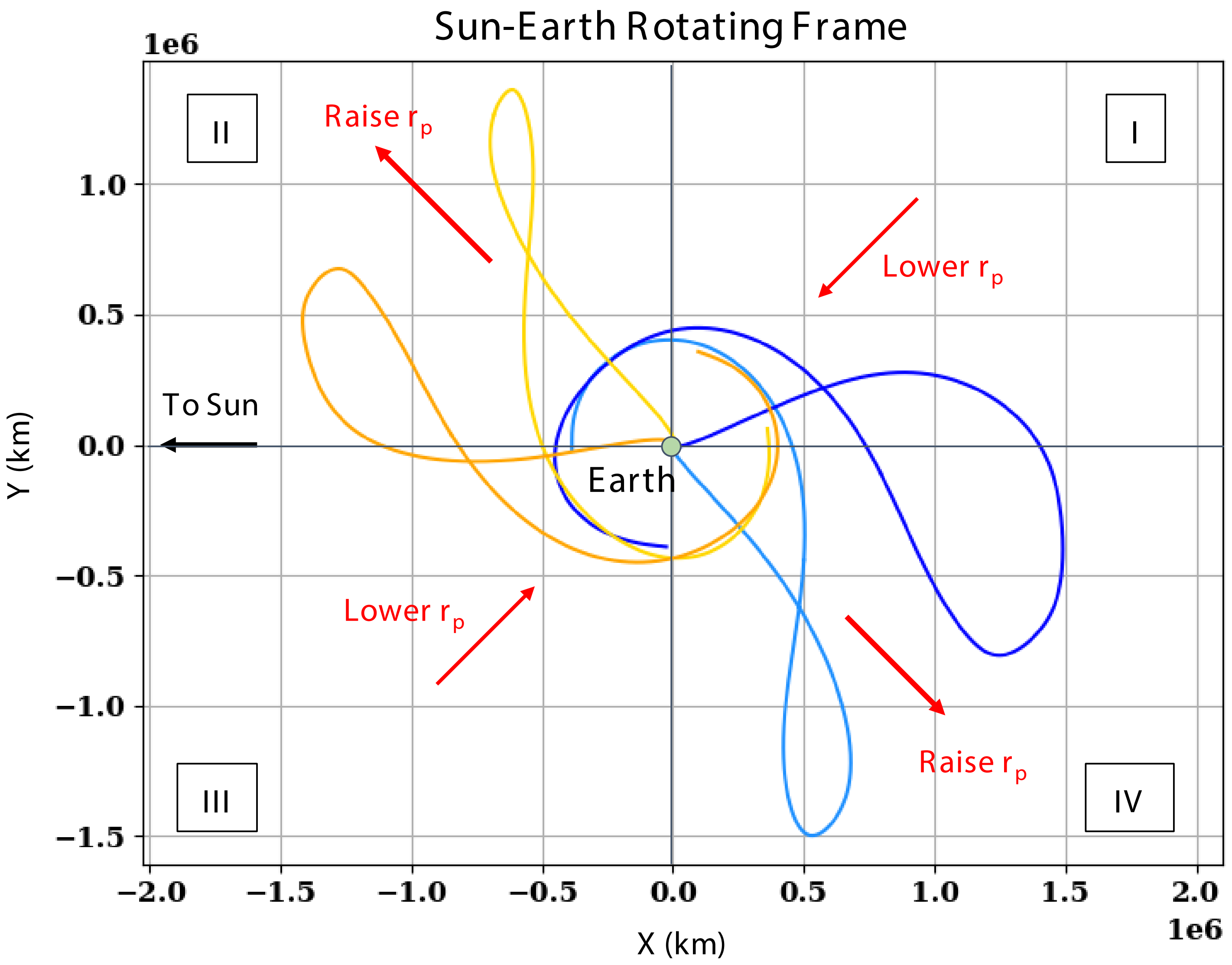


Ballistic Lunar Transfer viewed in J2000 frame



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 m^2, 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:
  - Sun & Earth point masses, states from DE430
  - **Moon 8x8 gravity field, GRGM660PRIM model**
  - 14,000 kg spacecraft
  - SRP Area: 23 m^2, 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: 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

	Phase-Free (NRHO perilune can occur at any epoch)	Phase-Fixed (Rendezvous with reference NRHO)
No lunar flyby	For 4 families of transfers, studied: • Day-to-day variation • Month-to-month variation • Eclipses during transfer	For 4 families of transfers, studied: • Day-to-day variation • Month-to-month variation • 6 options for insertion & rendezvous
With lunar flyby	For 6 families of transfers, studied: • Day-to-day variation • Month-to-month variation	For 6 families of transfers, studied: • Day-to-day variation • Month-to-month variation

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Families of Transfers

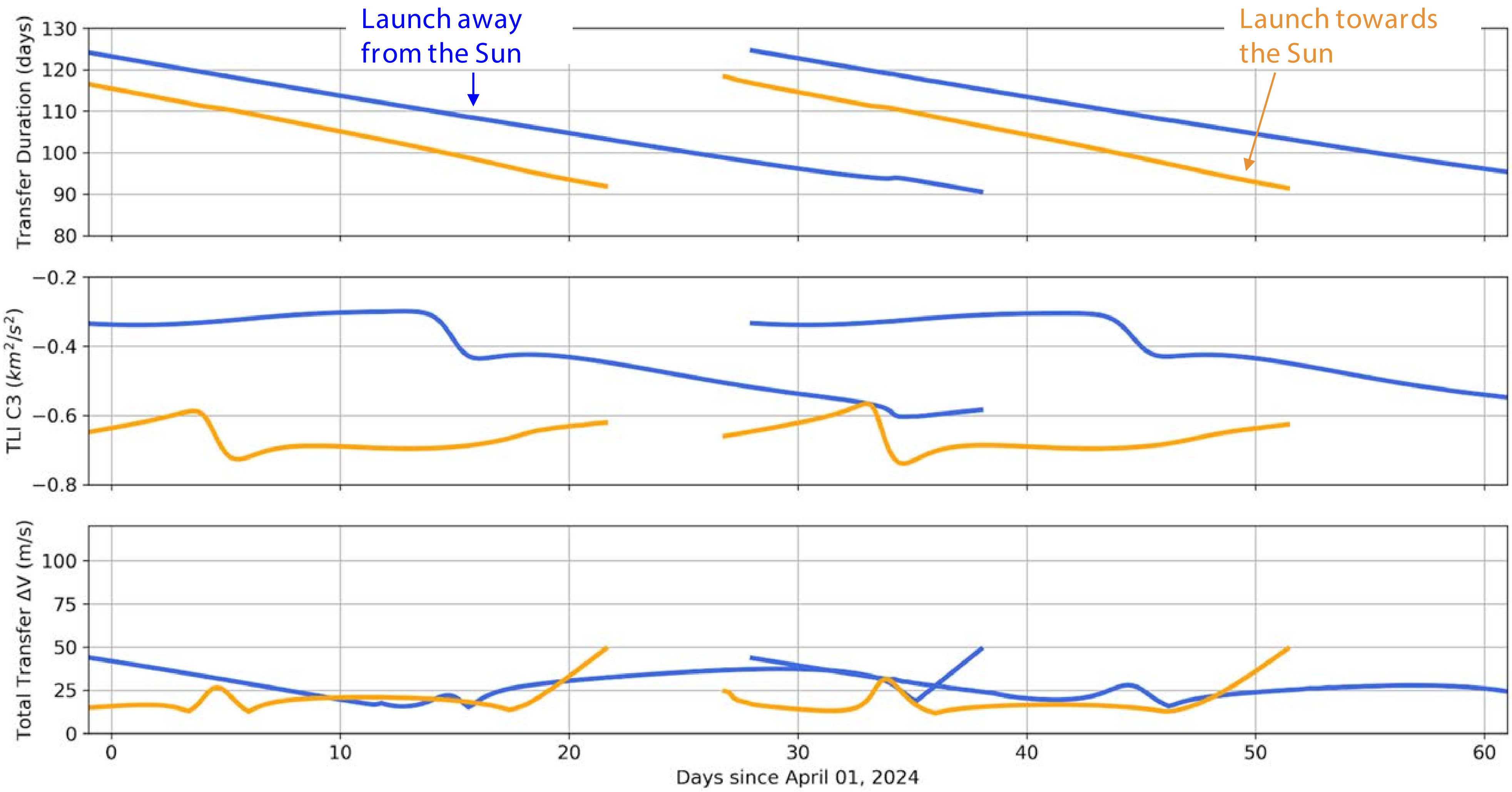
- Many families of transfers exist.
- This is a partial taxonomy.
- Each of these “families” has numerous “sub-families”, many of which are practically equivalent.

See reference:

Parker J.S., “Families of Low-Energy Lunar Halo Transfers”, Advances in the Astronautical Sciences, 2006.

#	Lunar flyby	Apogee quadrant	TLI approx. location	# of Moon orbits between flyby & insertion
1	No	II (towards Sun)	Ascending node	N/A
2	No	II (towards Sun)	Descending node	N/A
3	No	IV (away from Sun)	Ascending node	N/A
4	No	IV (away from Sun)	Descending node	N/A
5	Yes	II (towards Sun)	Ascending node	4
6	Yes	II (towards Sun)	Ascending node	5
7	Yes	II (towards Sun)	Ascending node	5-6
8	Yes	IV (away from Sun)	Ascending node	4
9	Yes	IV (away from Sun)	Ascending node	5
10	Yes	IV (away from Sun)	Ascending node	5-6
11	Yes	II (towards Sun)	Descending node	4
12	Yes	II (towards Sun)	Descending node	5
13	Yes	II (towards Sun)	Descending node	5-6
14	Yes	IV (away from Sun)	Descending node	4
15	Yes	IV (away from Sun)	Descending node	5
16	Yes	IV (away from Sun)	Descending node	5-6

Phase-Free BLTs - TLI near Ascending Node



Earth Departure Epoch

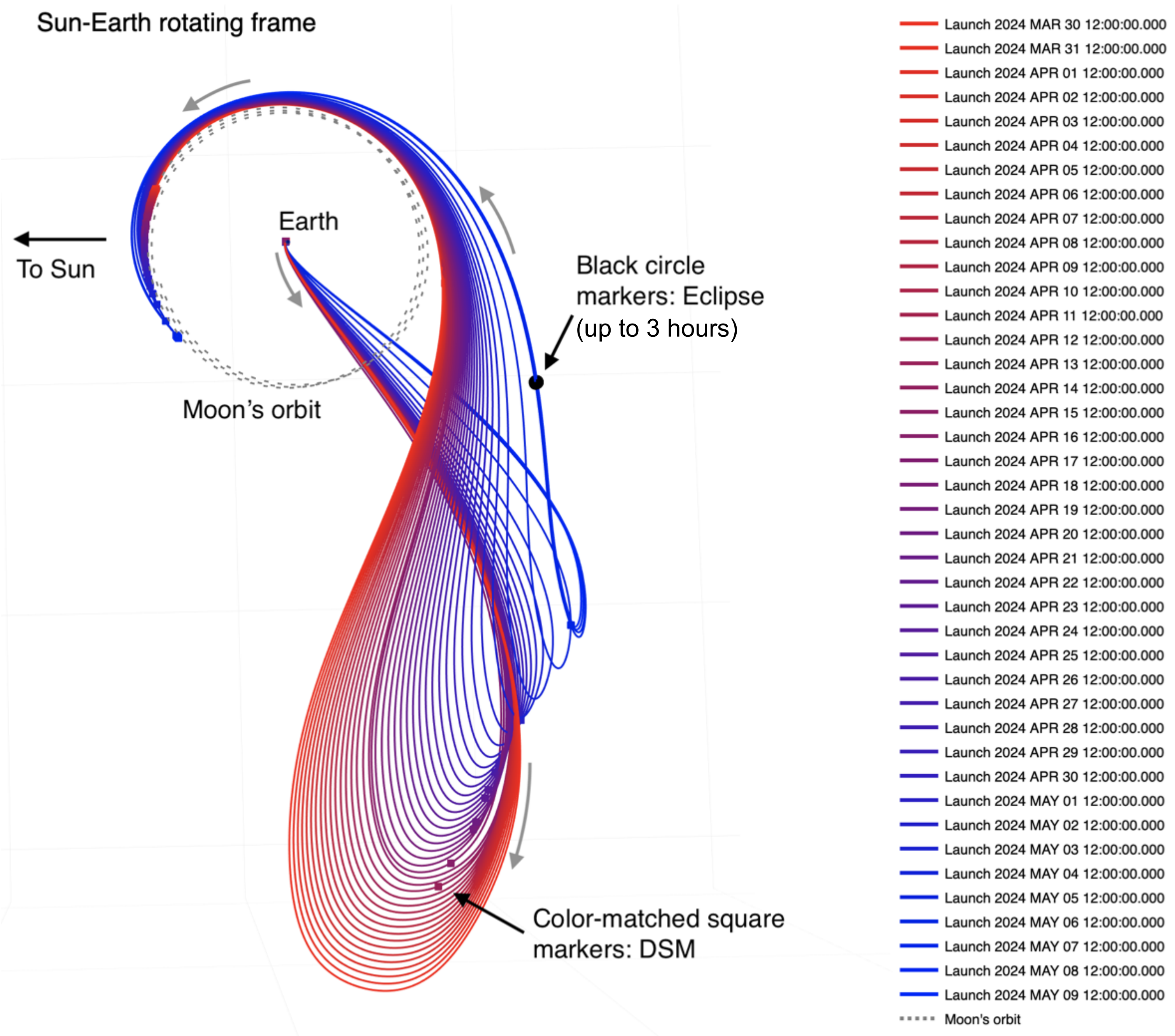
Phase-Free BLTs

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



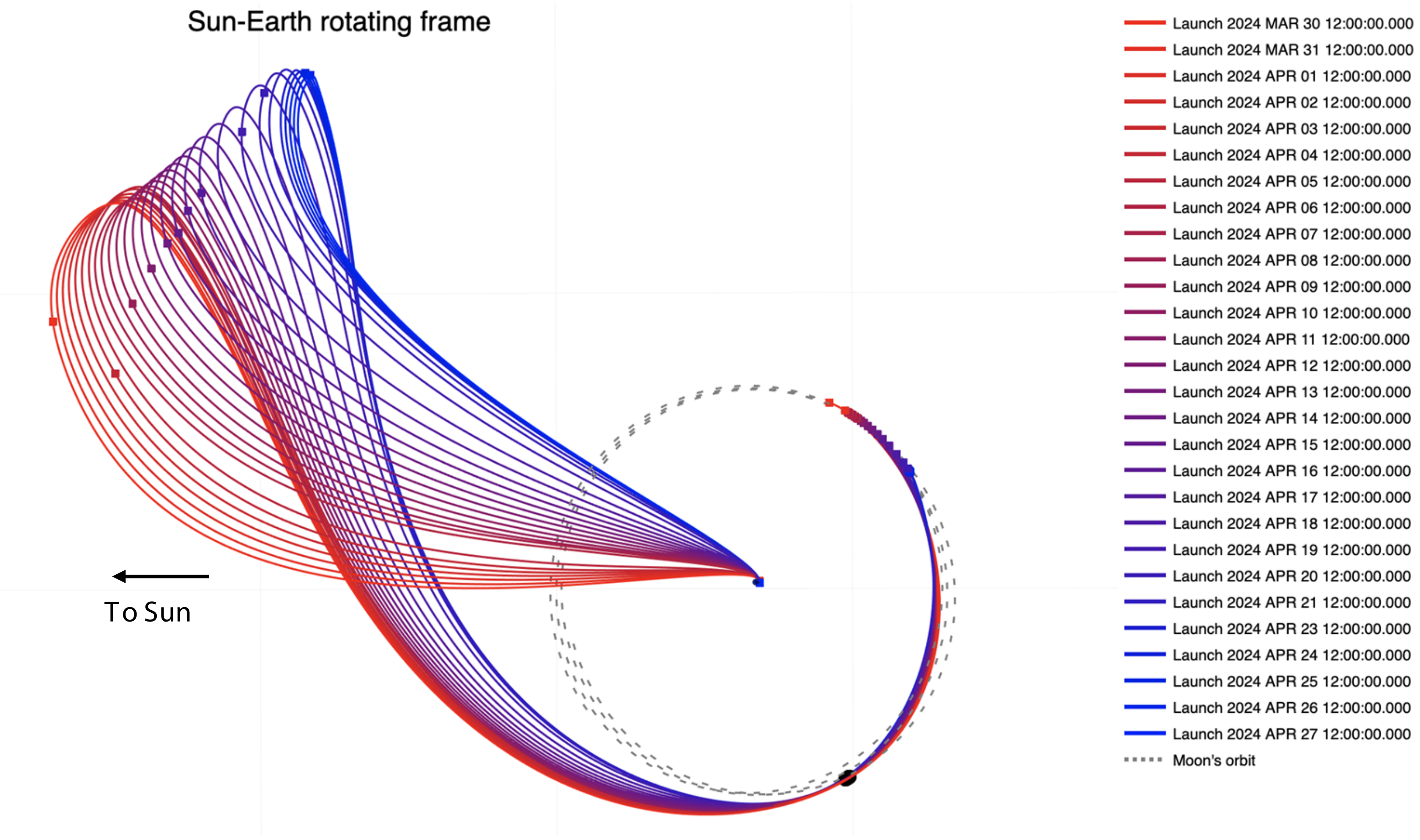
Phase-Free BLTs

Launch into quadrant II (towards Sun)

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

Family repeats every synodic month

Transfer time 85-125 days



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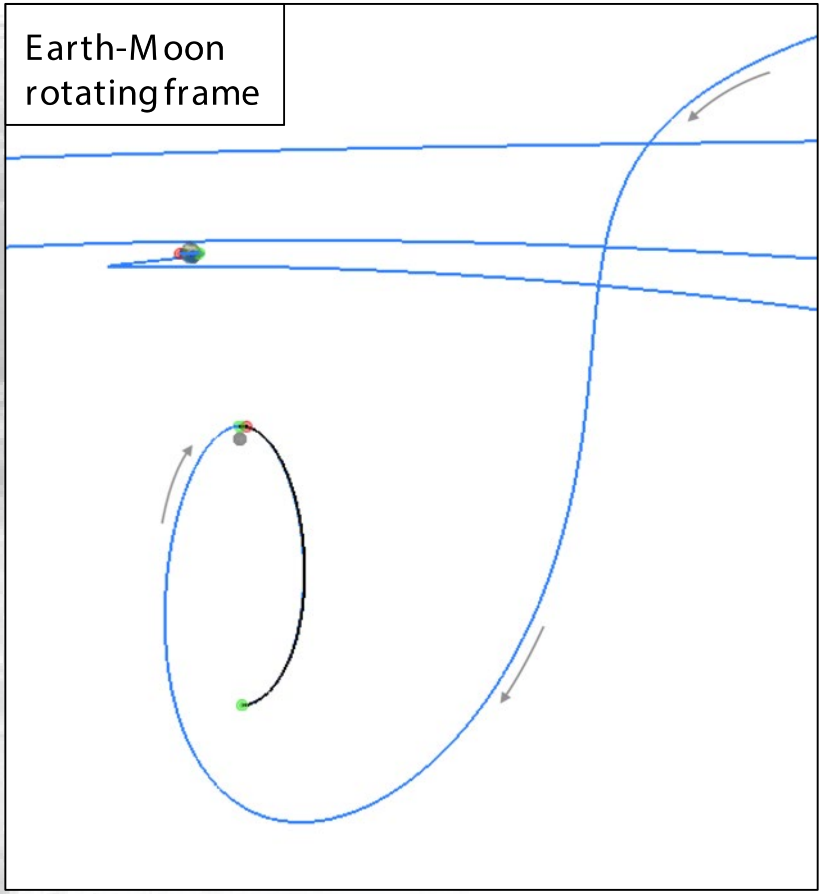
With lunar flyby	For 6 families of transfers, studied: ● Day-to-day variation ● Month-to-month variation	For 6 families of transfers, studied: ● Day-to-day variation ● Month-to-month variation

Phase-Fixed BLTs (Gateway Rendezvous)



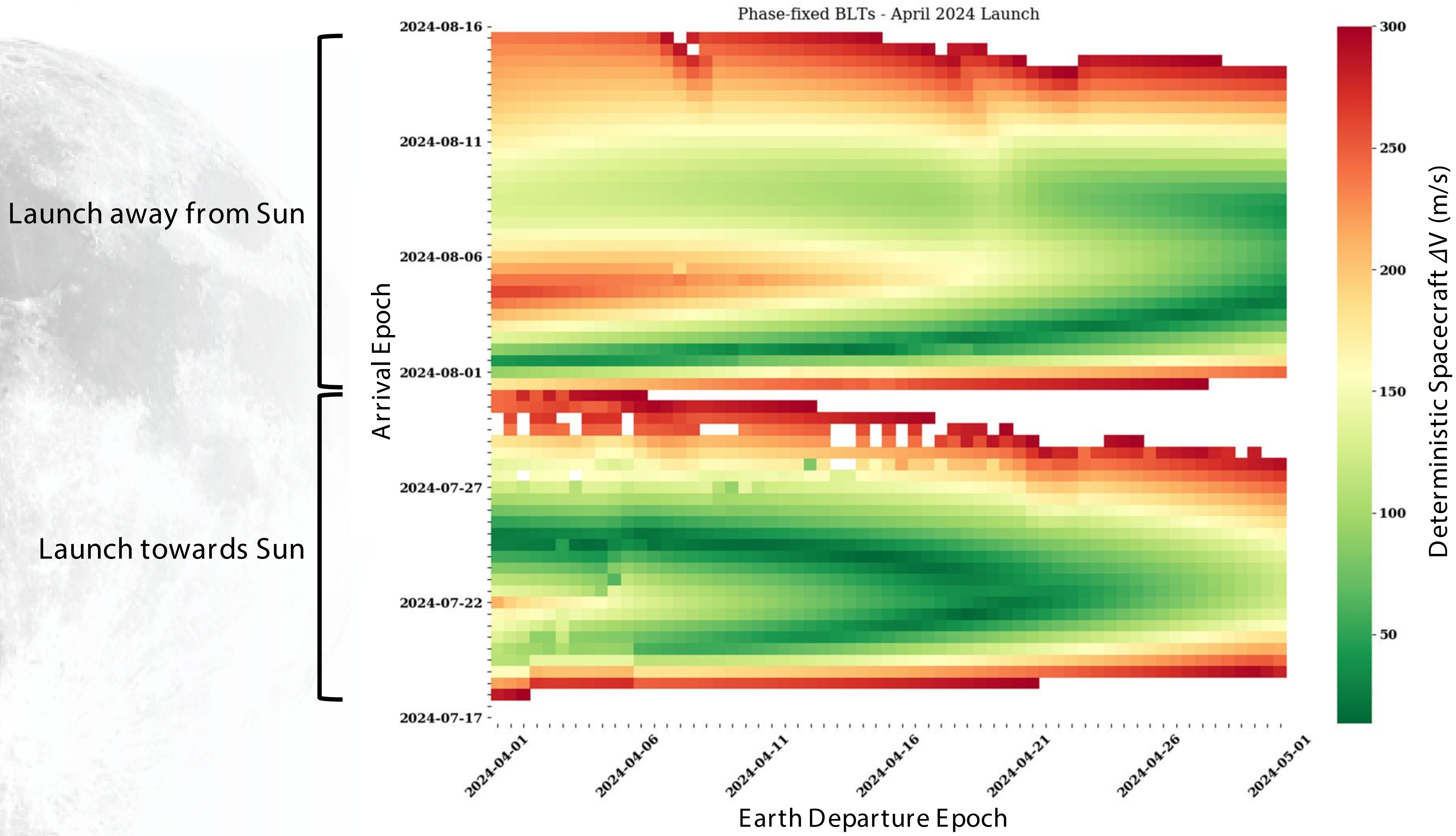
Questions:

- How does deterministic spacecraft ΔV change as a function of launch date and arrival date?
- When considering rendezvous with reference Gateway orbit, how are launch periods affected?

Notes:

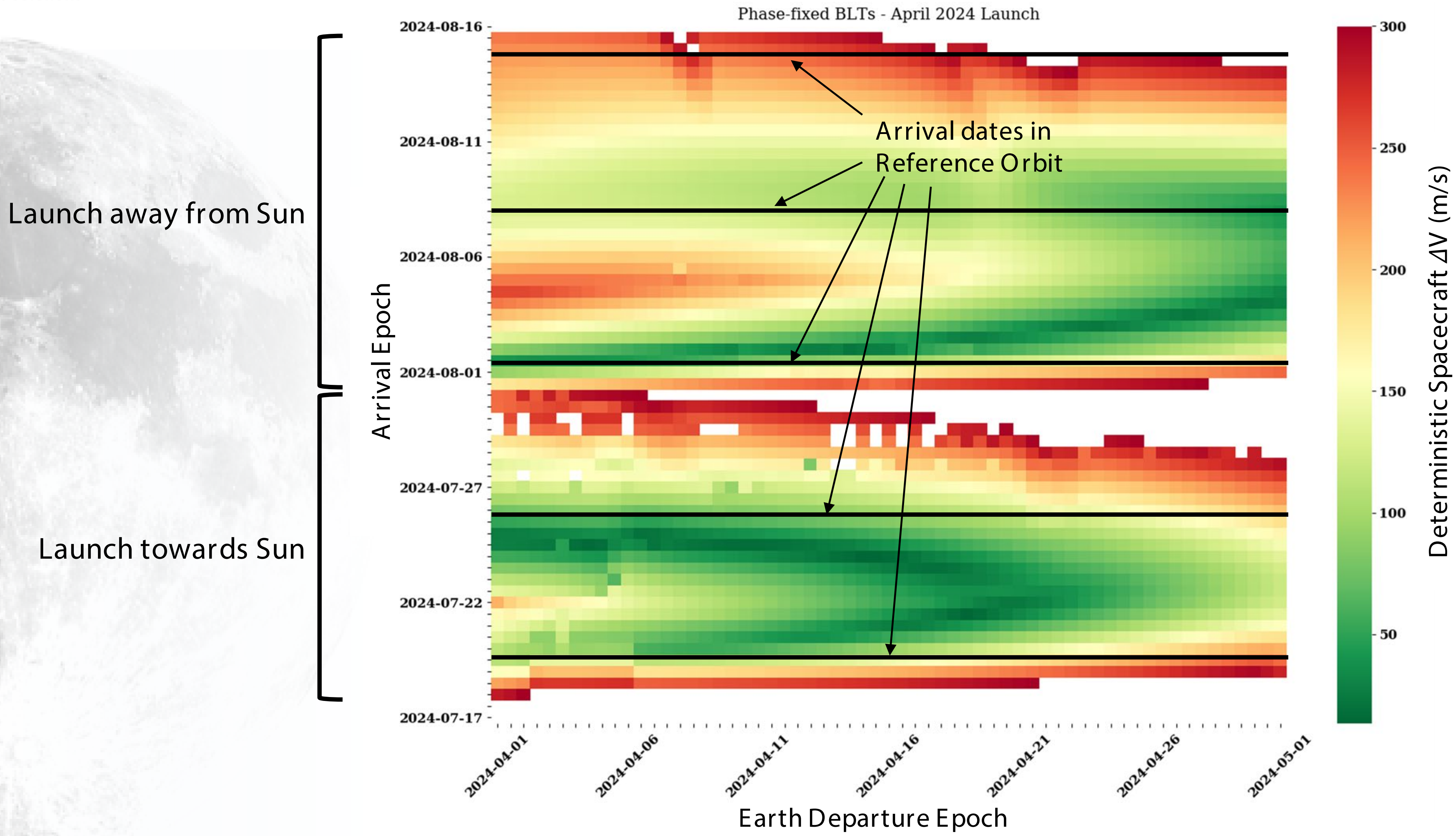
- Assume insertion into NRHO always occurs at perilune
- For phase-free cases, perilune insertion can take place at any epoch
- For phase-fixed cases, perilune insertion must take place at ~same epoch as Gateway perilune

Phase-Fixed BLTs (Gateway Rendezvous)

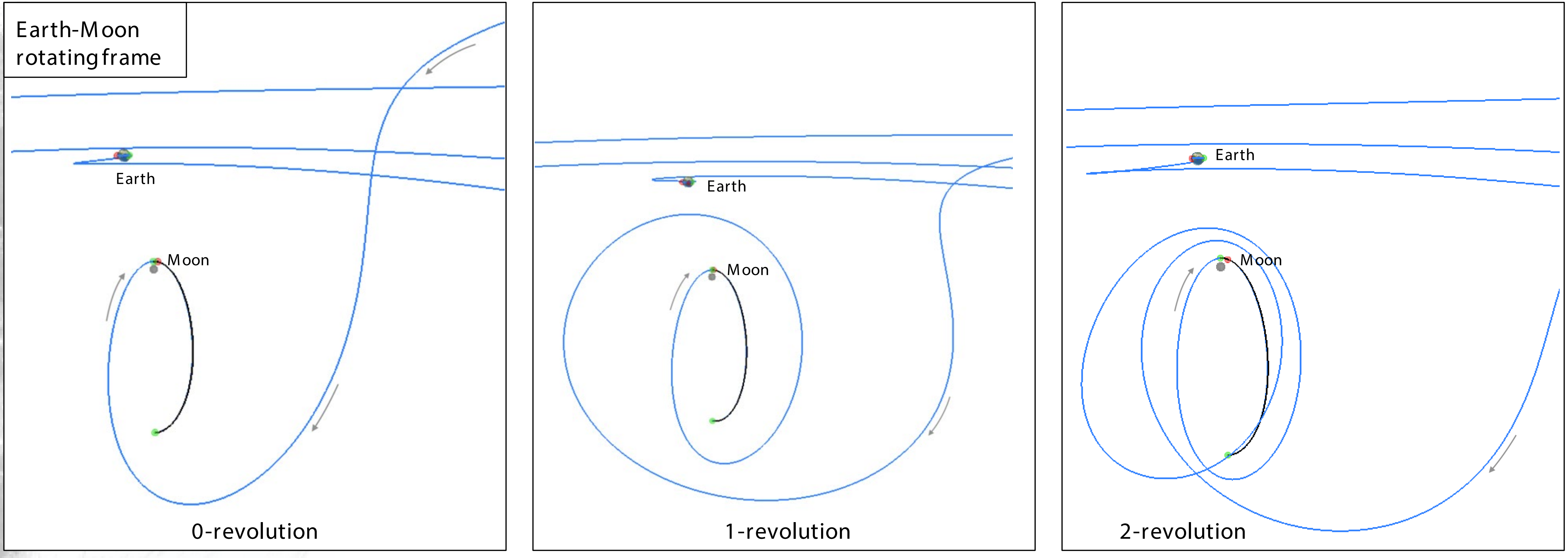


Advanced Space, LLC, Presented at 2019 AAS/AIAA Astrodynamics Specialist Conference

Phase-Fixed BLTs (Gateway Rendezvous)

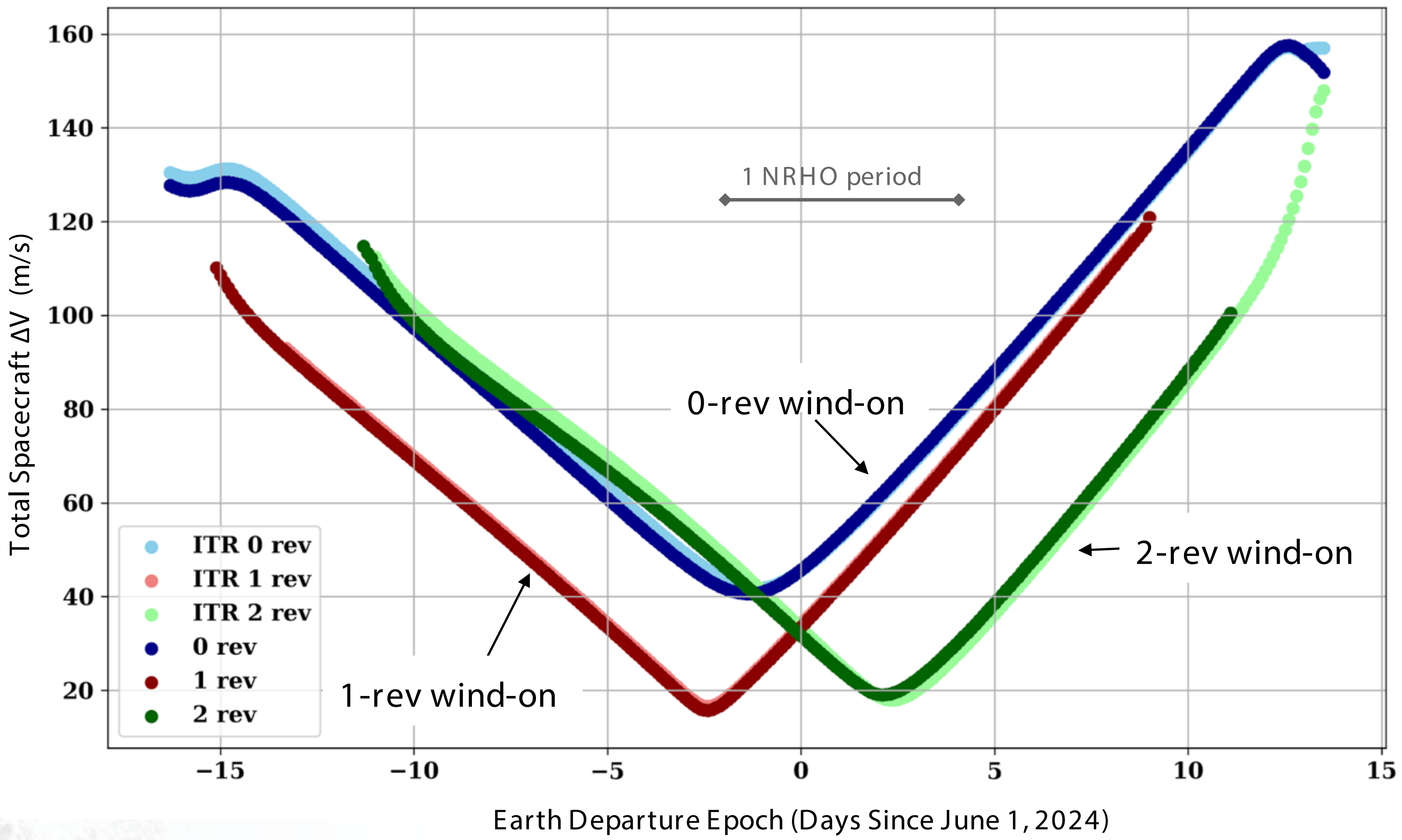


Insertion & Rendezvous Study



Increasing the number of revolutions of “wind-on” reduces deterministic insertion ΔV at the expense of time of flight.

Insertion & Rendezvous Study



- Most ΔV is in the DSMs

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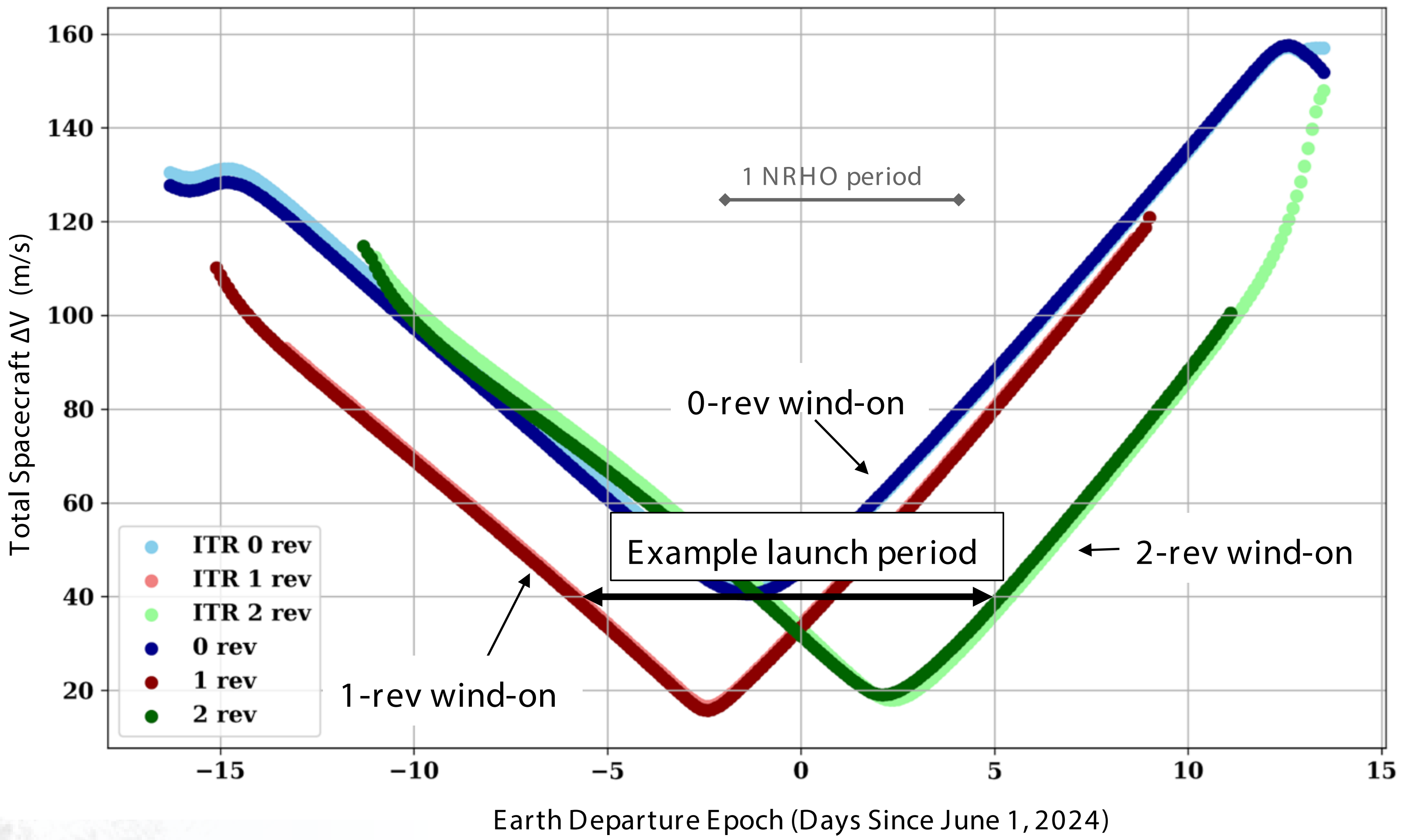
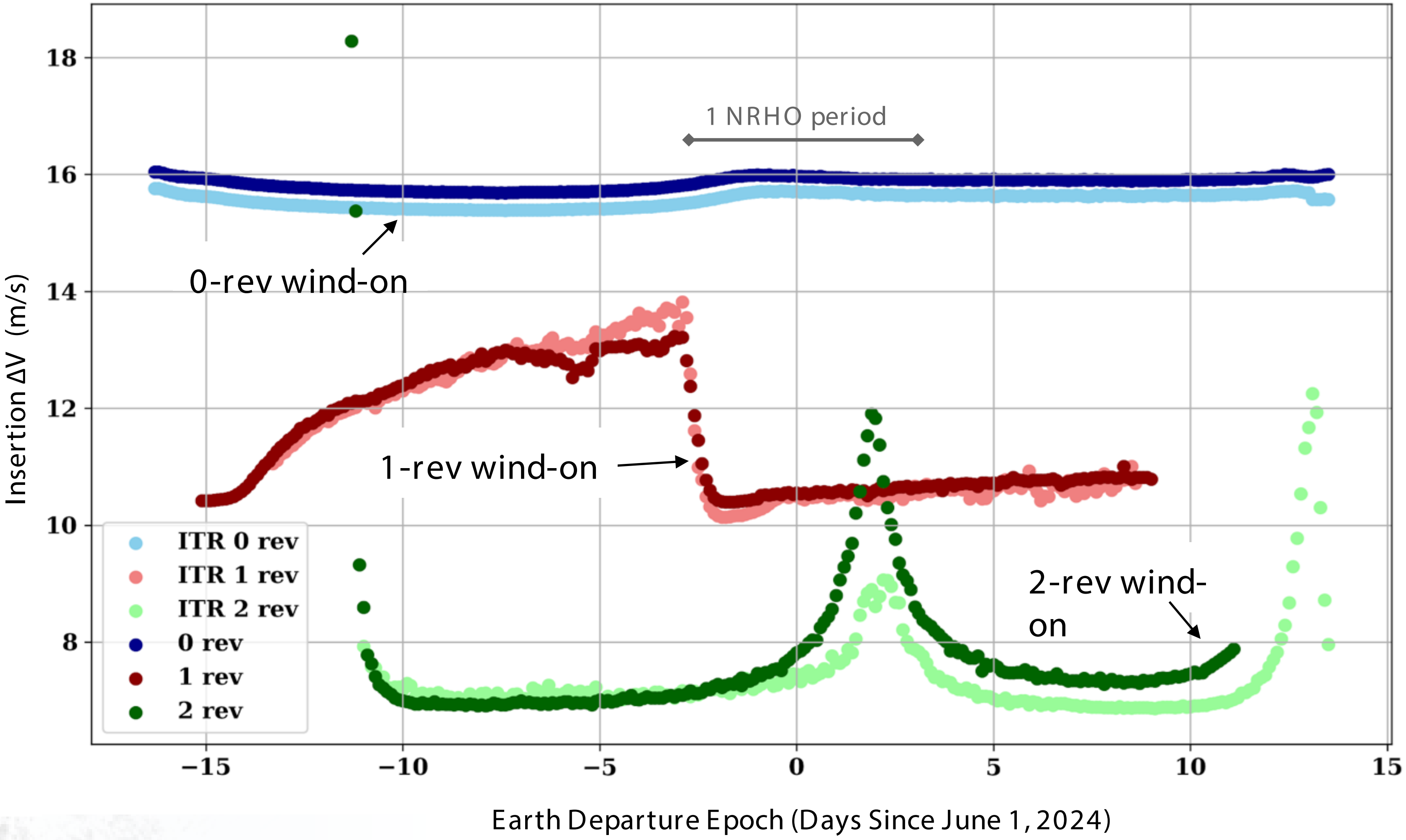


- Most ΔV is in the DSMs
- Launch period can be extended by 4-5 days by choosing different wind-on durations

Insertion & Rendezvous Study



- In general, adding revolutions to the arrival wind-on reduces the insertion ΔV.

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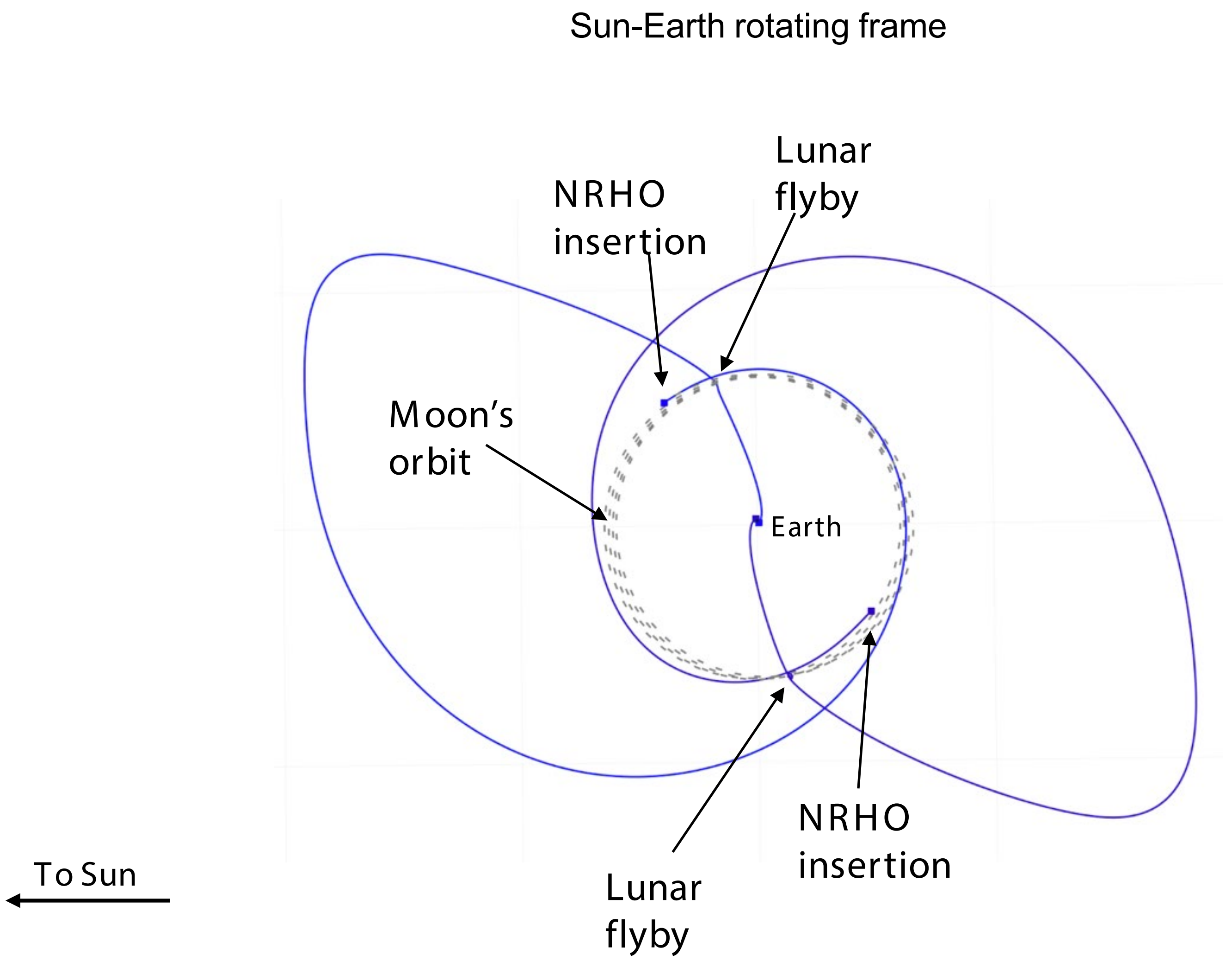
Phase-Free BLTs with Lunar Flyby

- Outbound lunar flyby reduces launch vehicle C3 requirement
- Additional geometry constraint introduced —reduces launch period
- Transfer options come in pairs every month



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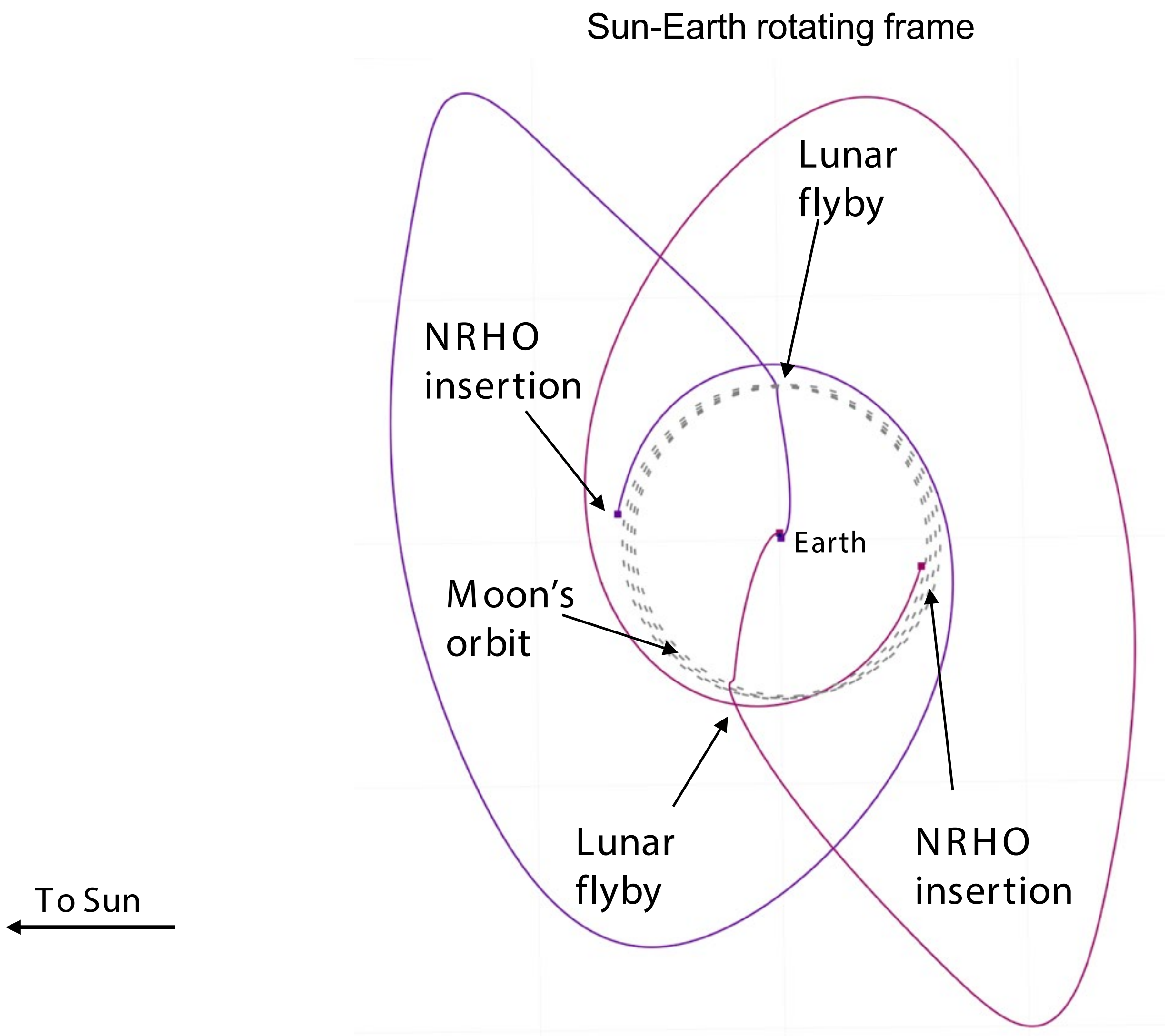

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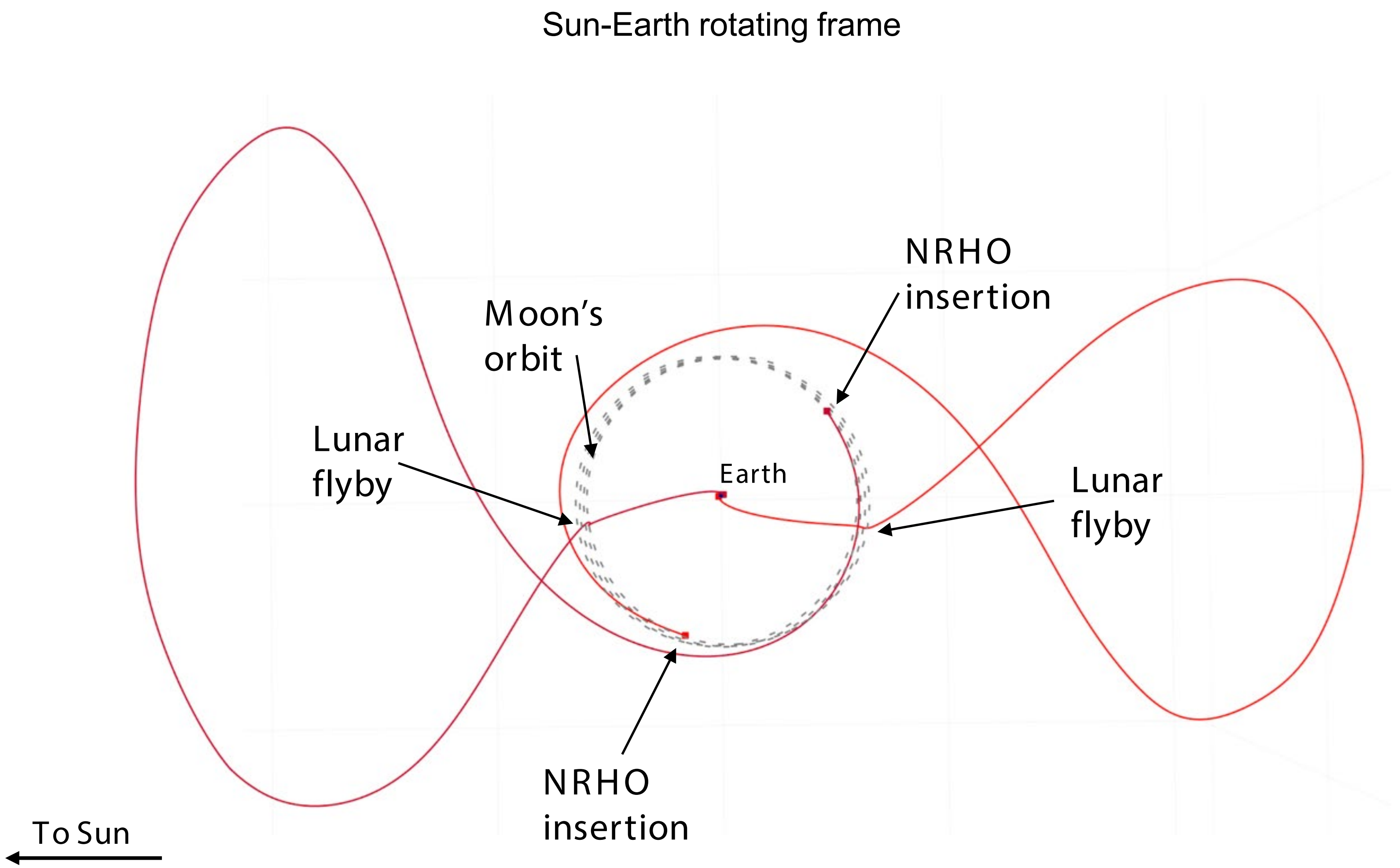

Phase-Free BLTs with Lunar Flyby

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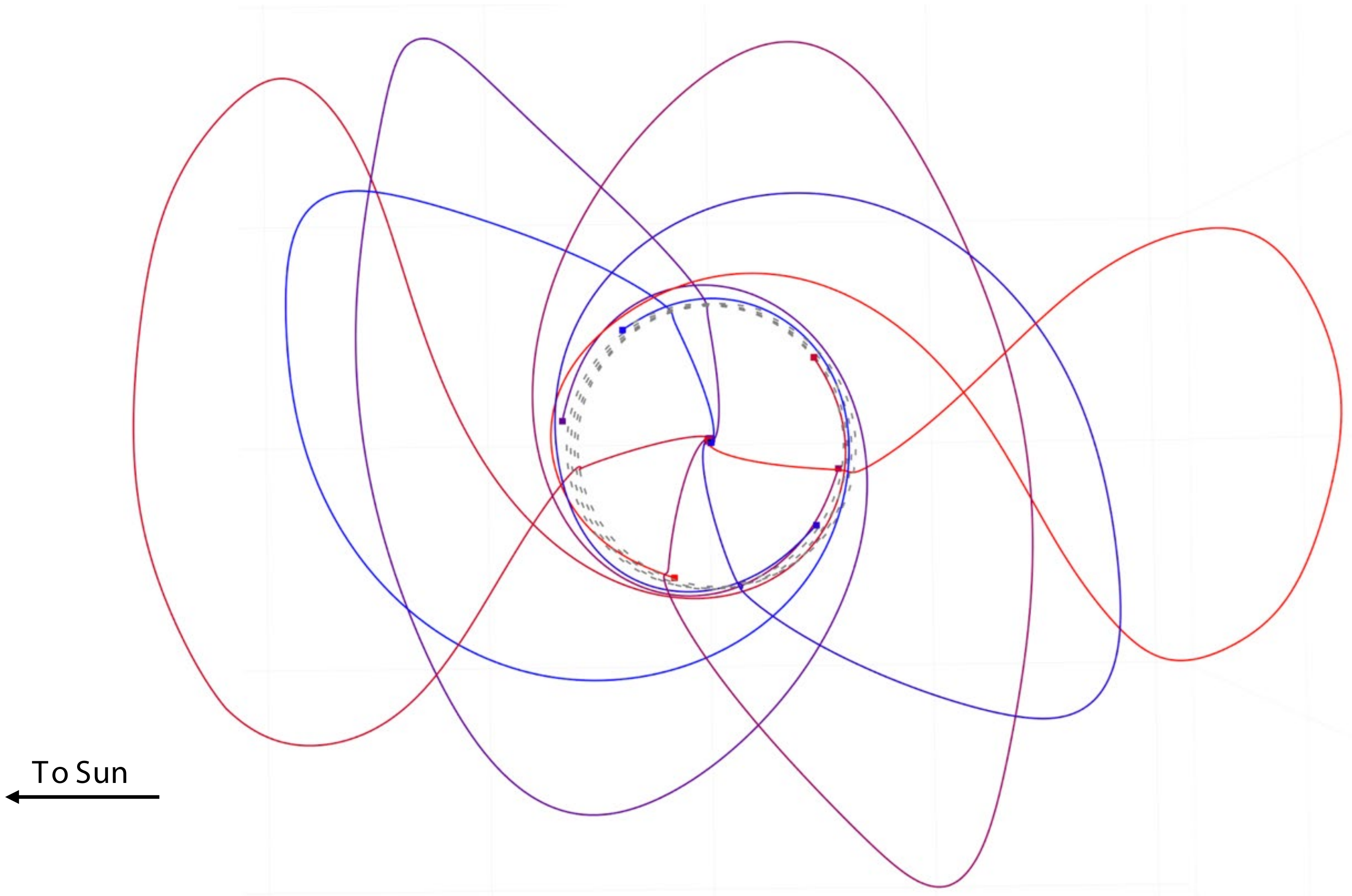
Sun-Earth rotating frame

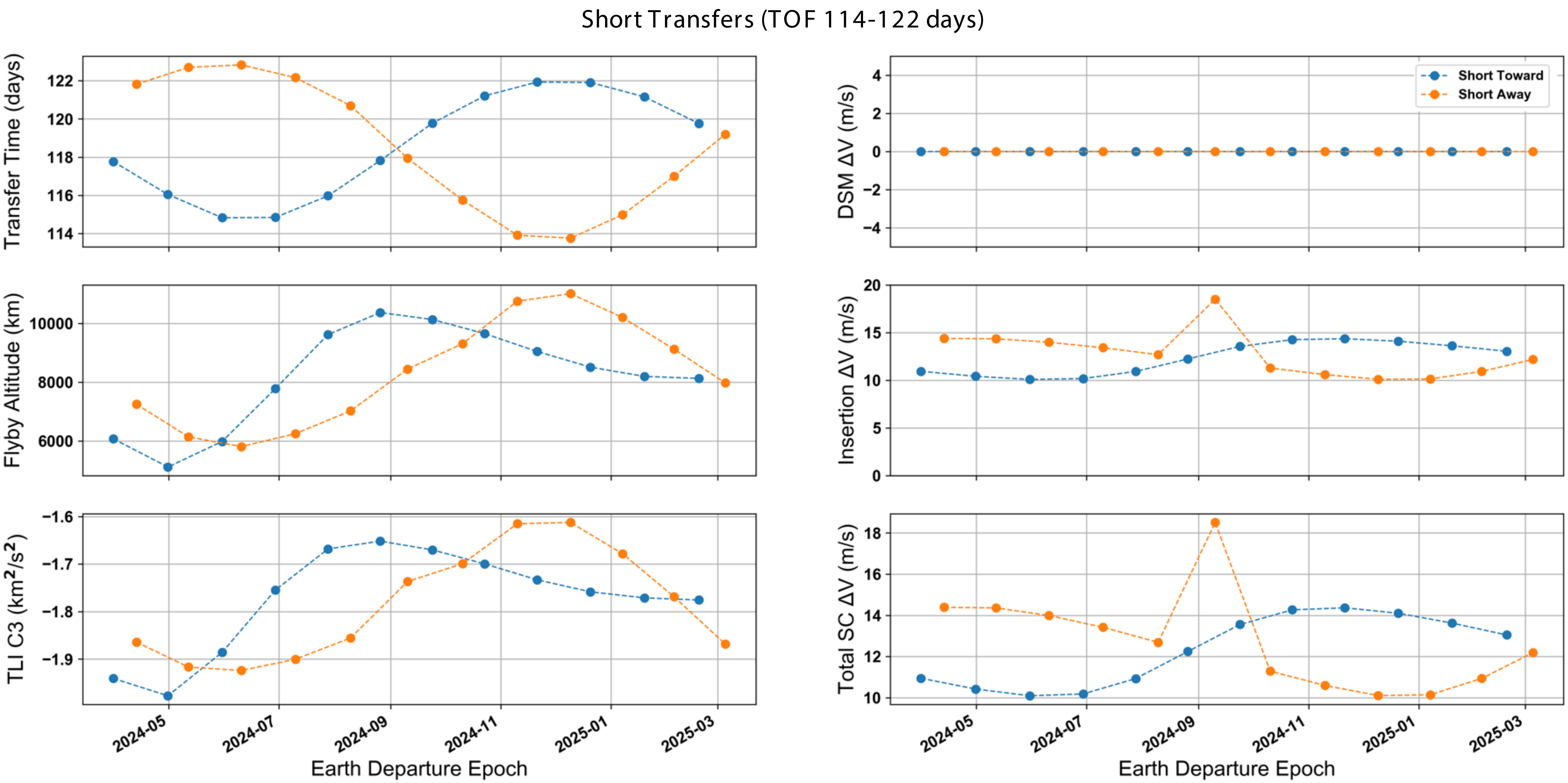


Phase-Free BLTs with Lunar Flyby

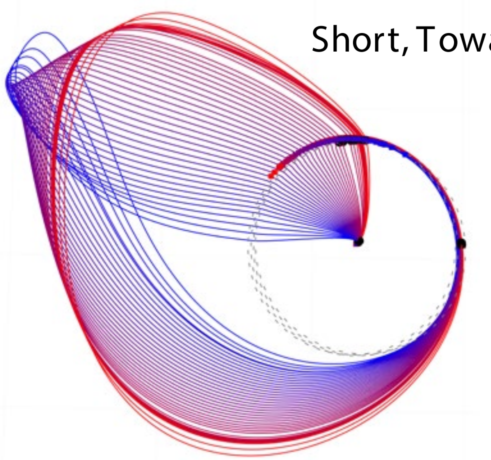
- Families characterized by:
  - “Short”, “Medium”, or “Long” time of flight
    - “Short” transfers: 114-122 days
    - “Medium” transfers: 135-150 days
    - “Long” transfers: 165-173 days
  - Towards or away from the Sun

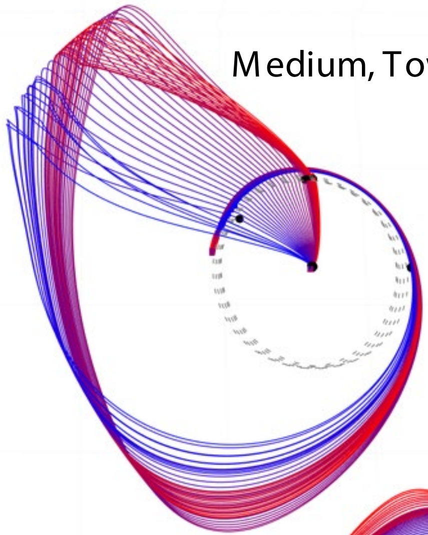
- Developed 78 seed solutions based on these families
  - Each family, every month for a year
- Then studied launch period of each family

Phase-Free BLTs with Lunar Flyby

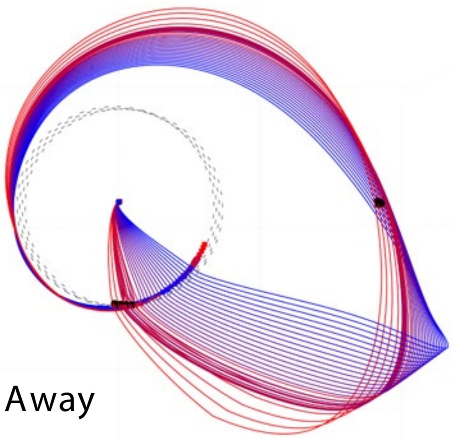


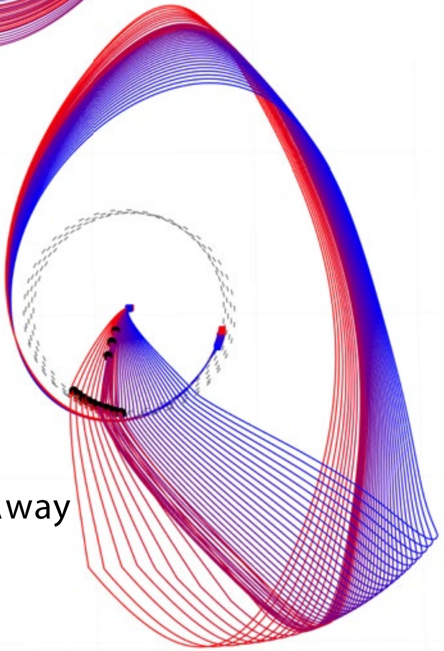
Phase-Free BLTs with Lunar Flyby

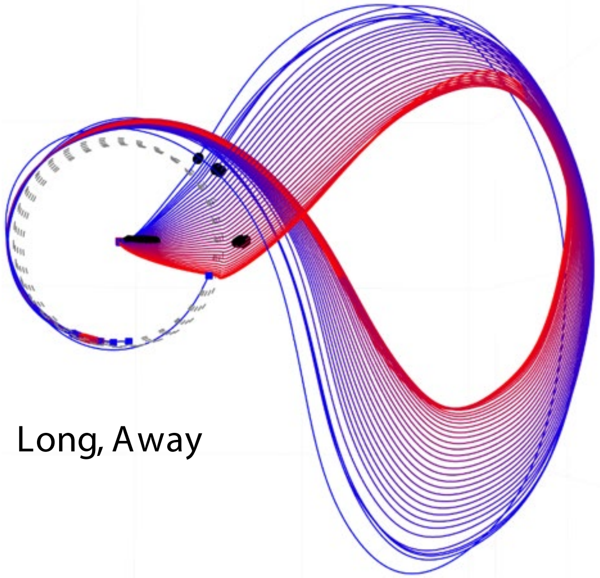

Short, Towards


Medium, Towards

Each of the “seed” solutions used to study the nearby solutions for every family.


Short, Away


Medium, Away


Long, Away

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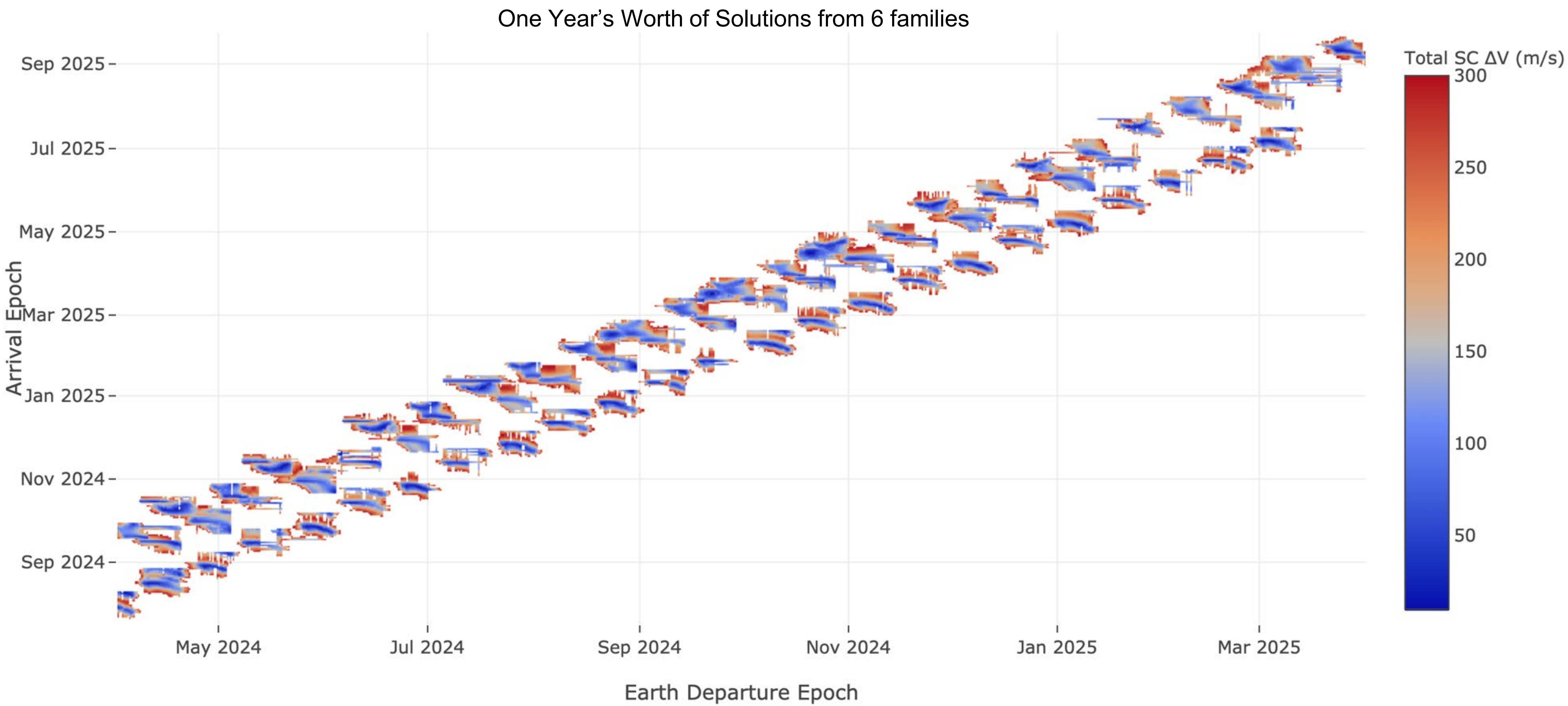
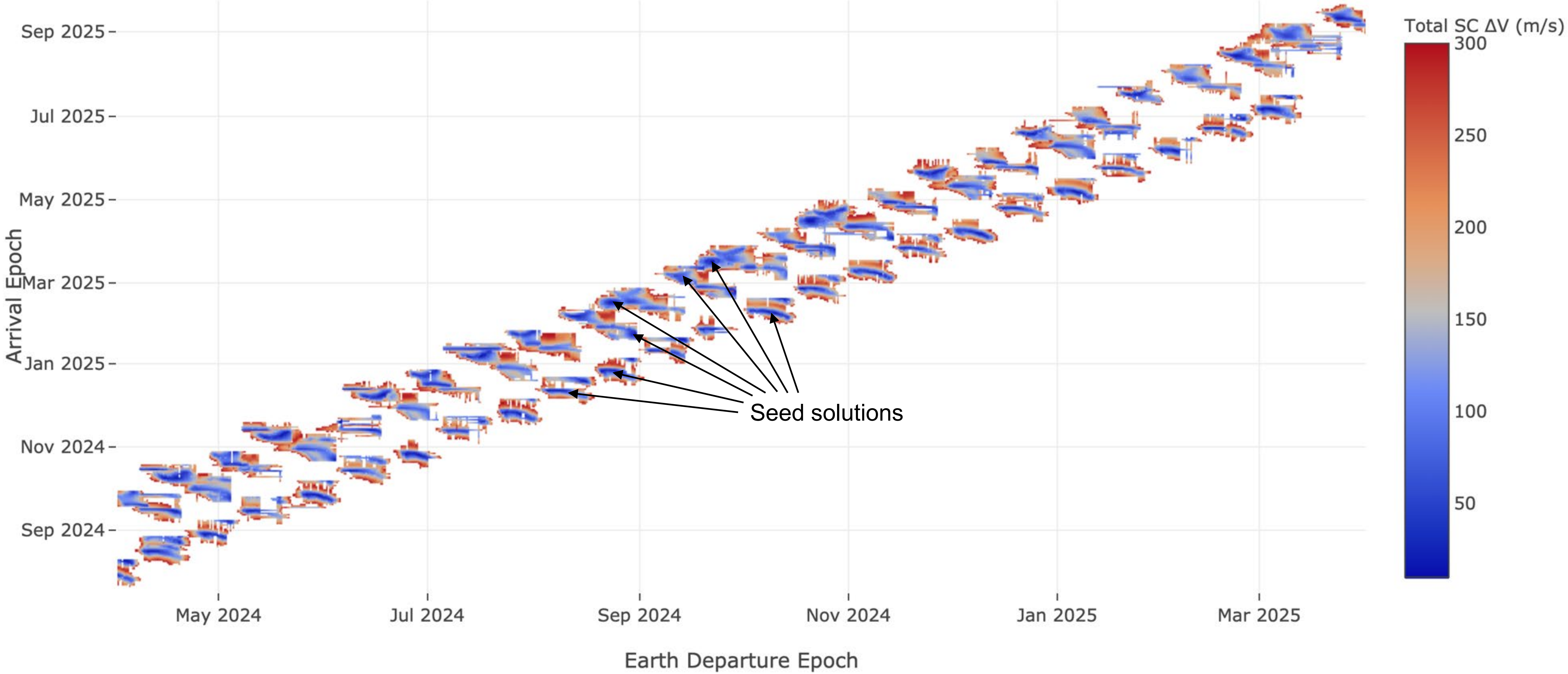
Phase-Fixed BLTs with Lunar Flyby

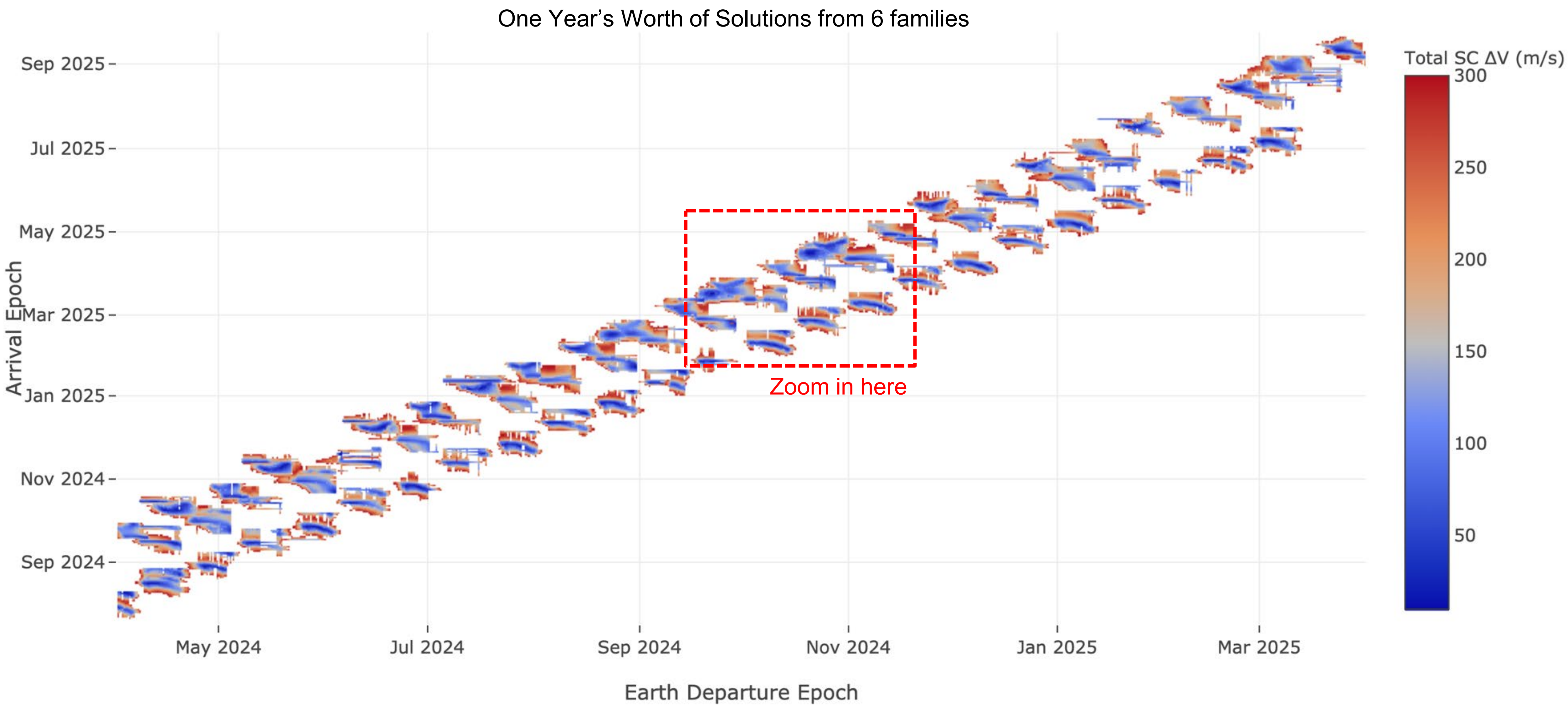


Phase-Fixed BLTs with Lunar Flyby

One Year's Worth of Solutions from 6 families



Phase-Fixed BLTs with Lunar Flyby



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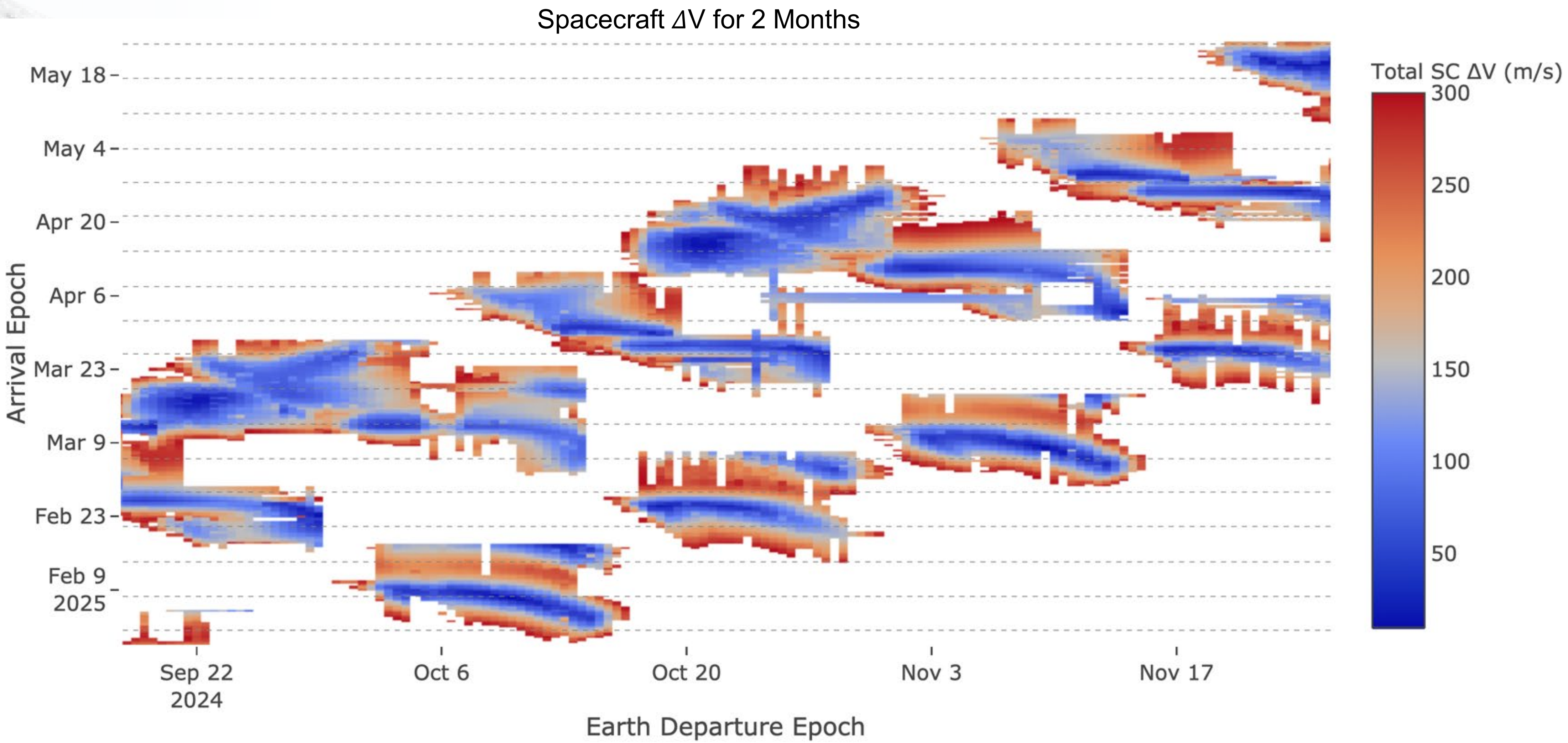
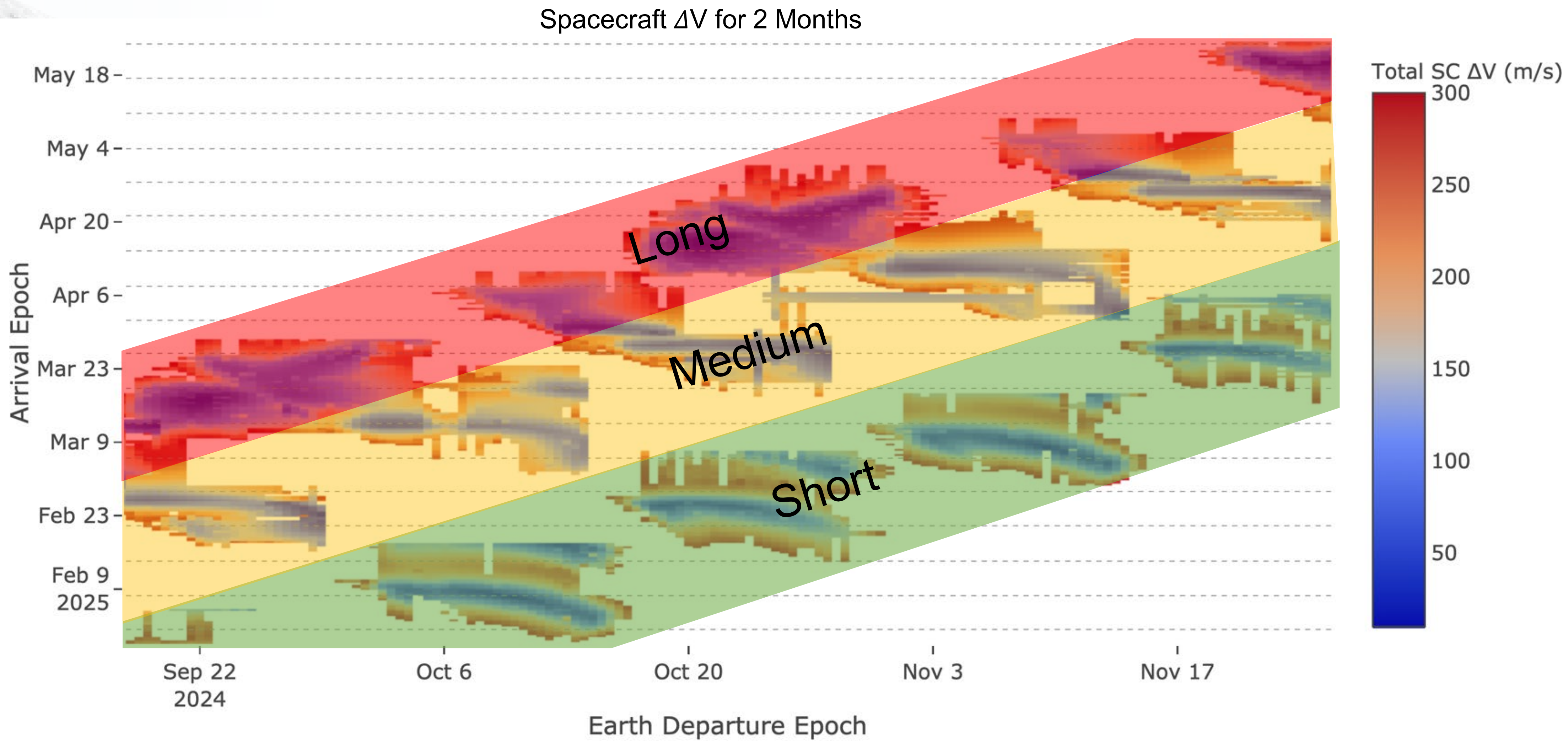
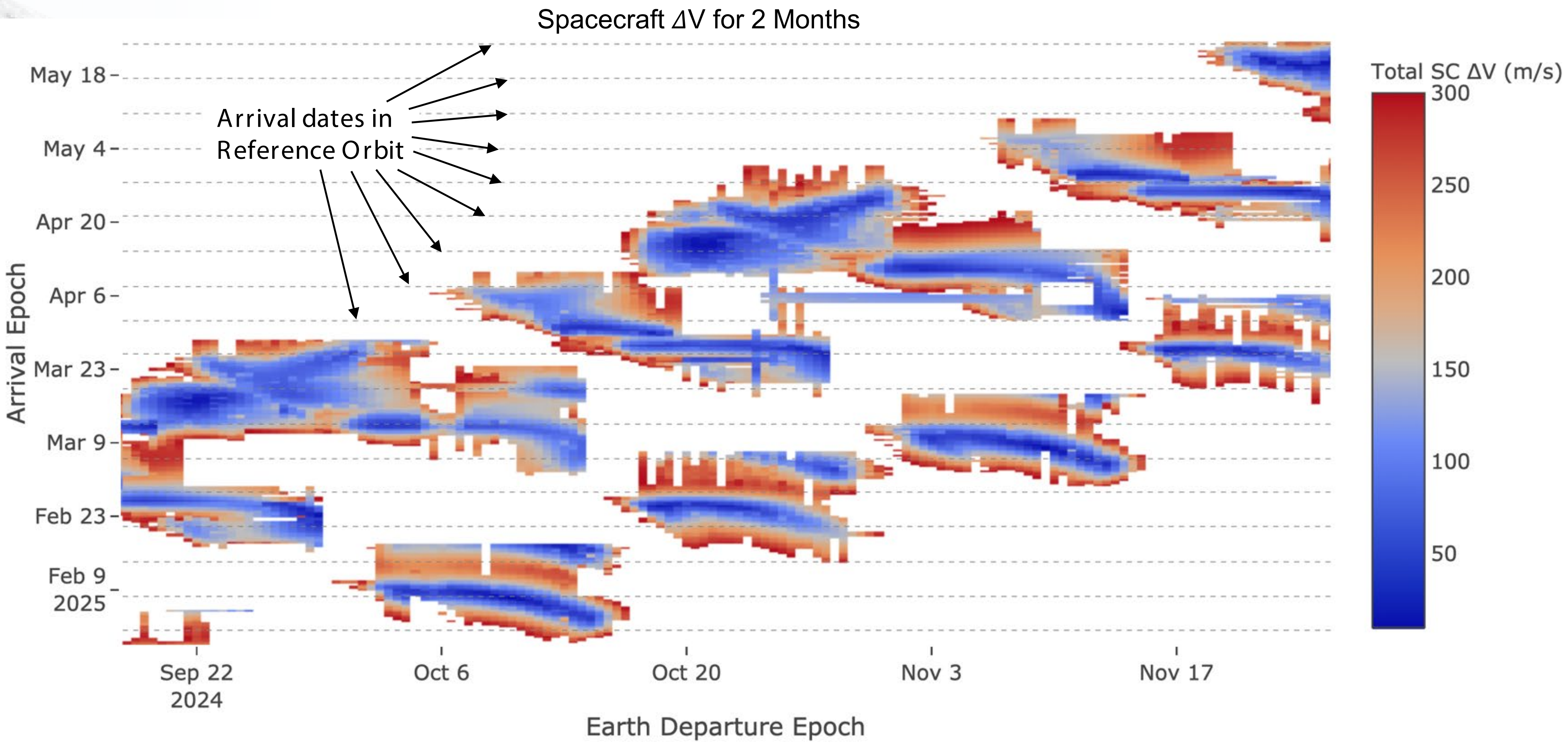


Phase-Fixed BLTs with Lunar Flyby



Phase-Fixed BLTs with Lunar Flyby



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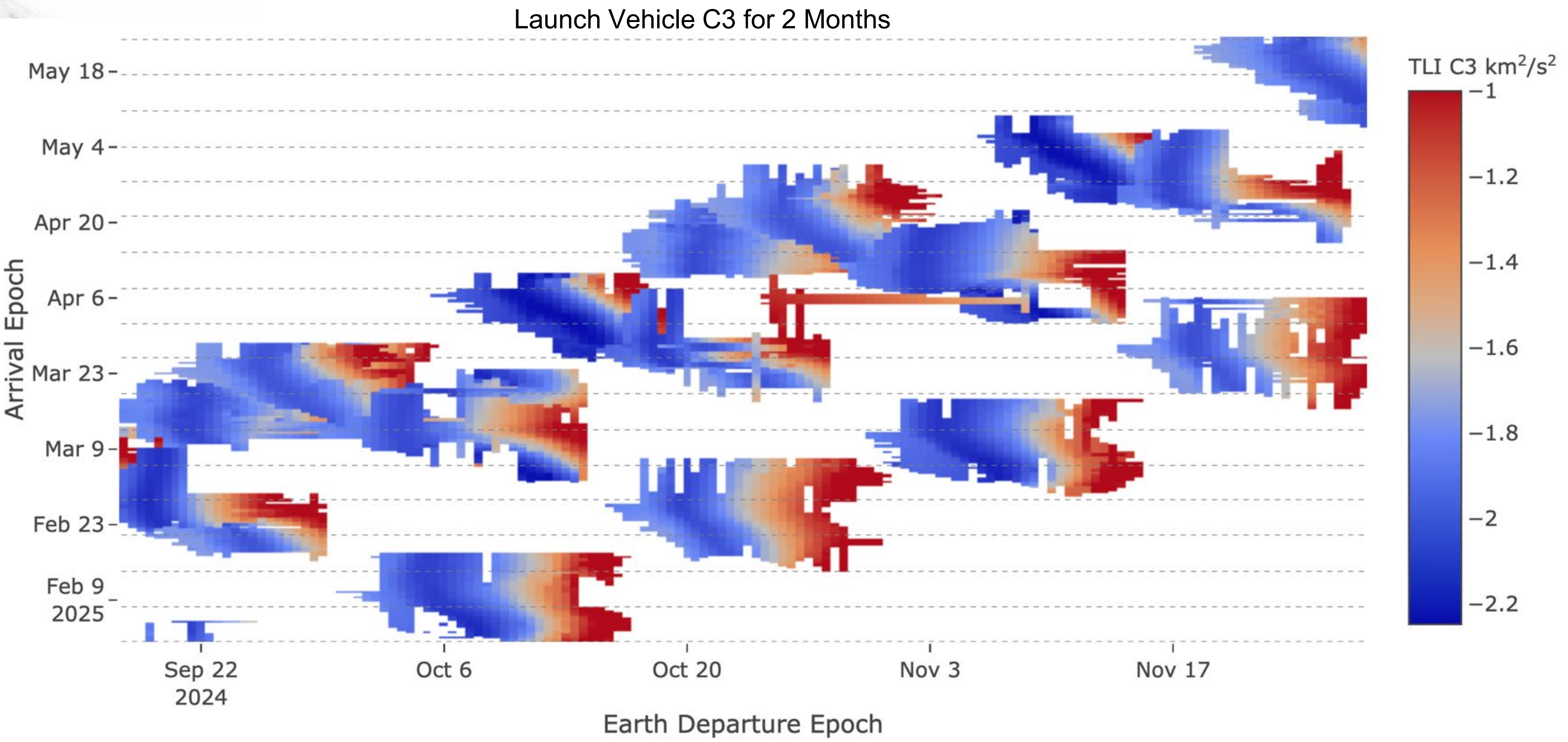
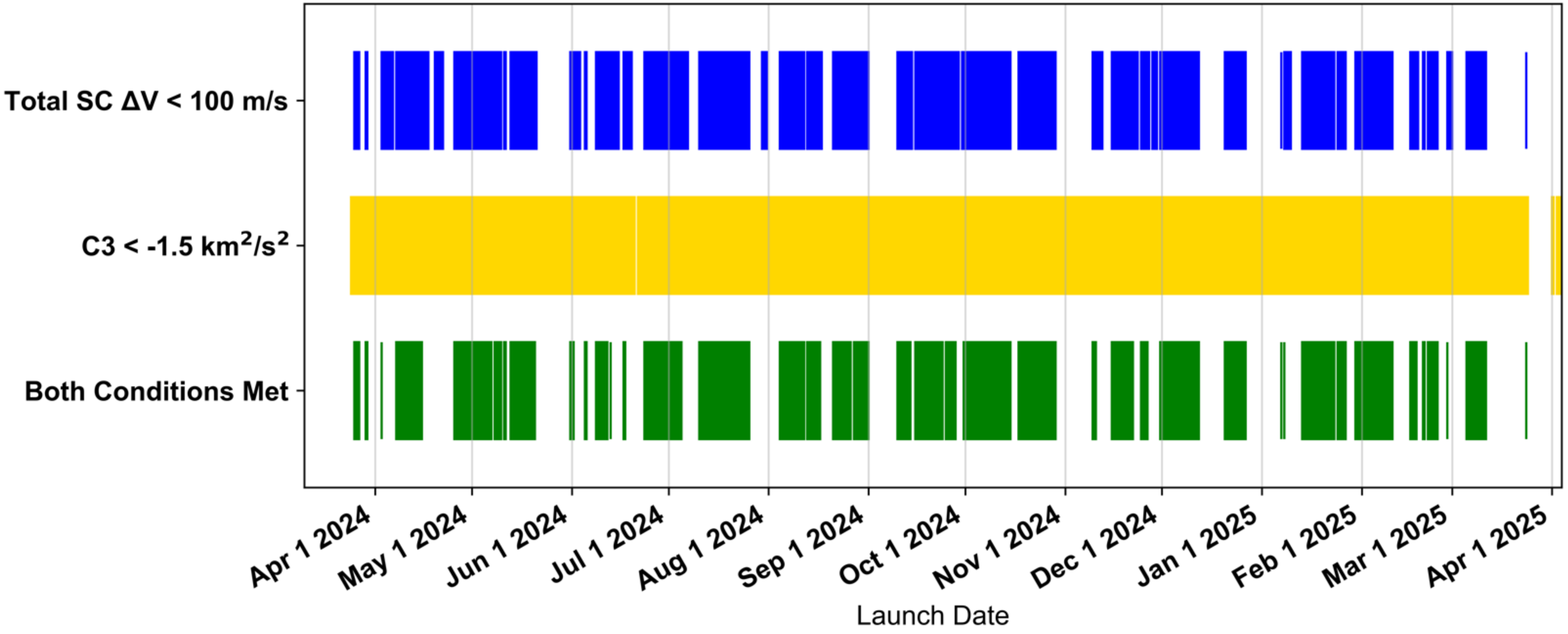


Phase-Fixed BLTs with Lunar Flyby



- 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

Summary

- BLT increases payload delivered to NRHO and reduces spacecraft ΔV compared to direct transfer
- Many launch opportunities exist
- Deterministic ΔV:
  - Insertion & rendezvous is <20 m/s
  - Launch and spacecraft performance determine deep space maneuvers (DSMs) and launch period availability
- Statistical ΔV 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.

Acknowledgements

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under contract 80NSSC19C0001

Delivering innovation to orbit.™

Thank you

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

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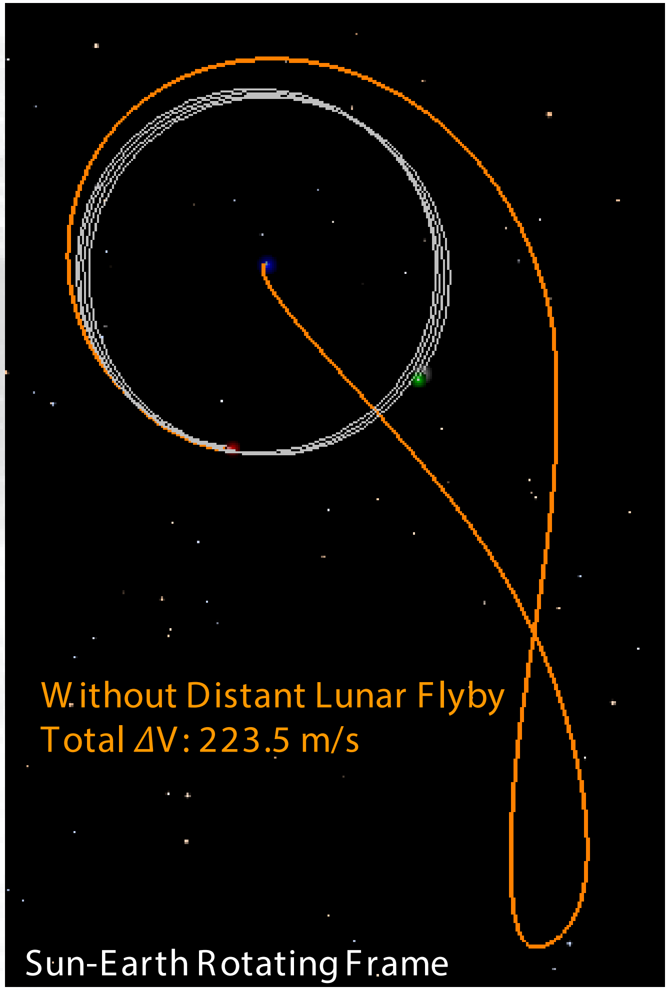
Backup

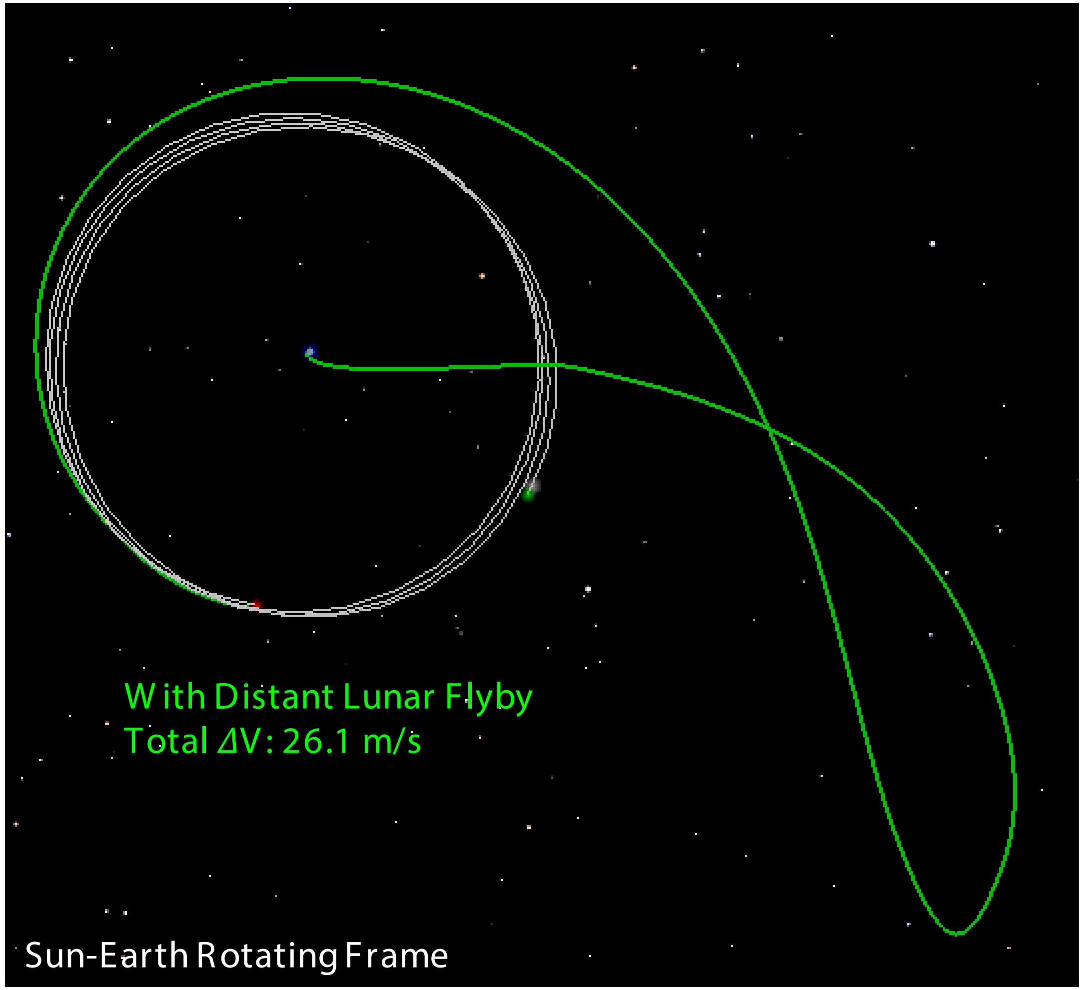
Phase-Fixed BLTs - Example Simultaneous Options

TLI Epoch: 2024 May 20 12:00



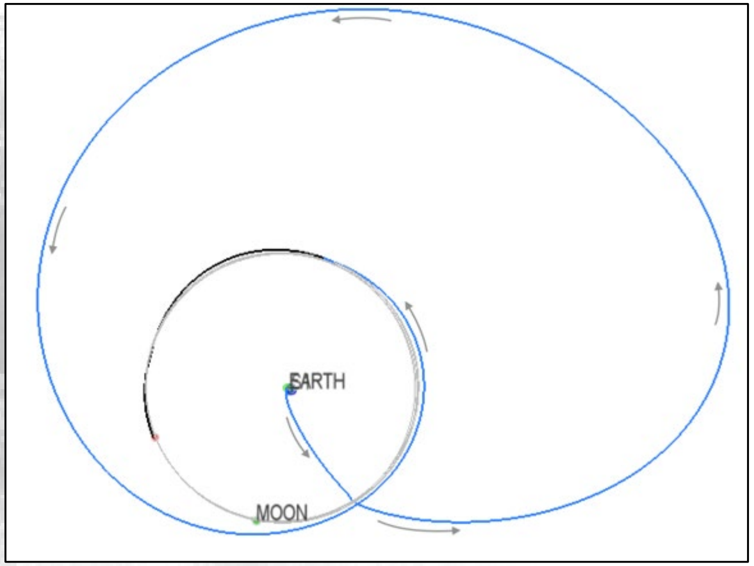
or

TLI Epoch: 2024 May 21 00:00

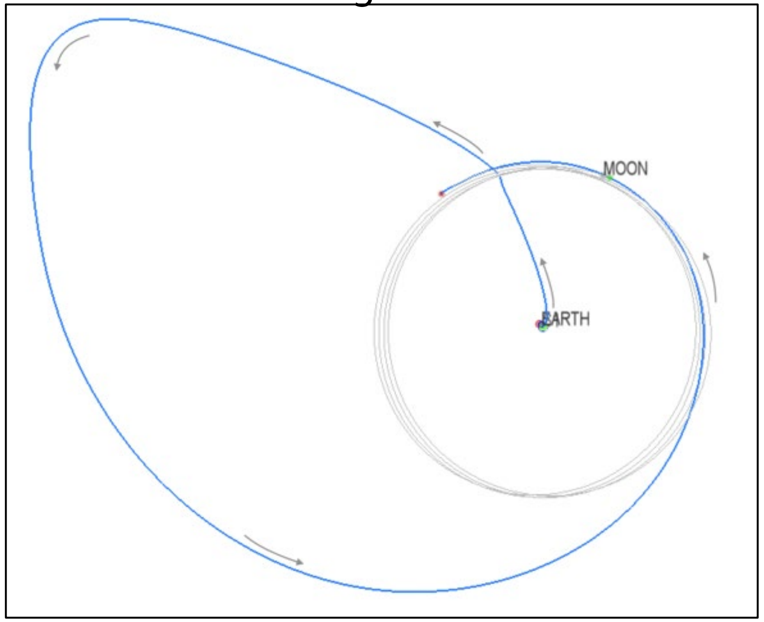


Summary - Representative Case

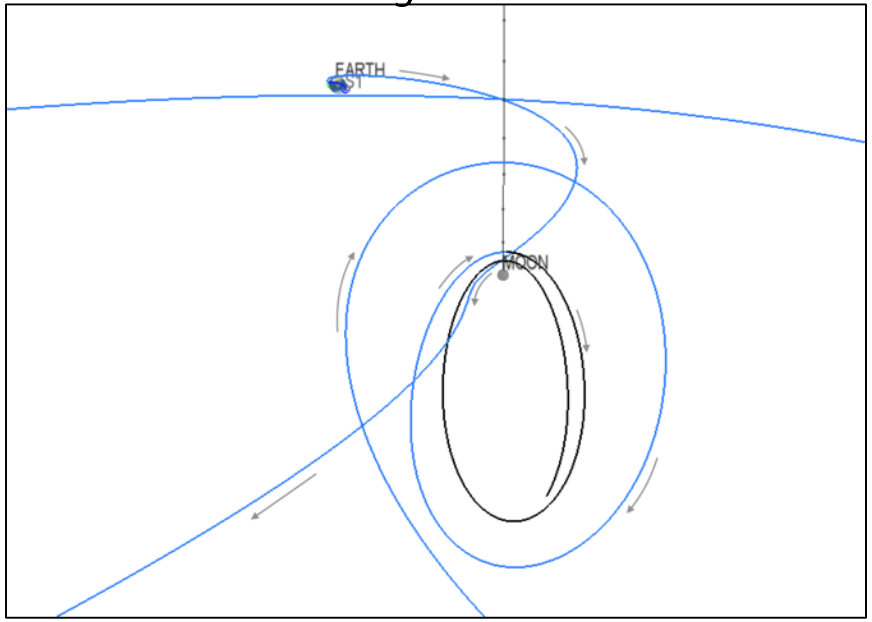
Inertial frame



Sun-Earth rotating frame



Earth-Moon rotating frame



Characteristics:

- Lunar flyby launch opportunity: March 27 - April 4, 2024
- Launch vehicle C3 requirement: -1.4 km^2/s^2
- 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