National Aeronautics and Space Administration

HLS NRHO to Lunar Surface and Back Mission Design

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Aug 9th, 2022
Joint Flight Mechanics / GN&C TDT Meeting

Agenda

- HLS In-Space and Powered-Flight Trajectory Design
- Fast Trajectory Scans using Initial Guess Generator
- End-to-End Optimization of the HLS Integrated Mission
- HLS-Orion Return RPOD Performance Analysis
- HLS Surface Abort Analysis
- Orion-Assisted Rescue of HLS Ascent Element

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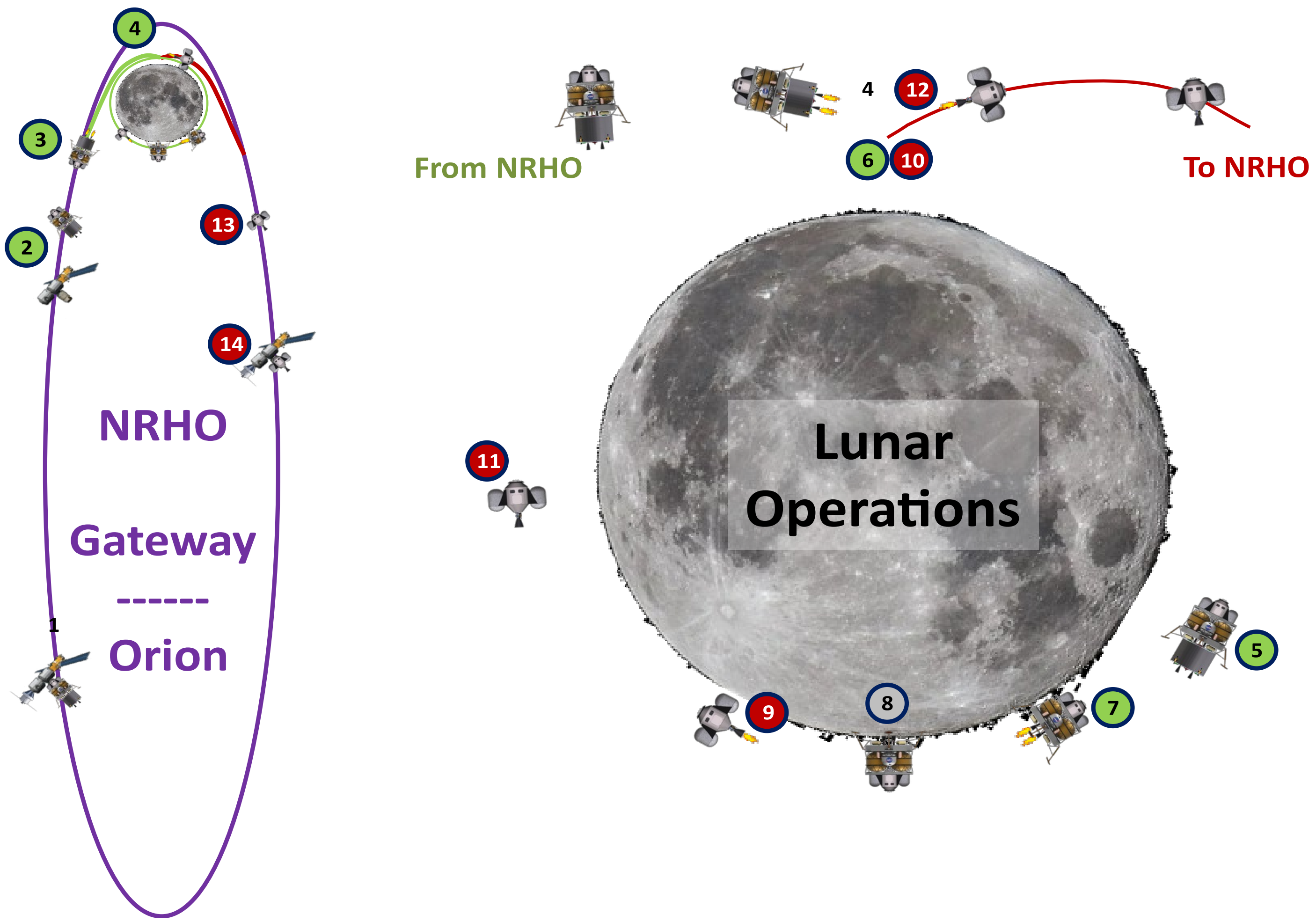
HLS Nominal Mission Schematic



1. NRHO Gateway: *9:2 Lunar Synodic Resonant, ~6.5 day Orbit Period, HLS Lunar Lander Attached to Gateway / Orion*
2. Separation from Gateway / Orion
3. NRD - NRHO Departure *to Moon*
4. LOI - LLO Arrival - *100km Circular Altitude*
5. Loiter in LLO *(3-4 revs)*
6. DOI *to 100x15.3km Altitude Ha x Hp*
7. PDI to Lunar Surface
8. Approximately 6 day lunar surface stay
9. Launch to 100x15.3km Altitude Ha x Hp
10. Circularization into a 100 km Altitude LLO
11. Loiter in LLO (3-4 revs)
12. LOD *back to Gateway*
13. NRI - NRHO Arrival
14. RPOD w/ Gateway/Orion

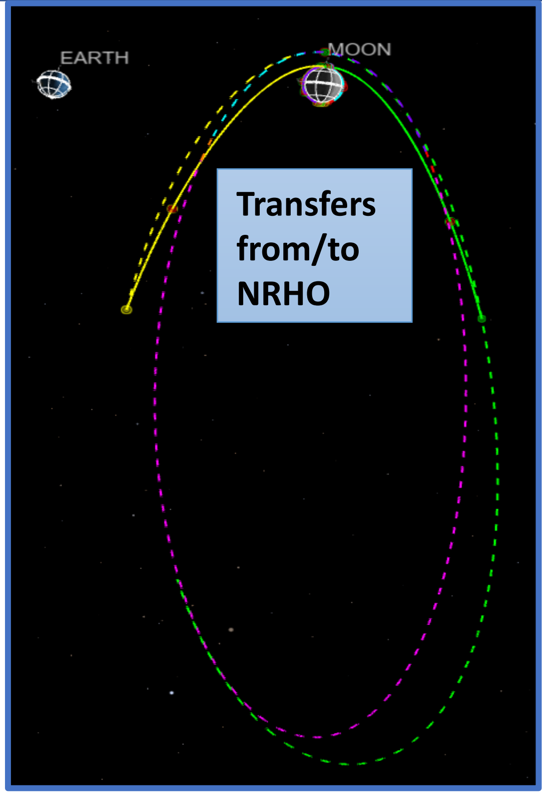
HLS Mission to lunar surface and back consists of In-Space, Powered Descent (PD), and Powered Ascent (PA) trajectory segments

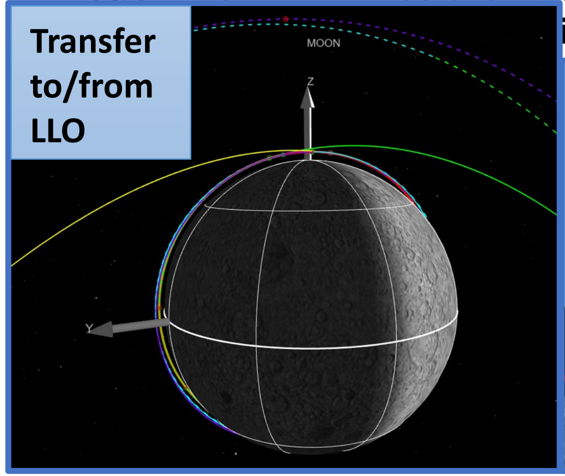
HLS Mission Design in Copernicus

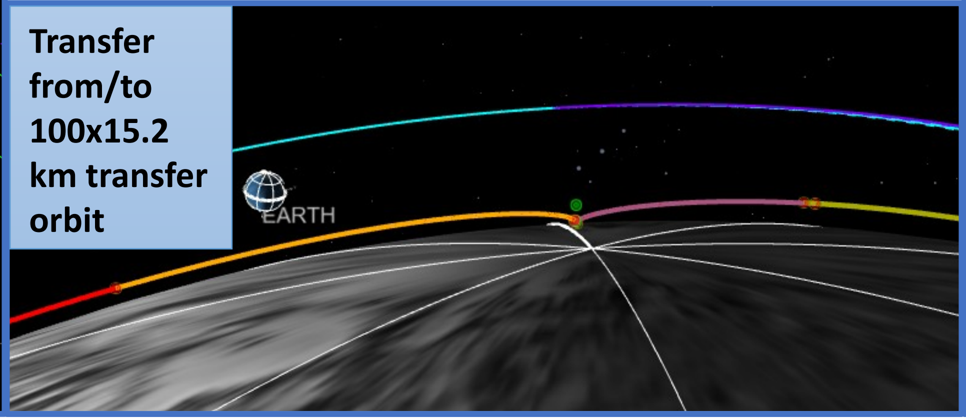
- Copernicus is a generalized 3-DOF trajectory design and optimization tool actively being developed at NASA-JSC. Extensively used for nominal and abort trajectory optimization for the Artemis program. It uses multiple-shooting direct method for transcription of the optimal control problem, which is numerically solved using state-of-the-art optimizers, such as, SNOPT and IPOPT.

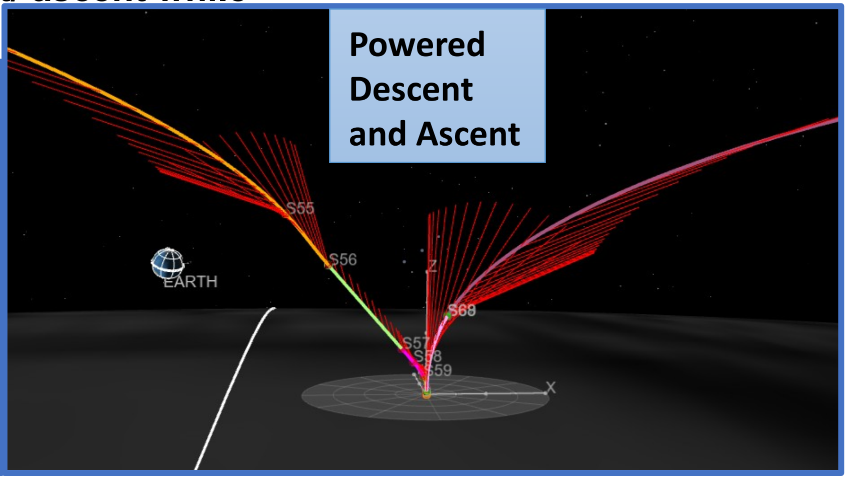
- For HLS mission design, a single Copernicus Ideck having a fully integrated 3-DOF Powered Descent (PD) and Powered Ascent (PA) model with the In-Space trajectory segments (NRHO-LLO transfers, LLO revs, etc.) is implemented.

- Copernicus optimizes the entire HLS mission in a high-fidelity dynamic model
  - Lunar gravity model: GL0660B 8x8 (GRAIL) and third-Body perturbations from Earth and Sun (DE421)
  - Also, models prop boil-off effects and mass impacts for executing TCMs
  - Optimizer minimizes the In-space Delta-V and prop mass used for powered descent/ ascent while ... ific constraints

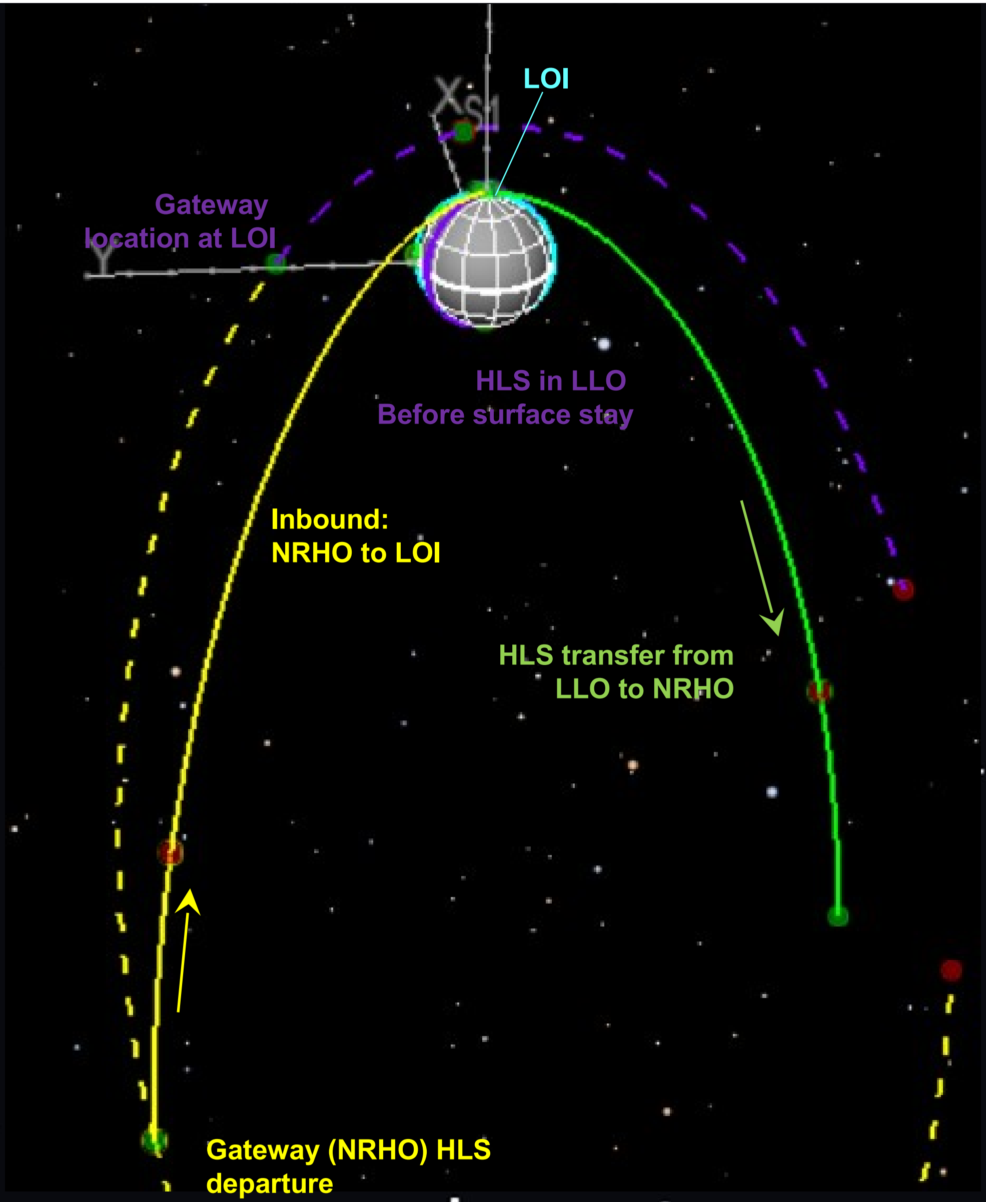


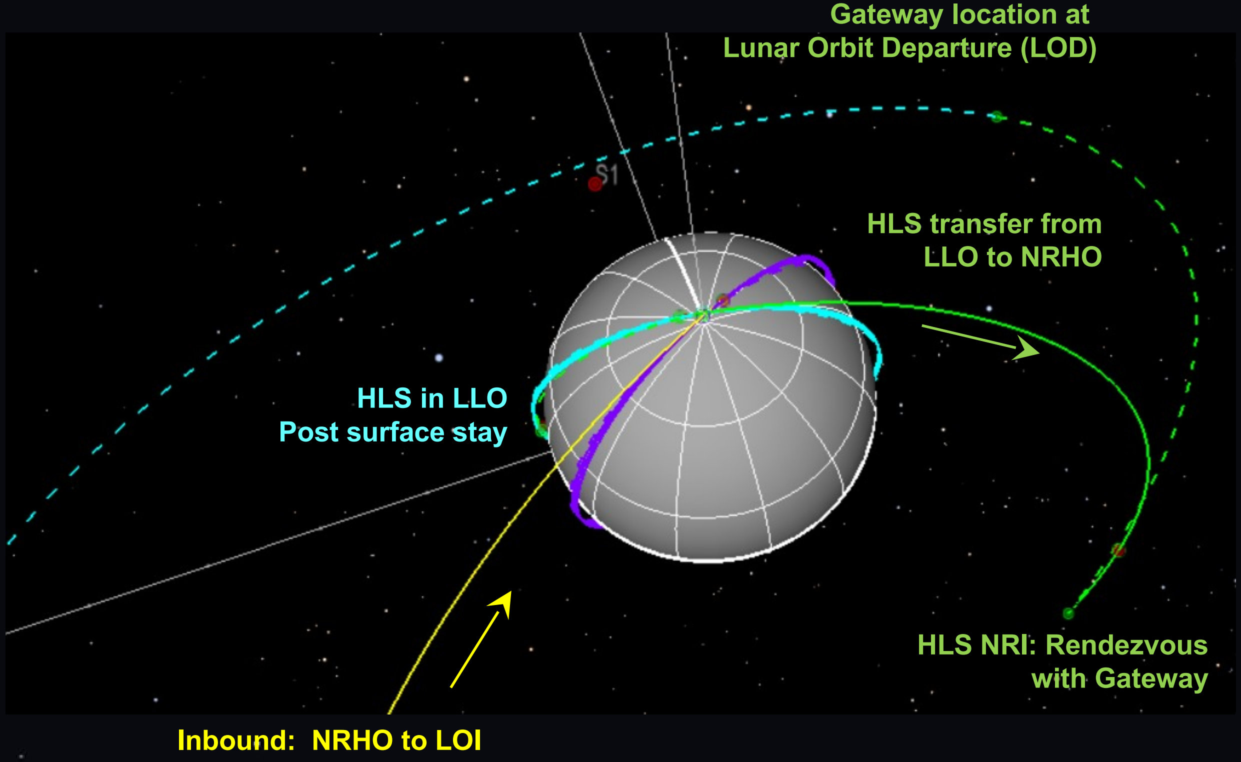






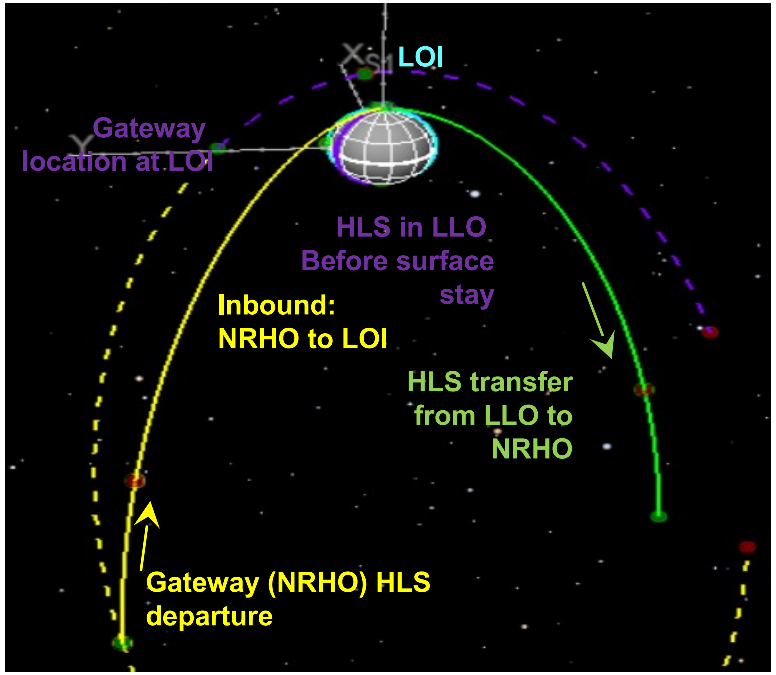
In-Space HLS Trajectory Segments



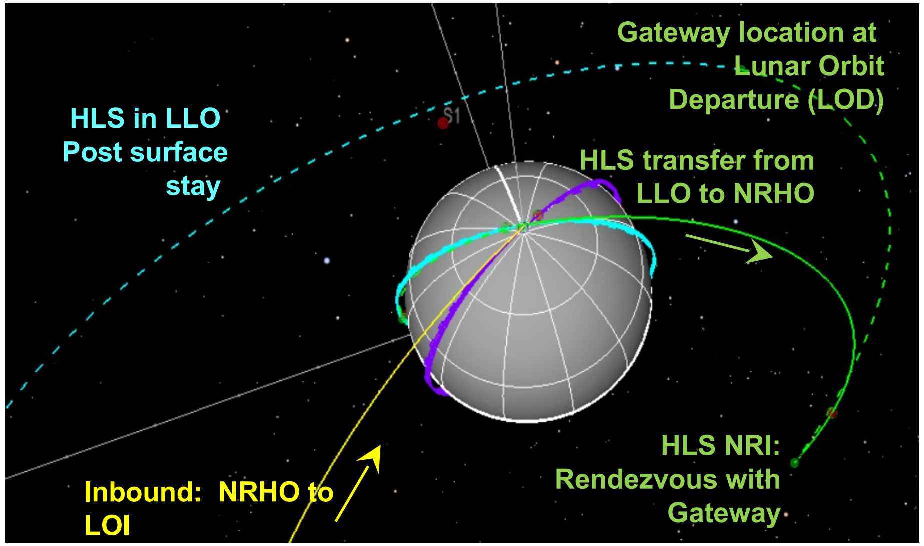


In-Space Mission Design & Optimization

- **In-space Trajectory Segments (Nominal Mission)**
  - Two-Burn 12-hr Transfers between NRHO and LLO
  - Two Full Loiter Revs in LLO (100 km alt.)
    - ✓ LLO approach provides multiple benefits including time for navigation state updates, “standard” operations approach, flexibility in accommodating crew timelines
  - A phasing Rev in LLO for aligning descent orbit perilune with the landing site
  - Coast in the elliptical transfer orbit (100 km apolune and 15.24 km perilune altitudes) before/after powered descent/ascent



- **In-Space Optimization in Copernicus**
  - Optimization Quantities (Controls)
    - ✓ NRD and NRI Burns and their TIG times
    - ✓ LOI and LOD Burns
    - ✓ Outbound and Inbound LLO Orbital plane Orientation (Inc and RAAN)
    - ✓ Phasing Revs in Outbound and Inbound LLO (True Anomaly)
  - Cost Function: Total In-space Delta-Vs: NRD, LOI, LOD, NRI, DOI, and LLO circ. burns

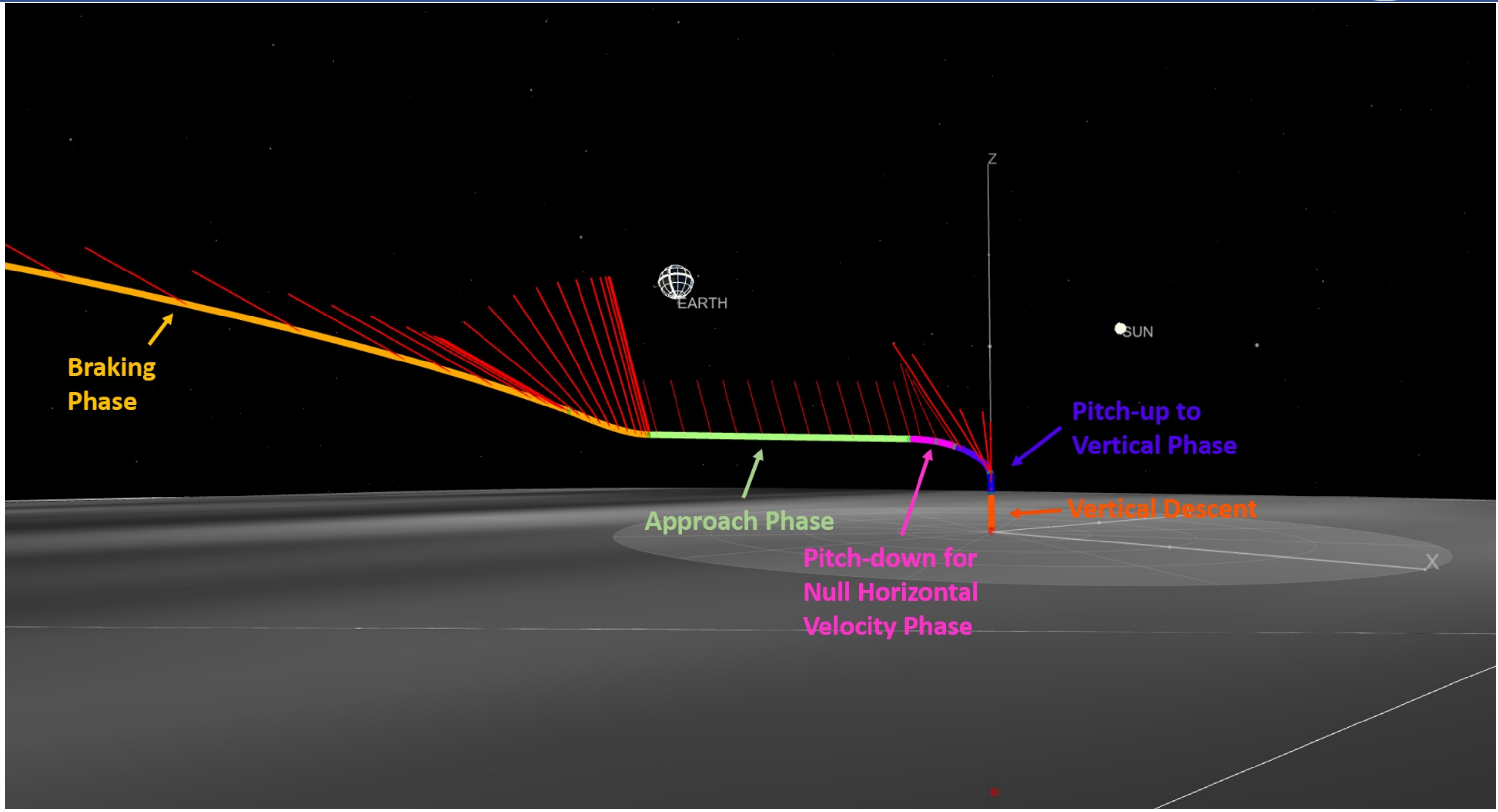


HLS Powered Descent Design in Copernicus

- **After DOI burn and coast in the elliptical transfer orbit with perilune altitude 15.24 km, PDI is performed near the perilune to start the braking phase of the powered descent**

- **The entire powered descent is divided into the following phases:**
  - **Braking Phase (BP)**
  - **Approach Phase (AP)**
  - **Pitch-down for Null Horizontal Velocity Phase (BN)**
  - **Pitch-up to vertical**
  - **Terminal (or Vertical) Descent (TD)**

- **Nominal Powered Descent uses in-plane steering with the 3-DOF PD trajectory coplanar with the LLO plane (no yaw steering is used in the nominal conops)**



- **Vehicle's pitch (and yaw) attitude is assessed from the thrust direction**
- **Copernicus optimizes the thrust in-plane direction (or pitch attitude) and throttle**
- **Vehicle's pitch and pitch-rate continuity are enforced across different phases, important for 6-DOF verification of the 3-DOF reference trajectory**

Powered Descent Optimization

Objective Function: Vehicle's post-touchdown mass

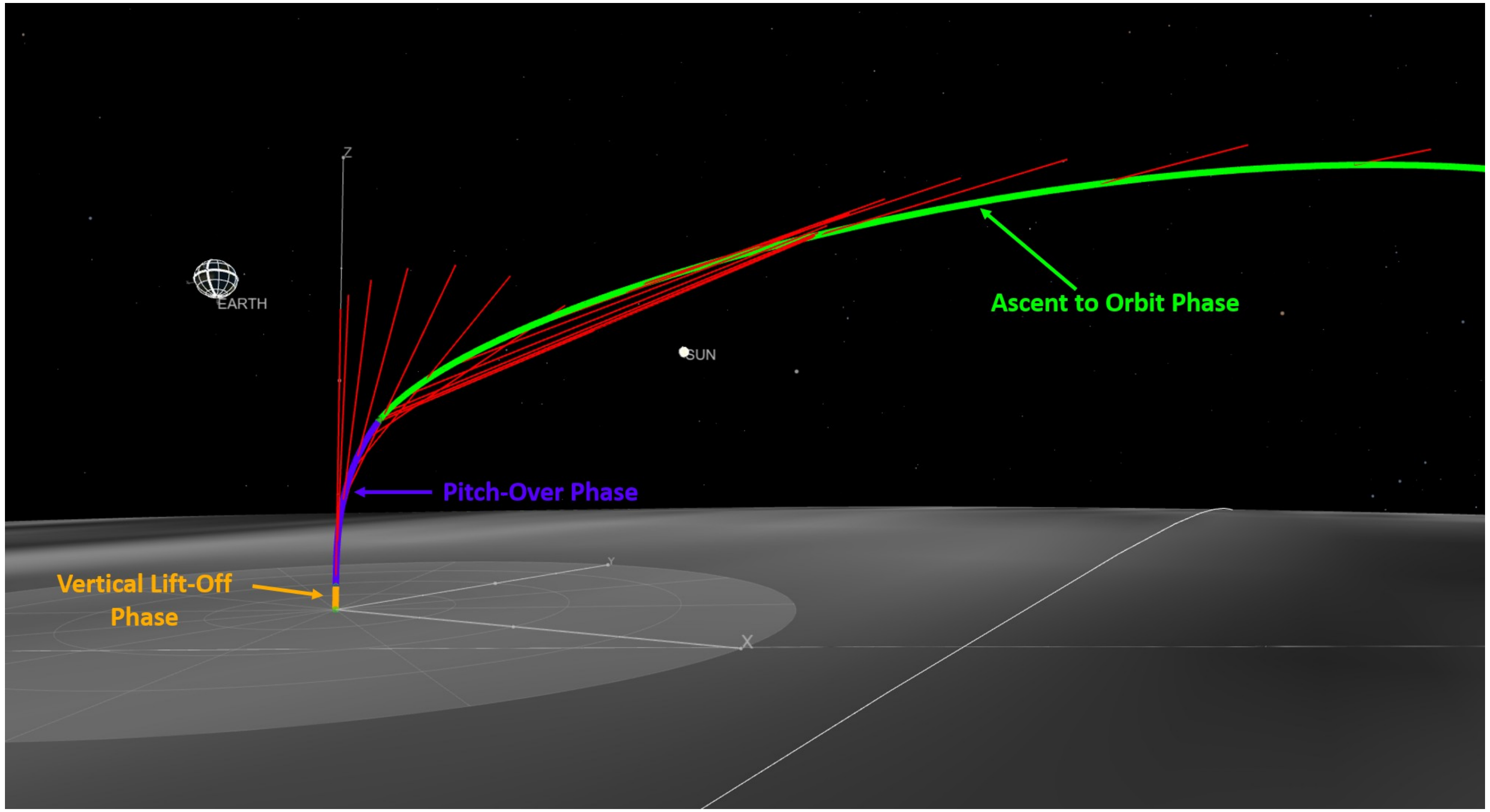
Controls	Constraints
PDI time	DE MPS Thrust > 20% for all the phases
BP duration and throttle	Max LVLH pitch rate = 5 deg/s
BP in-plane steering	Max LVLH pitch angular acceleration = 1 deg/s^2
AP thrust acceleration	AP starts at a range of < 2 km from the landing site
AP in-plane steering	Look angle during AP > 25°
AP out-of-plane steering	AP time duration > 45 s
BN duration	BN phase pitch from the vertical < 32°
BN thrust acceleration	TD starts at 200 m above the landing site
BN in-plane steering	TD initial descent rate = 15 m/s
Pitch-up to vertical phase duration	TD descent rate = 1 m/s at 10 m altitude
Pitch-up to vertical thrust acceleration	Constant 1 m/s descent rate from 10 m to 1 m altitude
Pitch-up to vertical in-plane steering	5 min < Powered descent duration < 20 min
TD phase duration	
TD phase thrust acceleration	

- **Powered Descent initial conditions are set by the optimized In-Space trajectories (patched mission)**
- **Copernicus' optimizer finds solution for the Control Variables to**
  - **Satisfy Constraints**
  - **Maximize/Minimize the Objective function, e. g., maximize the vehicle's post-touchdown mass**

HLS Powered Ascent Design in Copernicus

- After lunar surface operations, the ascent trajectory starts with vertical lift-off to raise altitude before final ascent to the orbit. MECO occurs near the perilune of the 100x15.24 km altitude ascent orbit

- The entire Powered Ascent is divided into 3 phases:
  - Vertical Lift-Off
  - Pitch-Over Phase
  - Ascent to Orbit phase



- Nominal Powered Ascent uses in-plane steering with the 3-DOF PA trajectory coplanar with the LLO plane (no yaw steering is used in the nominal conops)
- Copernicus optimizes the thrust in-plane direction (or pitch attitude) and throttle
- Vehicle’s pitch and pitch-rate continuities are enforced across different phases, important for 6-DOF verification of the 3-DOF reference trajectory

Powered Ascent Optimization

Objective Function: Vehicle's post-NRI Mass

Controls	Constraints
Vertical lift-off duration and throttle	Altitude=100 m at the end of vertical lift-off
Pitch-over phase duration	Max LVLH pitch rate = 5 deg/s
Pitch-over phase velocity azimuth	Max LVLH pitch angular acceleration = 1 deg/s^2
Pitch-over phase in-plane steering	Insertion into the ascent orbit at the end of the ascent phase
Pitch-over phase out-of-plane steering	Powered ascent total duration $<$ 9 min
Ascent phase duration and throttle	
Ascent phase in-plane steering	
Coast duration in the ascent orbit	

- **Powered Ascent initial conditions are set by the optimized In-space and powered descent trajectories (patched mission)**
- **Copernicus' optimizer finds solution for the Control Variables to**
  - **Satisfy Constraints**
  - **Maximize/Minimize the Objective function, e. g., maximize the vehicle's post-NRI Mass**

Summary & Future Work

- **Summary**
  - **A fully integrated HLS mission with In-Space, powered descent, and powered ascent (in 3-DOF mode) is implemented in a single Copernicus Ideck**
  - **Using the integrated HLS Ideck, the mission performance is optimized for a given landing site and mission epoch (or a range of epochs/sites for scans)**
  - **Reference trajectory from Copernicus is optimized in high-fidelity dynamic model and can be used for generating guidance (nominal or abort) targets and potentially as input to flight ops tools for computing vehicle burn plans (as is done currently for Artemis 1)**

- **Future Work**
  - **System weights capability in Copernicus to design the s/c from the mass elements perspective (one application is to track fuel and oxidizer masses separately)**
  - **Terrain Modeling capability in Copernicus for surface lighting and line-of-sight analyses**
  - **Guidance algorithms implementation in Copernicus for specific HLS segments using Copernicus plugins (either internal or using Genesis as plugin)**

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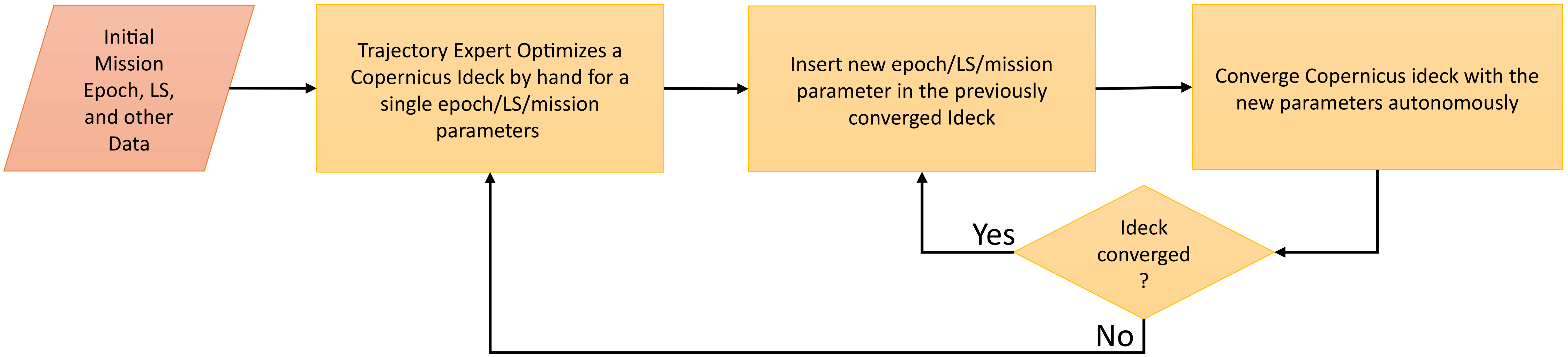
Trajectory Scans

- HLS trajectory scans are used to assess variation in mission performance across range of epochs and landing sites

- Typically, Copernicus' converged ideck and continuation method is used for trajectory scans



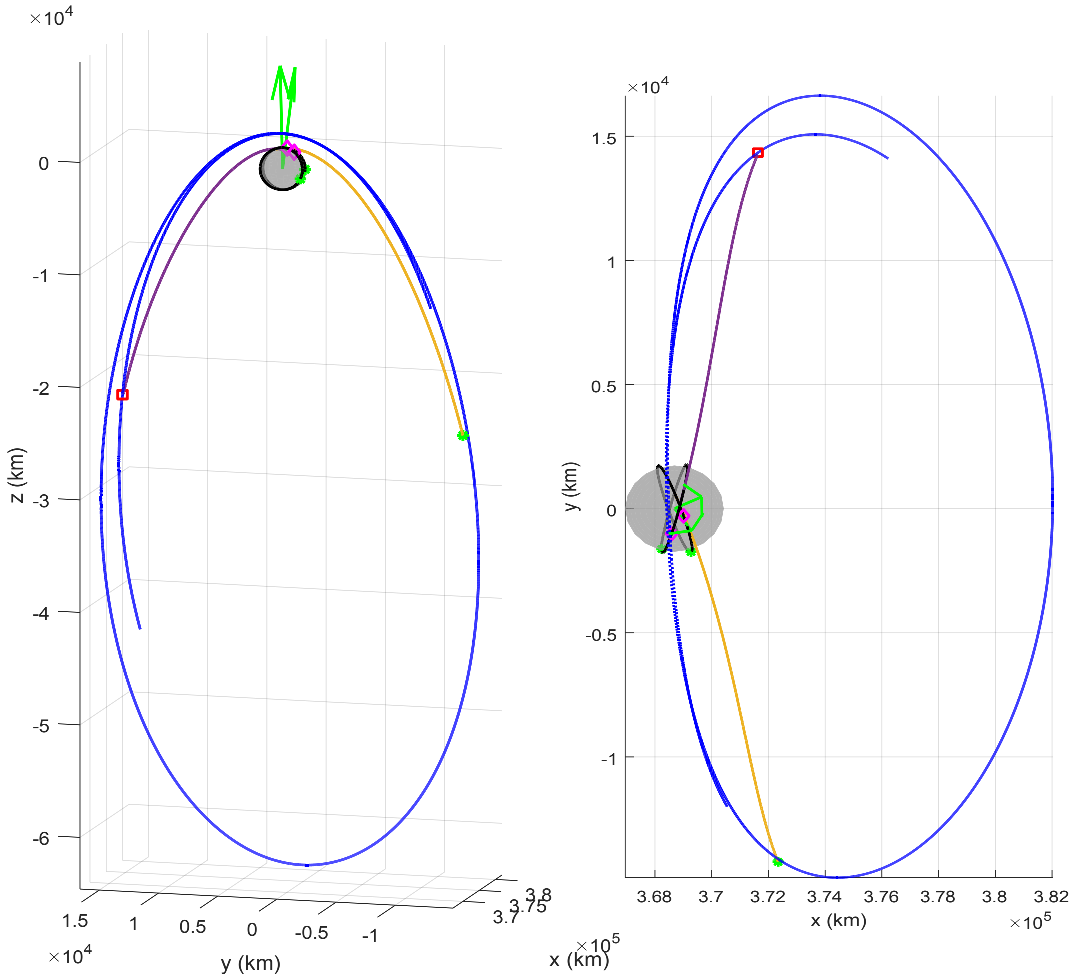
- Slow process and prone to non-convergence if the continuation steps are bigger. Additionally, small continuation steps increase computational load and execution time.

- For HLS trajectory scans, a new semi-analytic tool called as Initial Guess Generator (IGG) was developed to compute initial guesses quickly for the in-space trajectories

Initial Guess Generator (IGG)

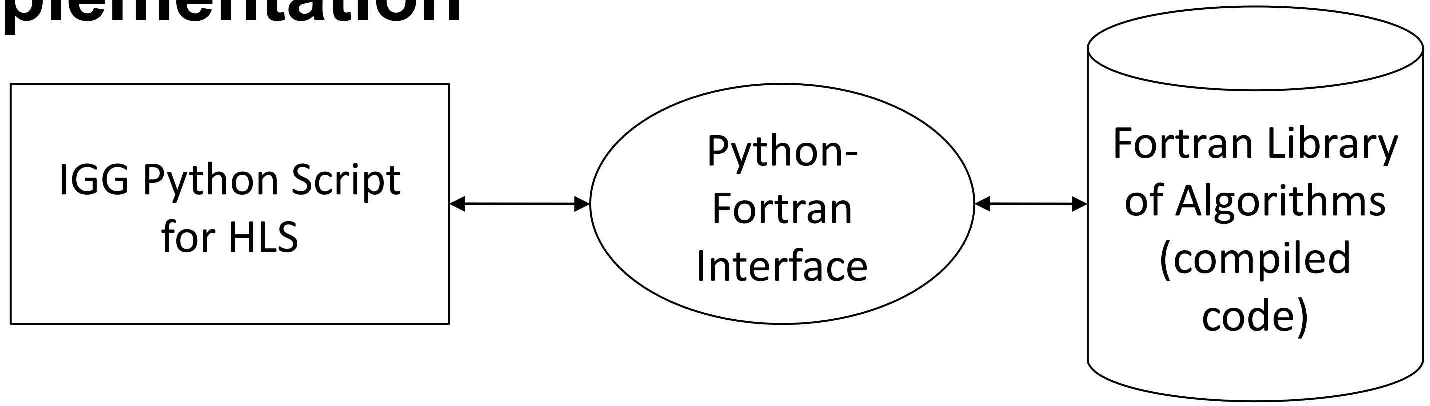
- IGG uses pseudo-state technique for computing trajectories
  - Superimposes Two-Body solutions to approximate Three-Body trajectories
  - Provides an approximate Lambert solver for the restricted three-body problem
  - Provides fast scan capability compared to Copernicus' numerical-optimization based scans
  - Provides good initial guesses for faster convergence of Copernicus idecks

- IGG Computations for HLS Nominal Mission
  - NRD, LOI, LOD, NRI time and ΔV states
  - LOD and LOI burn locations
  - Outbound and Inbound LLO plane orientation
  - Surface stay time/Surface Lift-off time
  - DOI and LLO circ. Burn time and locations

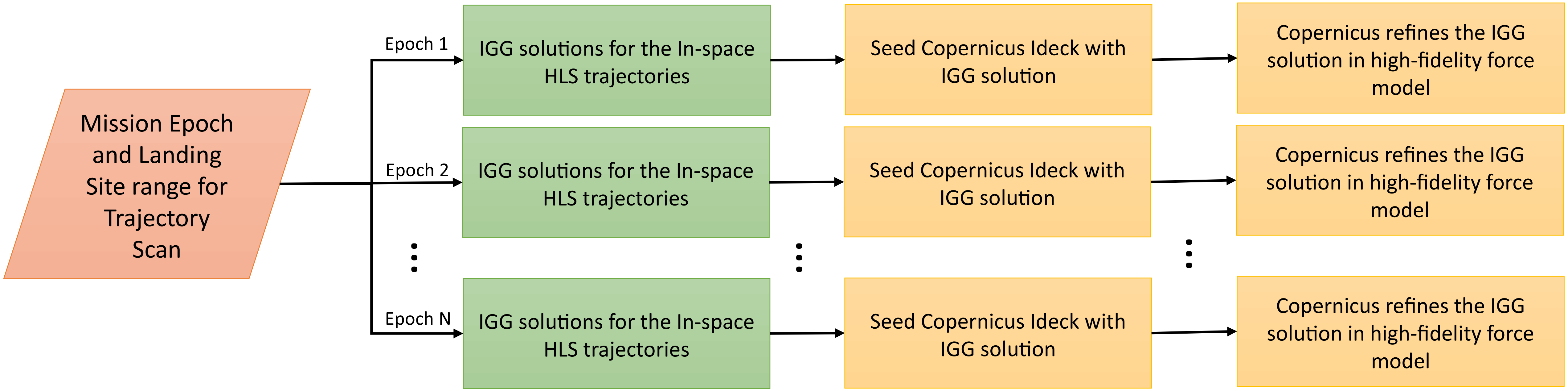


HLS Trajectory Scan Process using IGG

- **IGG Tool Implementation**

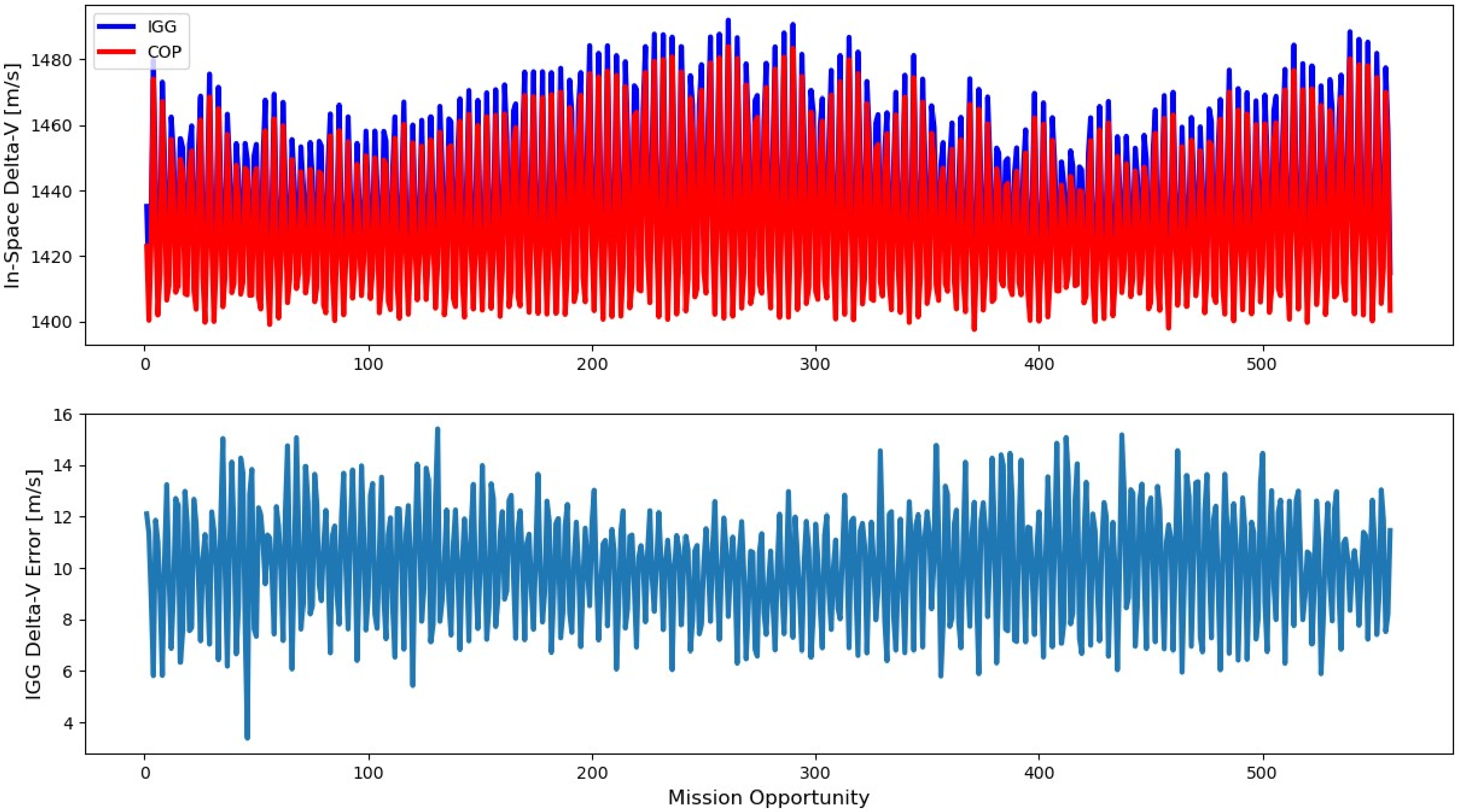


- **Parallelized HLS Trajectory Scan**



HLS In-Space Trajectory Epoch Scan using IGG

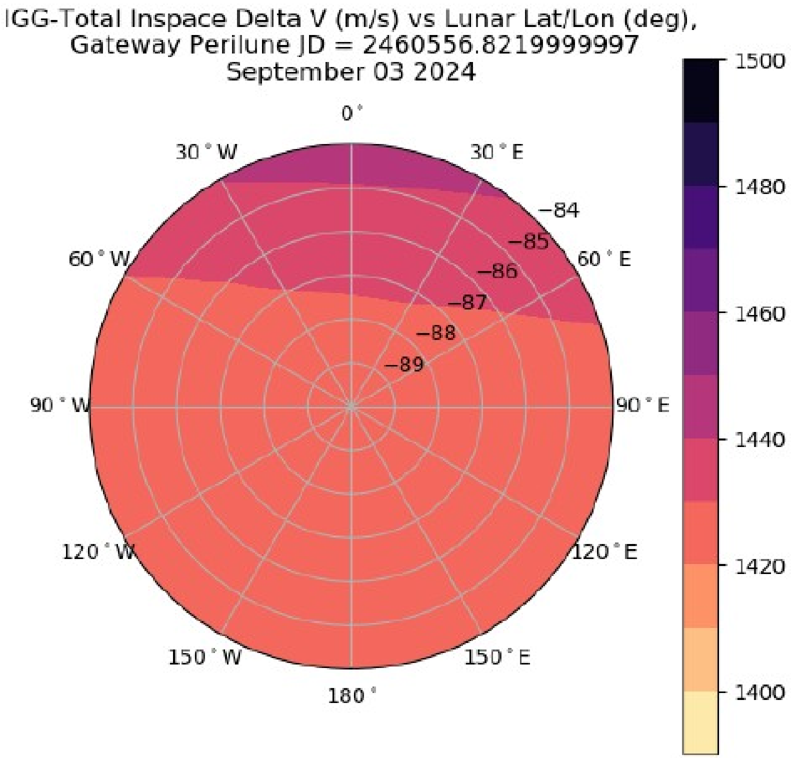
- **Start Epoch: Sep 3, 2024**
- **Scan Duration: 10 years (557 opportunities)**
- **Landing Site: Malapert (Latitude: -86.0 deg, Longitude: 2.4 deg)**
- **IGG Computation Time: 30 s (on laptop)**



IGG exhibits an error of <1% for Nominal In-Space Delta-V estimates with execution speed much faster than a similar Copernicus scan

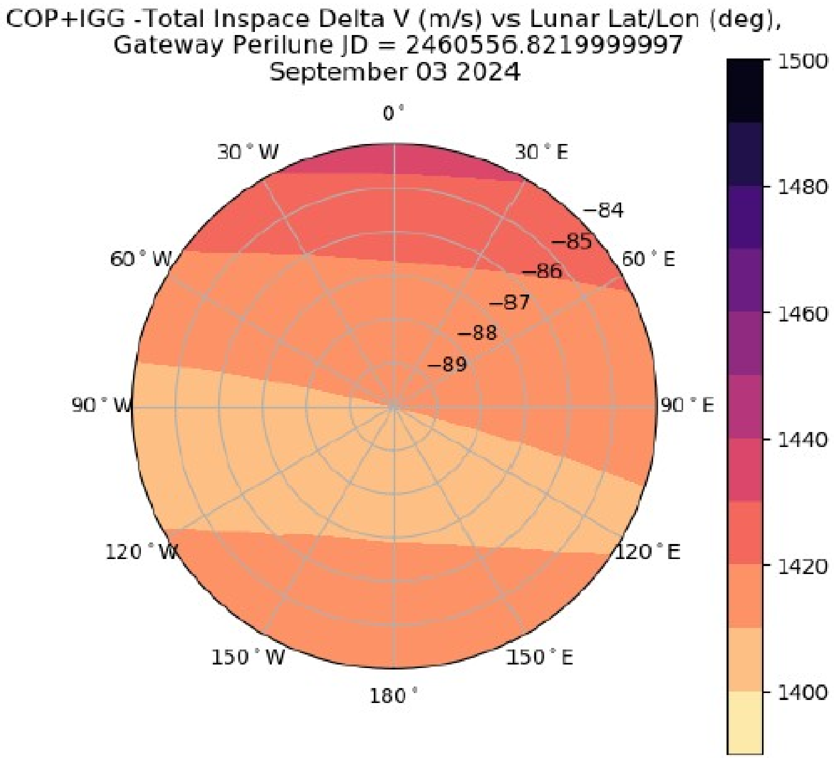
HLS In-Space Landing Site Scan using IGG (Near-Polar Region)

IGG Results for In-Space Delta-V



Max: 1444.63 m/s
Mean: 1425.42 m/s
Min: 1419.99 m/s

IGG-assisted Copernicus Results



Max: 1433.87 m/s
Mean: 1412.97 m/s
Min: 1407.71 m/s

IGG takes 4 s to complete a landing site scan for In-Space Delta-V estimate compared to 40 min taken by IGG-assisted Copernicus scan

HLS Global Access Performance Scan using IGG (1/2)

- **Mission epoch: Mar 25, 2028**
- **Heatmap shows HLS Total In-Space Delta-V Variation for Global Access from the NRHO**
- **The nominal mission parameters as used for near-polar landing sites were used**
- **IGG estimates were compared against a few Copernicus runs for verification**
- **High Delta-V regions are due to large plane change required during NRD and LOI burns to reach those sites**

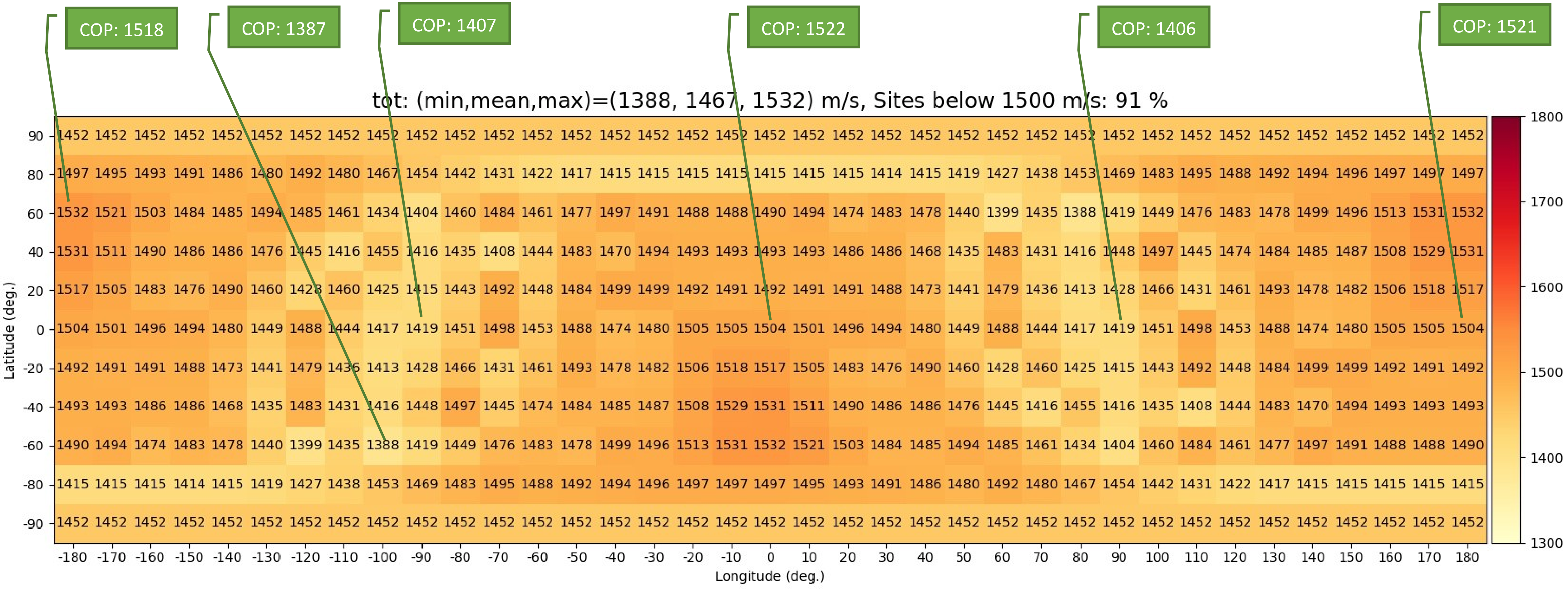
Copernicus Estimate:
1752 m/s

tot

Latitude (deg.) \ Longitude (deg.)	-180	-170	-160	-150	-140	-130	-120	-110	-100	-90	-80	-70	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
90	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	[illegible]	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452
80	1530	1528	1524	1519	1512	1503	1492	1480	1467	1453	1441	1430	1422	1417	1415	1415	1415	1415	1415	1415	[illegible]	1415	1415	1419	1427	1438	1452	1468	1482	1495	1506	1515	1521	1526	1529	1530	1530
60	1647	1644	1641	1637	1632	1626	1620	1612	1603	1581	1432	1488	1512	1521	1526	1530	1534	1538	1540	[illegible]	1545	1549	1556	1567	1590	1473	1525	1570	1598	1625	1643	1645	1647	1648	1650	1649	1647
40	1717	1715	1699	1664	1627	1589	1547	1500	1451	1414	1439	1506	1568	1620	1652	1646	1646	1646	[illegible]	1649	1653	1635	1591	1541	1487	1435	1415	1446	1496	1544	1589	1631	1668	1703	1718	1717	1717
20	1761	1724	1686	1645	1601	1554	1508	1459	1425	1415	1445	1494	1548	1601	1649	1693	1712	[illegible]	1711	1711	1671	1629	1581	1530	1480	1438	1414	1426	1464	1513	1562	1609	1654	1695	1733	1765	1761
0	1756	1718	1678	1633	1586	1538	1488	1444	1417	1419	1451	1499	1551	1601	1647	1692	[illegible]	1758	[illegible]	1718	1678	1633	1586	1538	1488	1444	1417	1419	1451	1499	1551	1601	1647	1692	1732	1758	1756
-20	1711	1711	1671	1629	1581	1530	1480	1438	1414	1426	1464	1513	1562	1609	1654	1695	1733	[illegible]	1761	1724	1686	1645	1601	1554	1508	1459	1425	1415	1445	1494	1548	1601	1649	1693	1712	1711	1711
-40	1646	1649	1653	1635	1591	1541	1487	1435	1415	1446	1496	1544	1589	1631	1668	1703	1718	1717	1717	1715	1699	1664	1627	1589	1547	1500	1451	1414	1439	1506	1568	1620	1652	1646	1646	1646	1646
-60	1540	1542	1545	1549	1556	1567	1590	1473	1525	1570	1598	1625	1643	1645	1647	1648	1650	1649	1647	1644	1641	1637	1632	1626	1620	1612	1603	1581	1432	1488	1512	1521	1526	1530	1534	1538	1540
-80	1415	1415	1415	1415	1415	1419	1427	1438	1452	1468	1482	1495	1506	1515	1521	1526	1529	1530	1530	1528	1524	1519	1512	1503	1492	1480	1467	1453	1441	1430	1422	1417	1415	1415	1415	1415	1415
-90	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452	1452

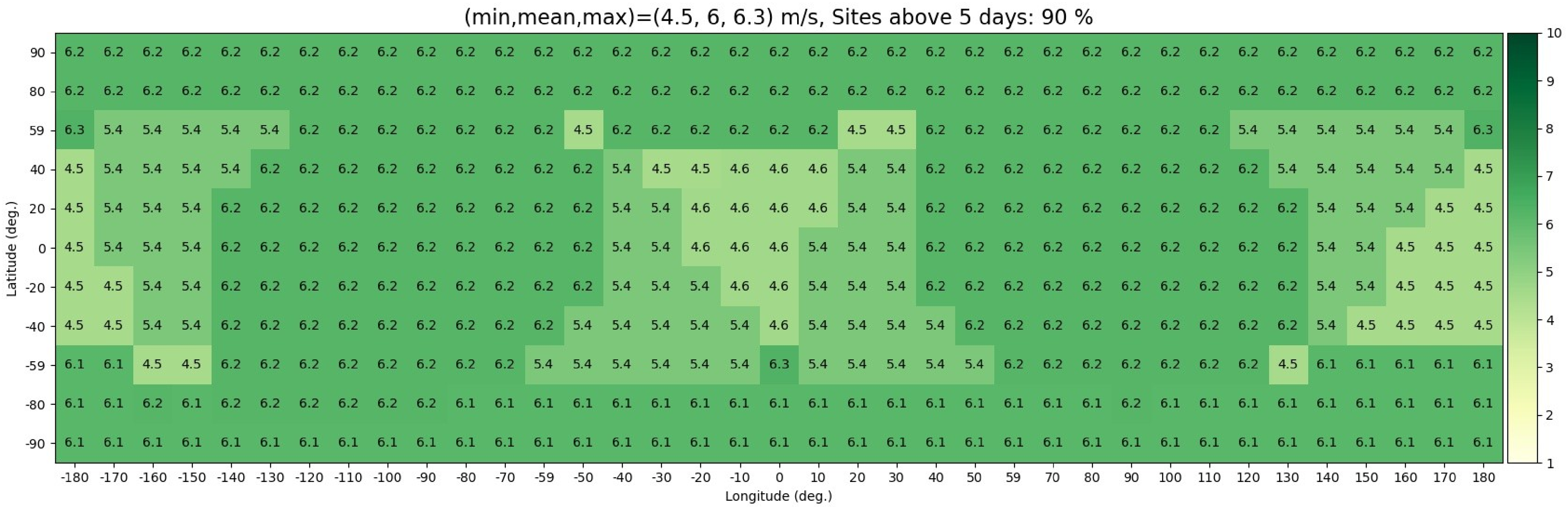
HLS Global Access Performance Scan using IGG (2/2)

- **Mission epoch: Mar 25, 2028**
- **The mission performance (In-Space Delta-V) was optimized by varying the nominal mission parameters**
  - **NRHO-LLO Transfer duration: 0.5-1.5 day**
  - **LLO revs between 1 and 12**
- **IGG estimates were compared against a few Copernicus runs for verification**

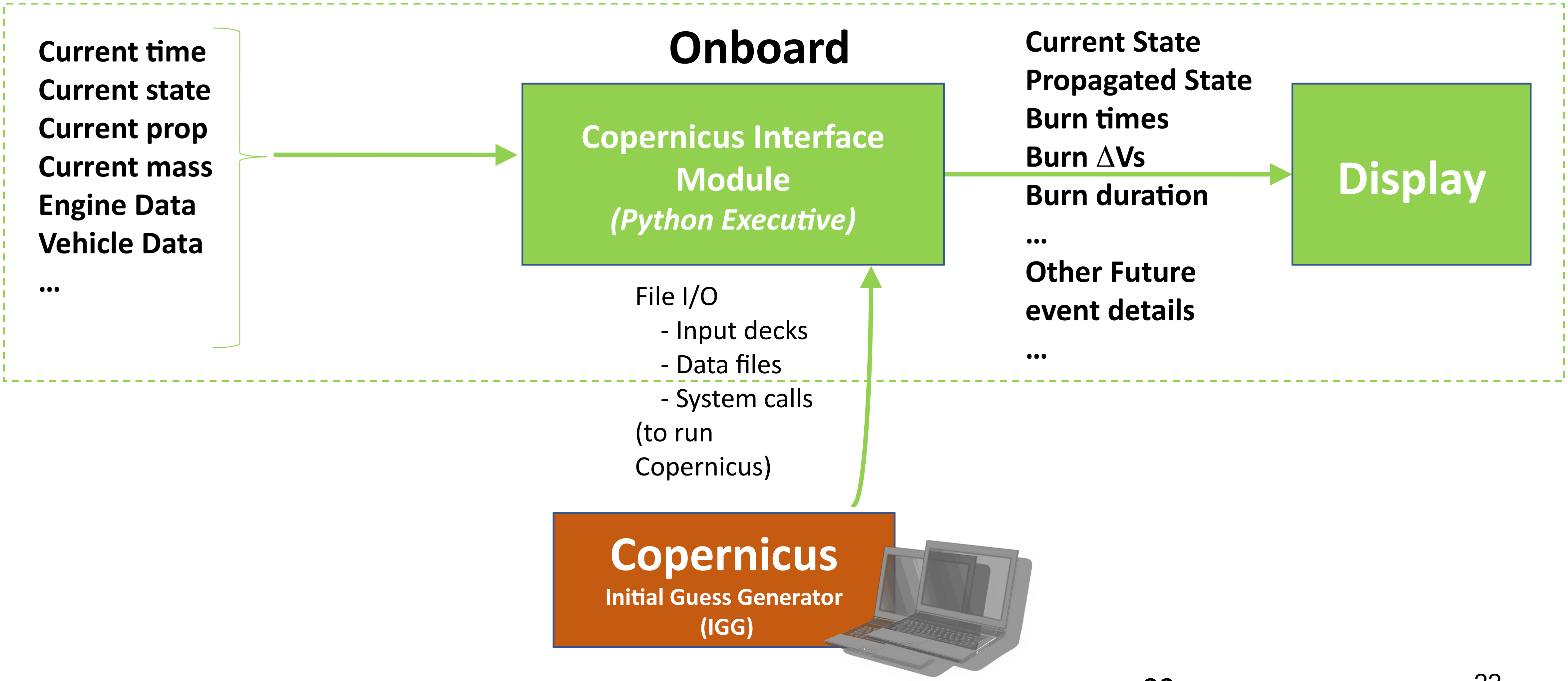


HLS Global Access Surface Stay Scan using IGG

- Mission epoch: Mar 25, 2028
- Heatmap shows HLS Surface Stay duration for each site
- The mission performance (In-Space Delta-V) was optimized by varying the nominal mission parameters
  - NRHO-LLO Transfer duration: 0.5-1.5 day
  - LLO revs between 1 and 12
- Surface stay duration is impacted the most for those landing sites that require maximum loiter in both the outbound and inbound LLOs
- With 2-3 LLO revs, the nominal surface stay duration is 6.1-6.2 days for this epoch



Potential Onboard Trajectory Planning Capability using IGG



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Summary & Future Work

- **Summary**
  - **IGG tool provides fast trajectory solutions using semi-analytic techniques and enables fast parallelized HLS trajectory scans**
  - **For near-polar landing sites, IGG exhibits an accuracy of ~1% for HLS In-Space Delta-V estimates and its results can be directly used for quick preliminary performance assessment**
  - **IGG can also be used for quick performance estimates for global lunar access from the NRHO**

- **Future Work**
  - **IGG for powered descent/ascent segments**
  - **Development of a multi-conic algorithm based IGG that has better accuracy for long term propagations in the cislunar space**
  - **Use of multi-conic based IGG for preliminary HLS abort analyses and to seed Copernicus-based HLS abort scans**
  - **IGG has the potential to augment Copernicus' capability for onboard autonomous mission plan capability that can provide real-time situational awareness for the crew and increase the probability to successfully complete a mission and/or return to Earth without required ground support.**

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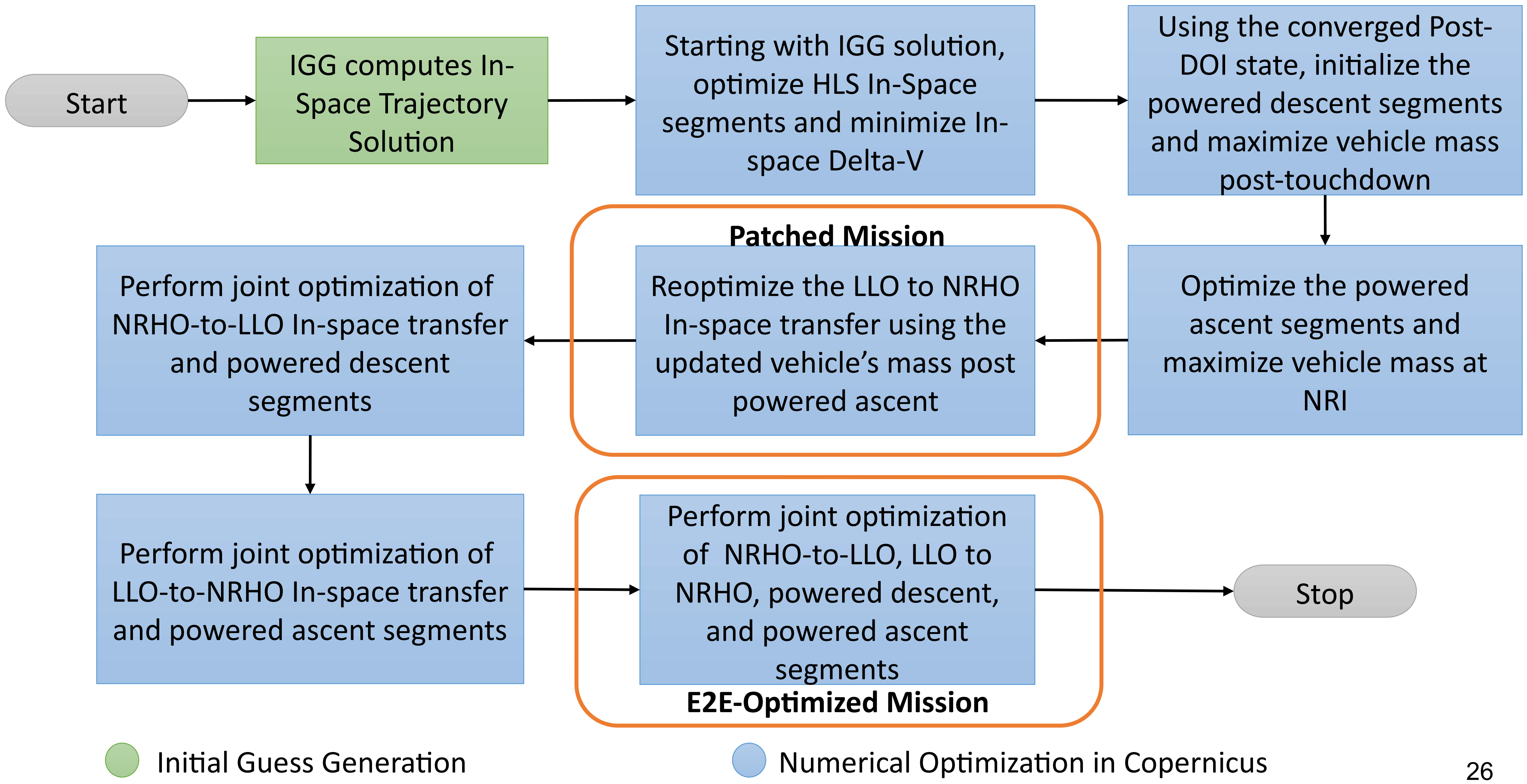
End-to-End (E2E) Performance Optimization

- **E2E Optimization Strategies for HLS**
  - **Separate tools for In-Space and Powered Flight segments**
    - ✓ **Grid of pre-computed In-Space trajectories from Copernicus, used in POST for initializing powered descent/ascent segments and performing overall optimization. In-space grid is parameterized by LLO Inc and RAAN.**
    - ✓ **Grid of pre-computed powered flight segments from POST, used in Copernicus to initialize in-space segments and performing end-to-end optimization. Powered flight grid is parameterized by Launch Azimuth.**
  - **Integrated optimization of In-space, powered descent, and powered ascent segments in Copernicus as part of a single optimization problem**

- **Benefits of E2E Optimization in Copernicus**
  - **Process less prone to bugs: optimization across all flight phases in a single tool and therefore, avoids bugs related to trajectory patching and reference frame misalignments**
  - **Better Optimization Accuracy: No interpolation is needed for optimization as in grid-based approach, All the control variables associated with the In-Space, powered descent, and ascent are simultaneously varied for finding the best (local) optimal solution.**
  - **Design of Descent Abort-Favored Nominal Mission**
  - **Faster trajectory scans**

E2E Optimization Process for HLS



Patched vs E2E-Optimized HLS Performance

HLS Mission Epoch: Jan 12, 2025; Landing Site: -84.2 deg Lat, 59.8 deg Lon

	Patched Sim (Baseline case)	Integrated Sim	Patched with +6 hr surface stay	Integrated with +6 hr surface stay
NRHO-to-LLO Δv [m/s]	**734.91**	-0.01	+0.46	+1.38
NRHO-to-LLO prop mass [kg]	**8360.86**	-0.09	+4.70	+14.05
DOI Δv [m/s]	**19.87**	0	0	0
PD Δv [m/s]	**1952.03**	-6.54	+6.90	-6.52
PD prop mass [kg]	**14924.08**	-36.72	+36.70	-42.79
PA Δv [m/s]	**1817.17**	-0.80	+54.89	-0.41
PA prop mass [kg]	**3832.25**	-1.14	+86.35	-0.65
LLO circ. burn Δv [m/s]	**19.87**	+0.13	0	+0.13
LLO-to-NRHO Δv [m/s]	**713.33**	0	+346.15	+340.35
LLO-to-NRHO prop mass [kg]	**1011.77**	+0.22	+394.89	+411.76
Total Δv [m/s]	**3770.69**	-7.22	+408.40	+334.93
Total prop mass used [kg]	**28392.83**	-37.73	+522.64	+382.37

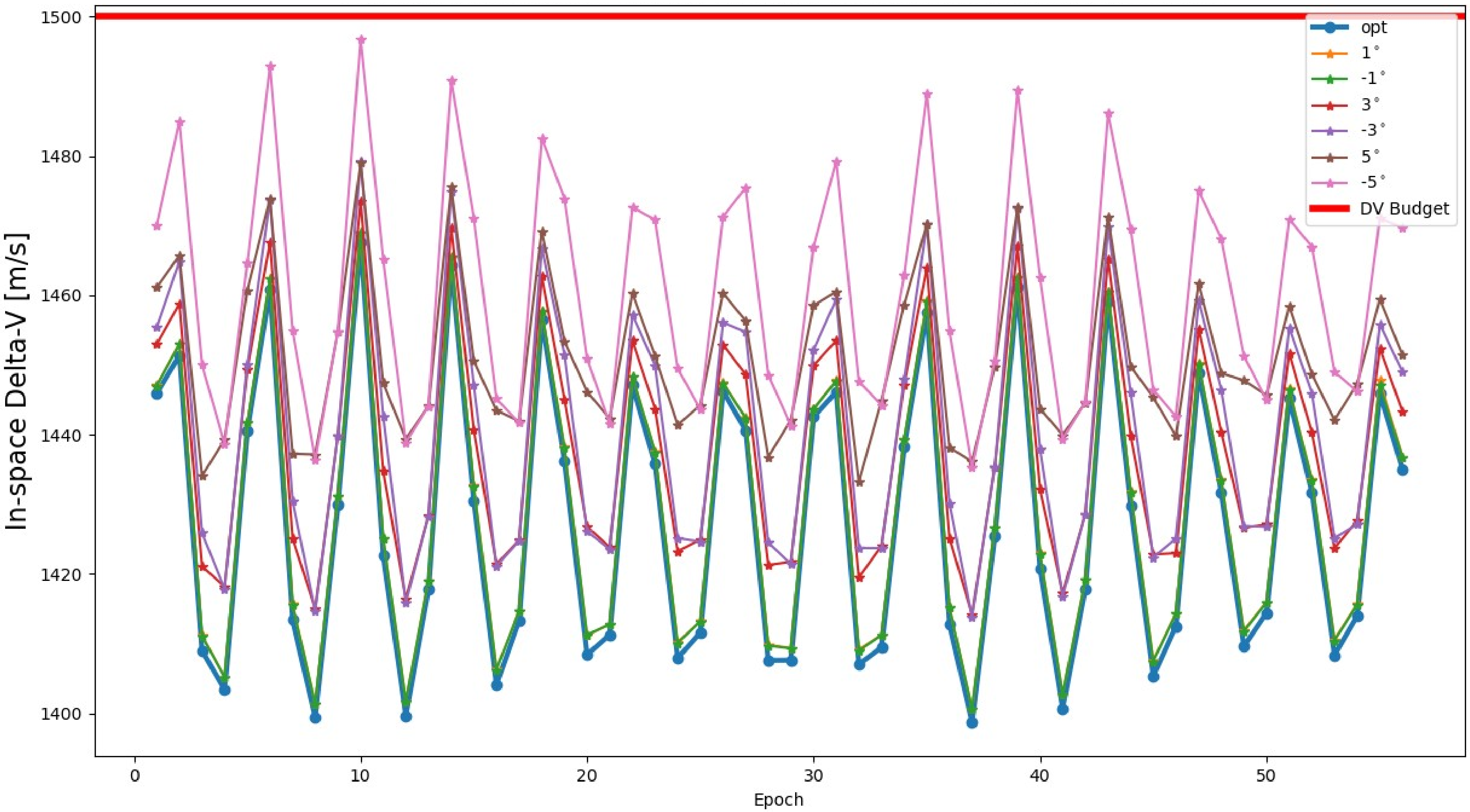
Nominal Case

Non-Nominal Case

Note: quantities in the right-most three columns indicate delta over the baseline performance numbers

- **For the nominal configuration, E2E-optimized HLS mission shows insignificant improvement over the patched mission**
- **End-to-end optimization approach is more efficient in improving the mission performance when mission parameters are perturbed**

E2E-Optimized HLS Scans for different PD Approach Directions
Starting Epoch: Jan 6, 2025; Scan Duration: 1 year



Note: In-space Delta-V includes NRD, LOI, LOD, NRI burns

E2E optimization capability enables quick assessment of performance impact on the In-Space segments due to changes in the powered flight segments and vice-versa

Summary

- **Summary**
  - HLS Integrated Ideck in Copernicus provides an end-to-end optimization capability for HLS.
  - In E2E optimization, the HLS trajectories from NRHO departure to lunar landing and from lunar lift-off to NRHO insertion are optimized simultaneously for minimizing the total prop needed for executing the mission
  - E2E optimization of the HLS can squeeze out the maximum performance out of the given mission configuration

- **Future Work**
  - Use of E2E optimization of the HLS Integrated Ideck for surface aborts
  - Enable yaw steering in the Integrated Ideck for improving performance for HLS surface aborts

Agenda

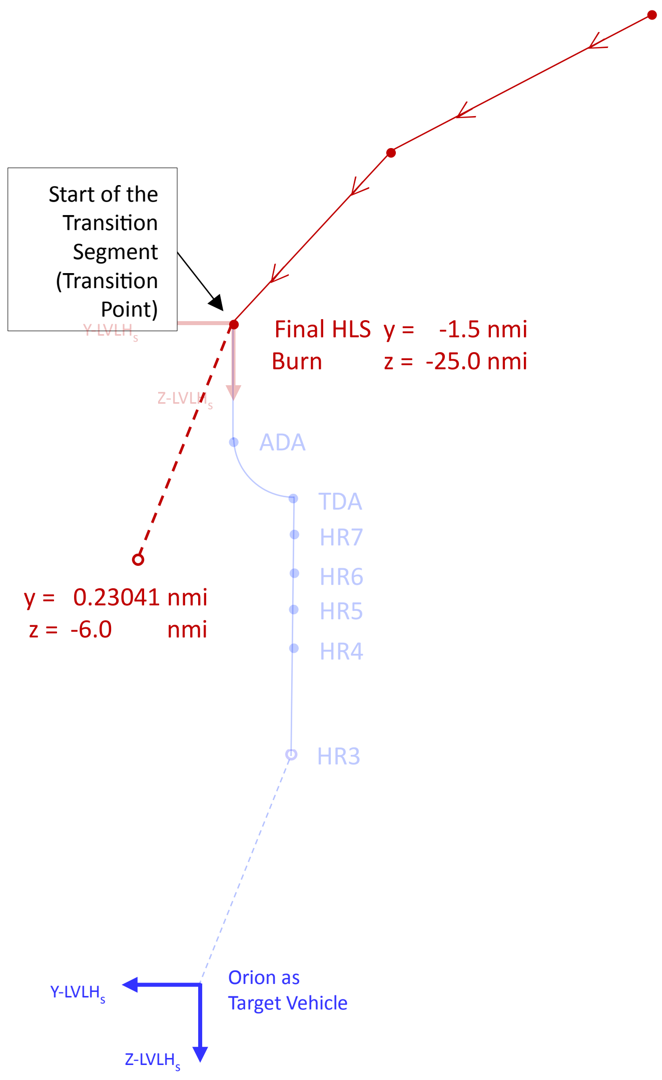
- HLS In-Space and Powered-Flight Trajectory Design
- Fast Trajectory Scans using Initial Guess Generator
- End-to-End Optimization of the HLS Integrated Mission
- **HLS-Orion Return RPOD Performance Analysis**
- HLS Surface Abort Analysis
- Orion-Assisted Rescue of HLS Ascent Element

HLS-Orion Return RPOD

- **After HLS NRI, HLS acts as the chaser vehicle and performs a Final Rendezvous Burn (FRB) to approach Orion from a fixed direction and with a fixed velocity. After FRB, Orion becomes the chaser vehicle and completes the rest of RPOD sequence**

- **The FRB injects HLS onto a transition segment defined by the initial transition point and the targeted position in the Sun-referenced LVLH (s-LVLH) frame along with the transfer time duration***

Final HLS Rendezvous Burn	Value
X, Y, Z Burn Position (in Orion centered s-LVLH coordinates)	(0, -1.5, -25) nmi
X, Y, Z Targeted Position (in Orion centered s-LVLH coordinates)	(0, 0.23041, -6) nmi
Burn Transfer Time	60 minutes [TBR]
X, Y, Z (3-sigma) Arrival Position Dispersions at the Targeted Position (in Orion centered s-LVLH coordinates)	(787.4, 787.4, 787.4) ft [TBR]



*Reference: Pete Spehar (NASA-JSC/EG6), Proposal for Chaser Vehicle Transition Point During 2nd Orion/HLS RPOD on Artemis III

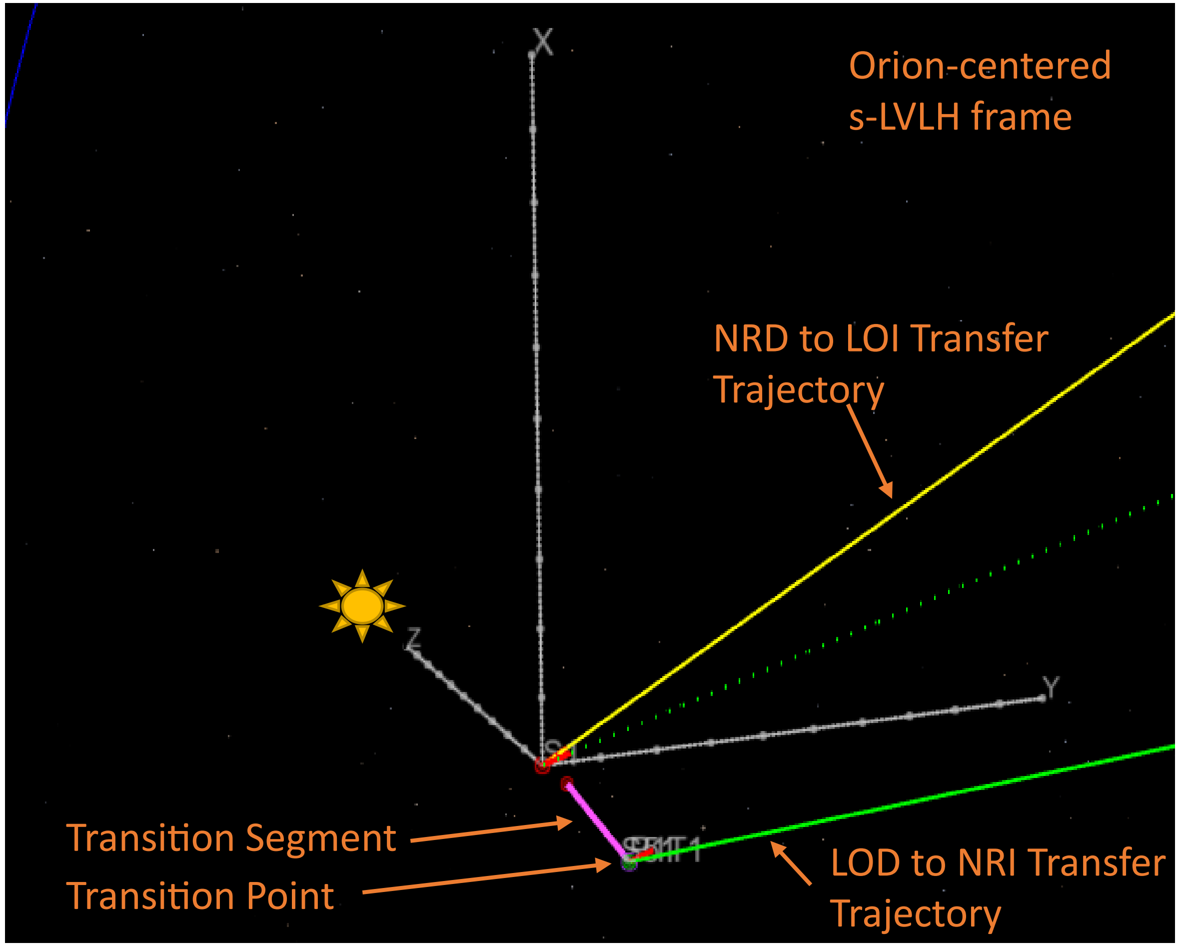
HLS-Orion Return RPOD Analysis

- A Copernicus plugin was implemented to
  - Provide the definition of the Sun-Referenced LVLH frame
  - Model the transition-segment constraints in the Sun-Referenced LVLH frame
  - Model the HLS' FRB burn and include that in the optimization cost function

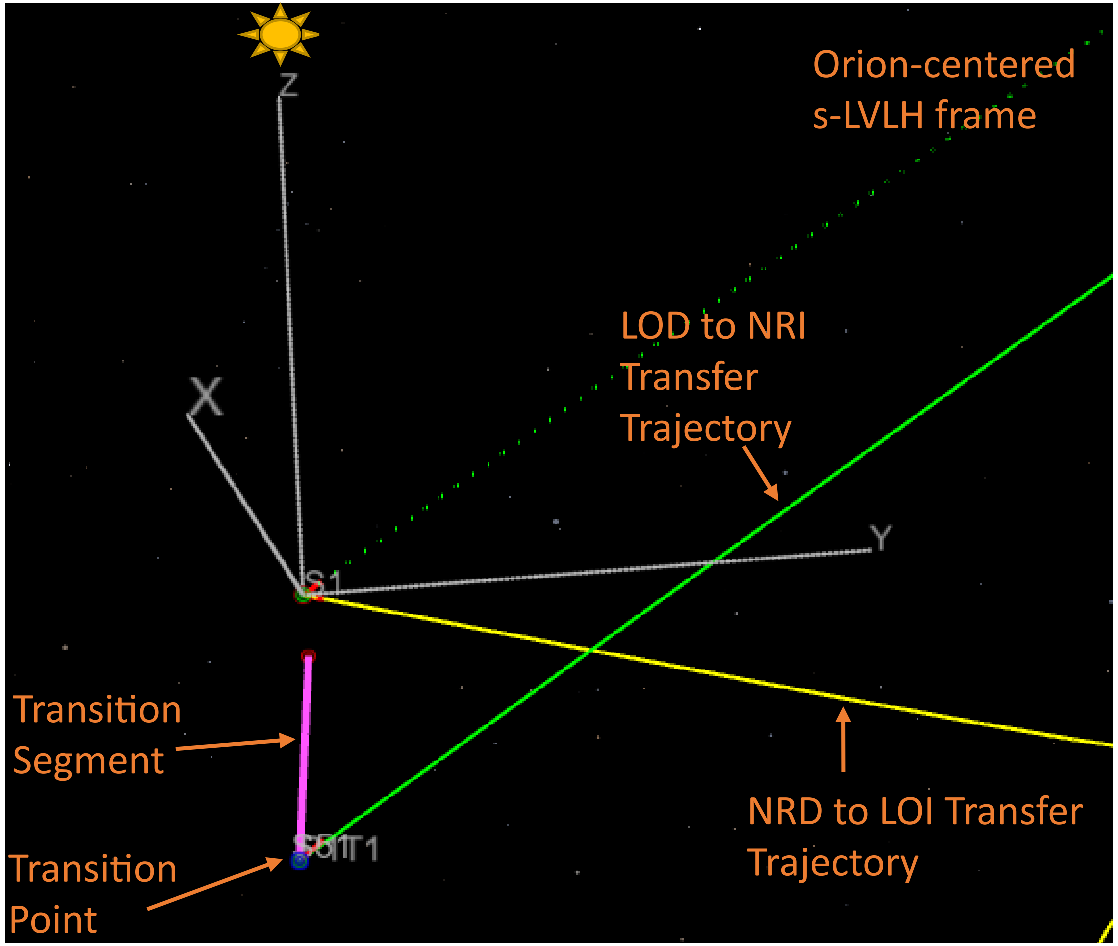
- For performance analysis, a 1-year trajectory scan of HLS mission with HLS-Orion Return RPOD is performed
  - Epochs: Oct 6, 2024 to Sept 30, 2025 (56 HLS missions)
  - Landing site: Connecting Ridge
  - HLS Nominal Mission Architecture
    - ✓ Two 12 hrs. transfers between the NRHO and 100x100 km LLO
    - ✓ Orion is assumed to be in the reference 9:2 resonant NRHO
    - ✓ 3-4 revs in the LLO before/after injection into the 100x15.3 km descent/ascent orbit

HLS-Orion Return RPOD Trajectories

- Mission Epoch: Nov 14, 2024
- Combined NRI and FRB is applied at the Transition Point



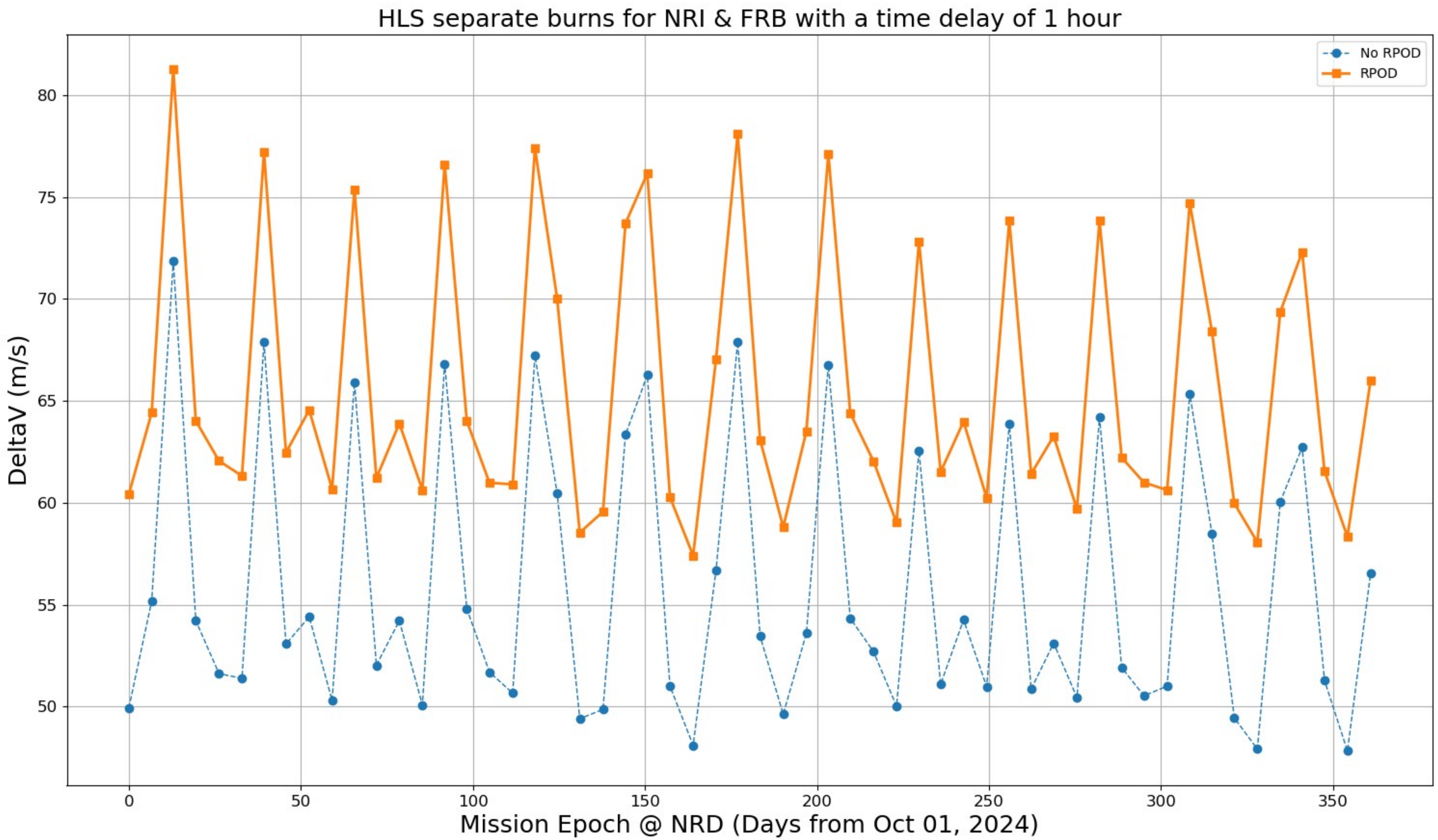
- Mission Epoch: May 30, 2025
- Combined NRI and FRB is applied at the Transition Point



Depending on the mission epoch, HLS can approach the transition point from different directions

NRI + FRB Delta-V Scan for Return RPOD

- Burn Sequence:
  - NRI @ transition point to drive relative velocity to 0
  - Coast for 1 hour (no significant relative motion for small time durations)
  - FRB @ transition point to target the end of the transition segment.



Delta-V difference between "No RPOD" and Return "RPOD" cases is ~ 10 m/s for all mission epochs

Summary & Future Work

- **Summary**
  - **For Two-burn Return RPOD case, HLS In-Space ΔV varies with epoch and is always greater than the "No RPOD" case by 9.1-10.5 m/s during a one year scan starting from Oct 6, 2024.**

- **Future Work**
  - **Implement HLS-Orion Return RPOD transition in the Integrated HLS Ideck**

Agenda

- HLS In-Space and Powered-Flight Trajectory Design
- Fast Trajectory Scans using Initial Guess Generator
- End-to-End Optimization of the HLS Integrated Mission
- HLS-Orion Return RPOD Performance Analysis
- **HLS Surface Abort Analysis**
- Orion-Assisted Rescue of HLS Ascent Element

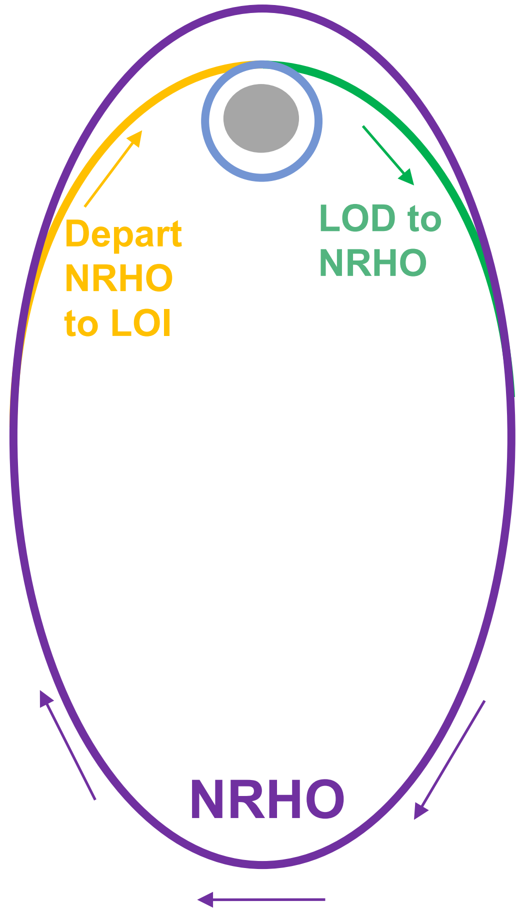
Anytime Surface Abort Options

Subsequent to surface abort launch:

1. **HLS ascends into the ascent orbit followed by LLO circularization burn. It loiters in LLO for 2-3 revs followed by LOD burn to NRHO.**
   - Abort mission cost is generally more than the nominal cost depending upon the abort initiation time and the transfer time.
   - Total mission duration can be lower or higher than the nominal duration.

2. **HLS ascends into the ascent orbit followed by LLO circularization burn. It loiters till the nominal time for LOD.**
   - Abort mission cost is expected to be similar to the nominal mission cost, however more work is needed to confirm that optimal LLO orbit plane can be attained for any time surface abort launch from the surface.
   - Total mission duration is same as the nominal duration.

3. **Surface abort direct to NRHO with no loitering in LLO**
   - Abort Delta-V and transfer times will vary based on the specific transfer.



Abort Transfer Solution Types

- **Minimum Delta-V 2-burn transfers**
  - **Flight times can be much longer than the nominal return transfer**
  - **Total mission duration may exceed the nominal duration as well as max vehicle time limit**

- **Minimum Time 2-burn transfers**
  - **Flight time reduces to its lower limit with exceedingly high Delta-V requirements**

- **Minimum Time 2-burn transfers with Limited Delta-V**
  - **Compromise between min-DV and min-Time abort transfers**
  - **Within the Delta-V budget, provides fastest abort transfer**

- **3-burn transfers**
  - **May have lower Delta-V requirements than min-DV 2-burn transfers**
  - **Flight times may be higher than the min-DV 2-burn transfers**

- **Multi-rev transfers**
  - **Loiter in phasing orbits until the transfer window with lower Delta-V requirements opens up**

GR&As for Any time Surface Abort Analysis

- **HLS mission for Nov 14, 2024 with Connecting ridge as the landing site is used**

- **The nominal HLS states are used to initialize the abort trajectories at the abort initiation time**

- **Coplanar powered ascent (& descent) is assumed**

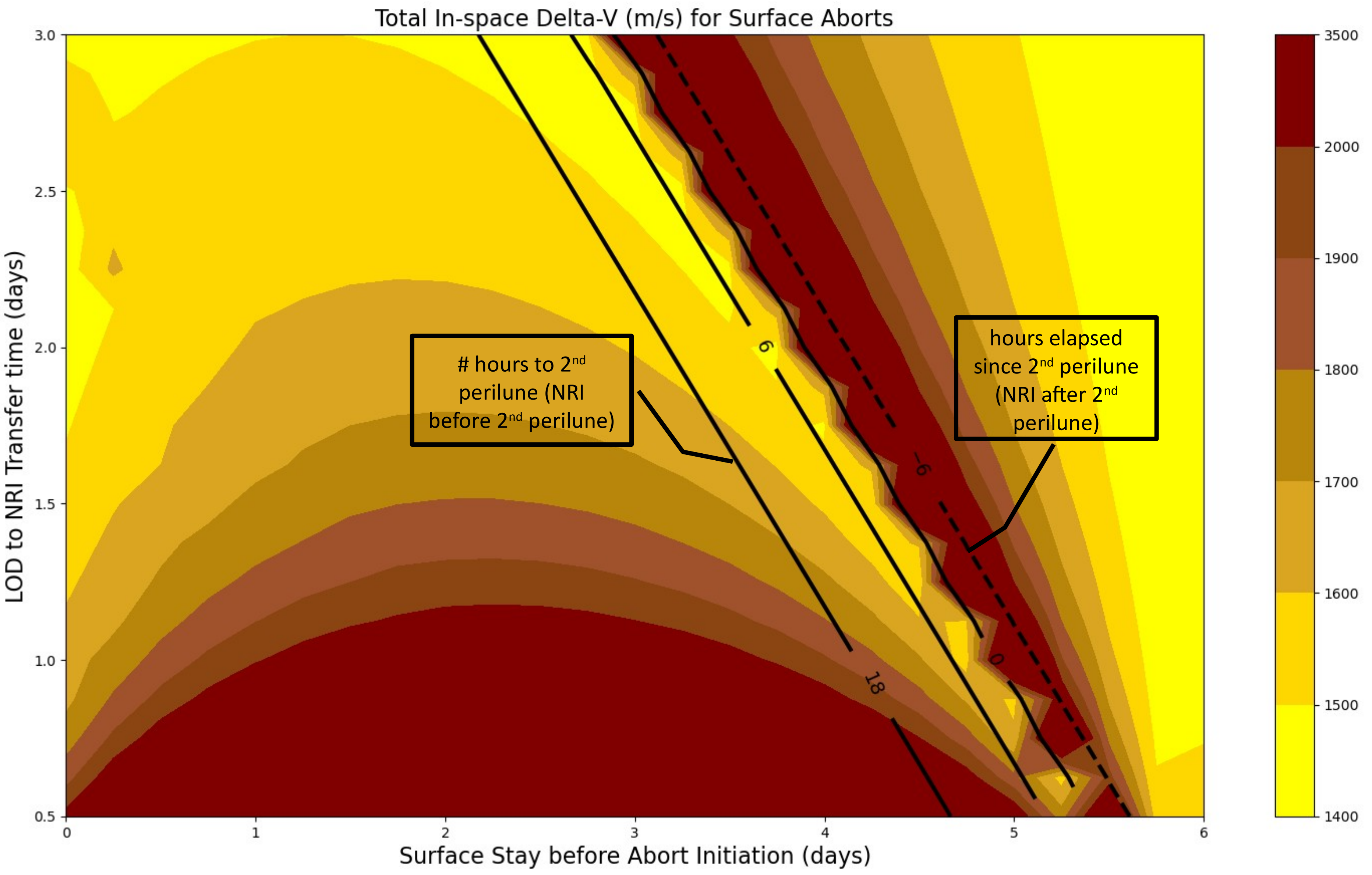
- **Only In-space Delta-V for the abort transfers is minimized. The NRD and LOI burns cost is frozen and is not optimized.**

- **In all cases, HLS loiters in LLO for 2-3 revs before the LLO-NRHO transfer**

- **Vehicle max limits are based on govt. reference HLS mission**

Any-time Surface Abort Space
Site: Connecting Ridge; Epoch: Nov 14, 2024

- Nominal Descent (NRD+LOI) Delta-V = 704.9 m/s
- Only two-burn abort transfers are considered
- NRHO RPOD blackout period: +/- 6 hrs from the perilune passage time (tp)
- Full RPOD with reattempts can take up to 12 hrs, so RPOD cannot be started after (tp-18) hr

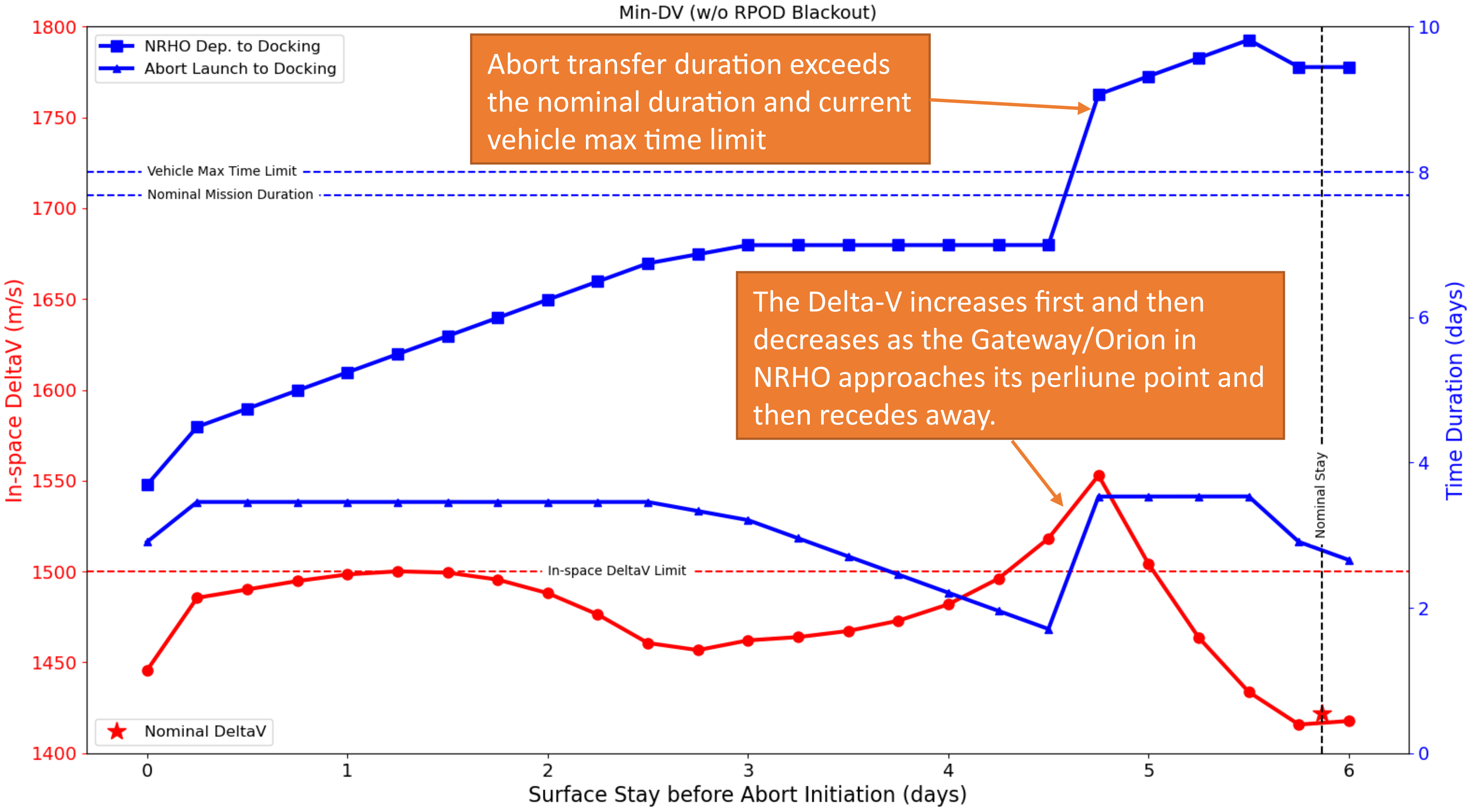


*Surface stay time resolution = 6 hrs, LOD to NRI Transfer time resolution= 3 hrs

Minimum Delta-V Surface Abort Transfers

- 2 < Abort TOF < 3.75 d
- 4 < Mission Duration < 10 d
- 1420 < Delta-V < 1550 m/s
- Nominal NRD+LOI Delta-V=704.5 m/s
- Return RPOD Time: 6 hr
- Nominal Return TOF = 0.75 d
- **RPOD is assumed to start immediately after NRI. Some transfers have NRI near NRHO perilune.**

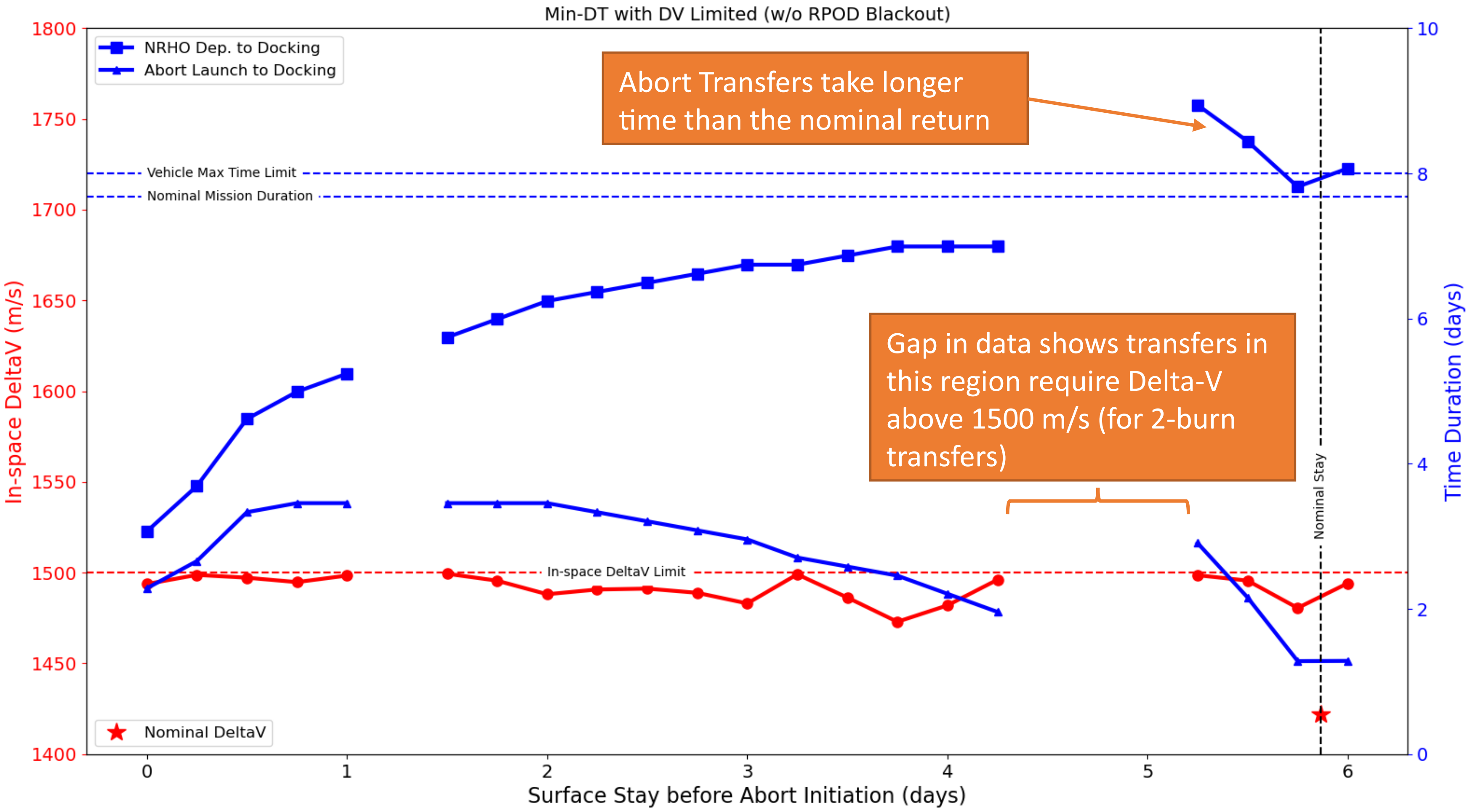
Abort Transfer Time and Mission Duration vs Abort Time



Minimum-Time Surface Abort Transfers
In-space Delta-V Limited to 1500 m/s

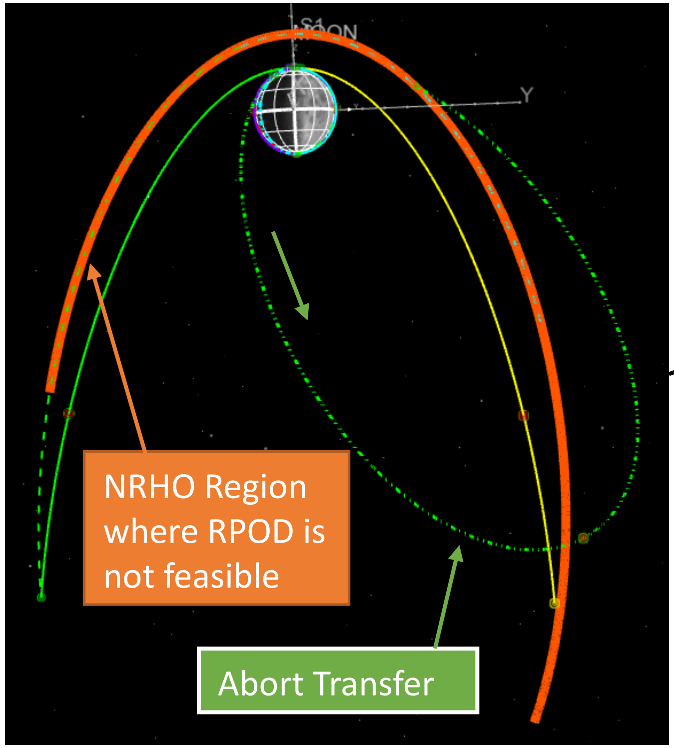
- **Abort Delta-V limited to 795.5 m/s**
- **Nominal NRD+LOI Delta-V=704.5 m/s**
- **1.5 < Abort TOF < 3.75 d**
- **3 < Mission Duration < 9 d**
- **Return RPOD Time: 6 hr**
- **Nominal Return TOF = 0.75 d**
- **RPOD is assumed to start immediately after NRI. Some transfers have NRI near NRHO perilune.**

Abort Transfer Time and Mission Duration vs Abort Time

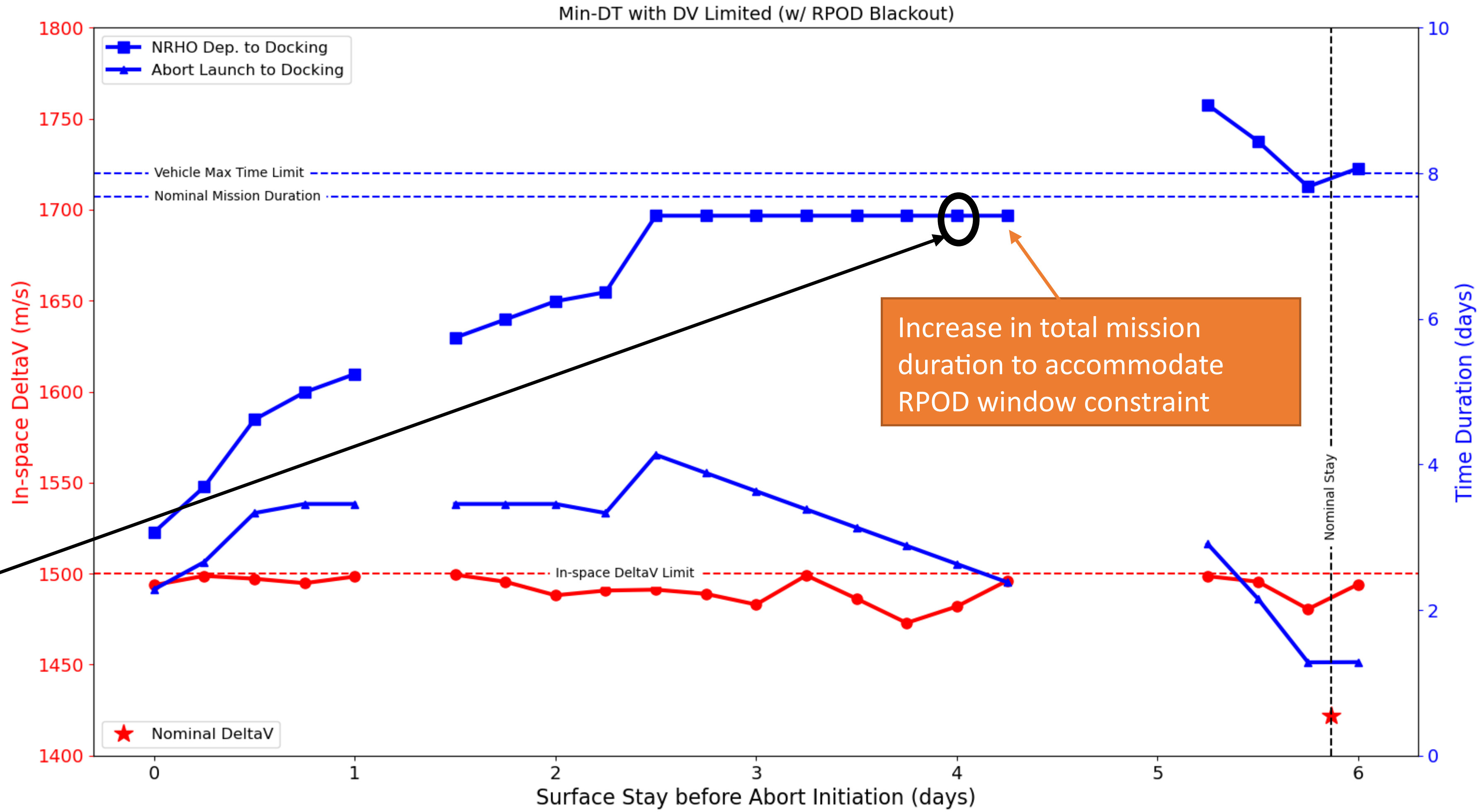


Minimum-Time Surface Abort Transfers
In-space Delta-V Limited to 1500 m/s (w/ RPOD window constraint)

- RPOD window closes from -18 to +6 hr w.r.t. perilune time
- RPOD is initiated +6 hr post perilune passage
- 1.5 < Abort TOF < 3.75 d
- 3 < Mission Duration < 9 d
- Return RPOD Time: 6 hr

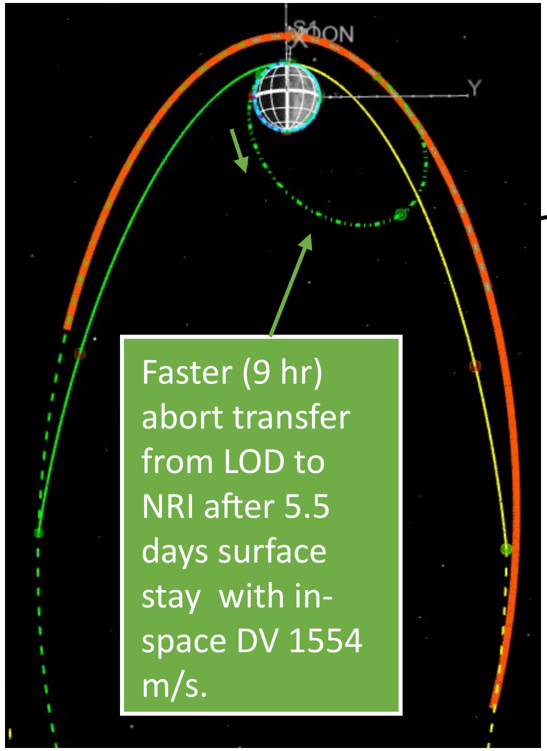


Abort Transfer Time and Mission Duration vs Abort Time

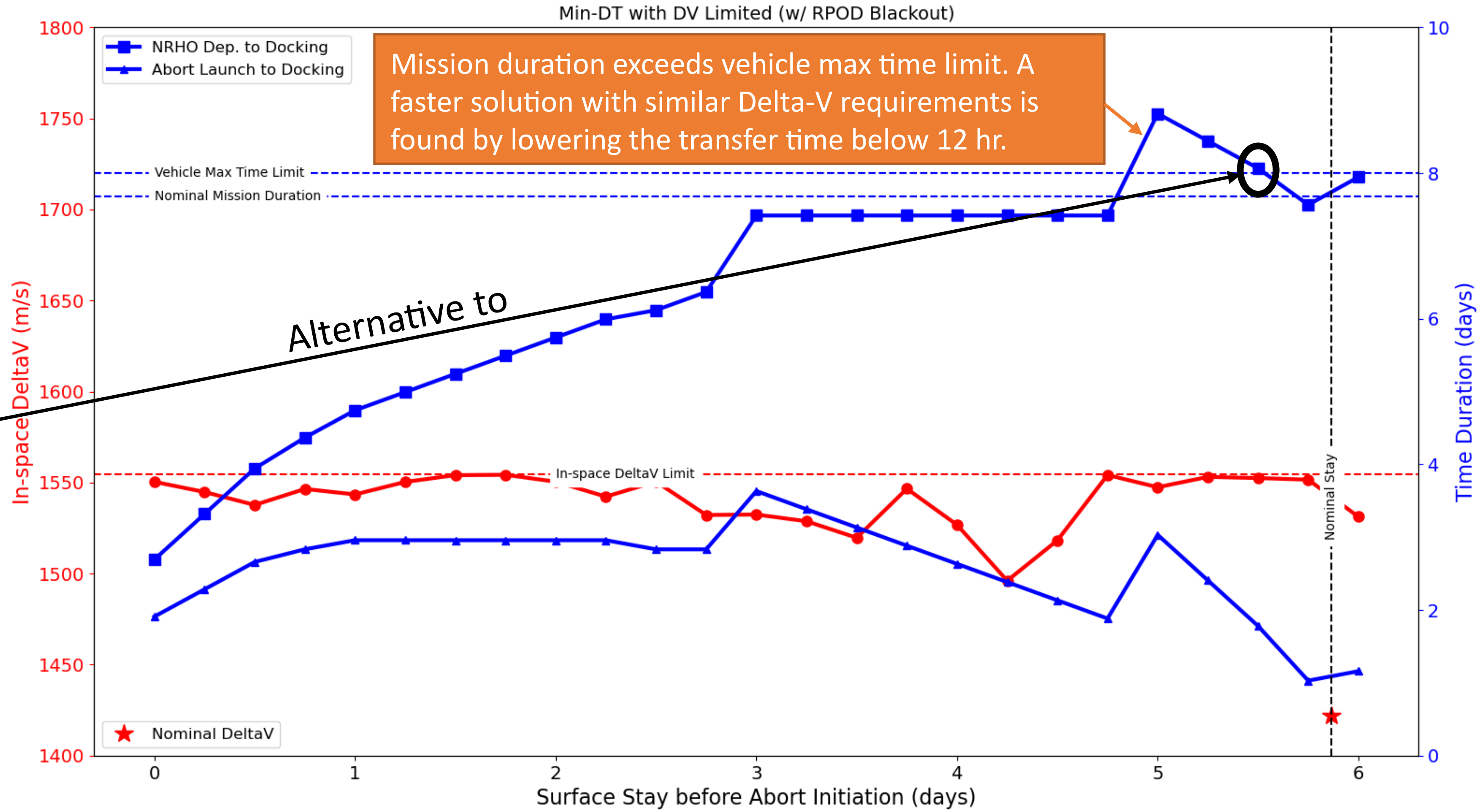


Minimum-Time Surface Abort Transfers
In-space Delta-V Limited to 1554.5 m/s (w/ RPOD window constraint)

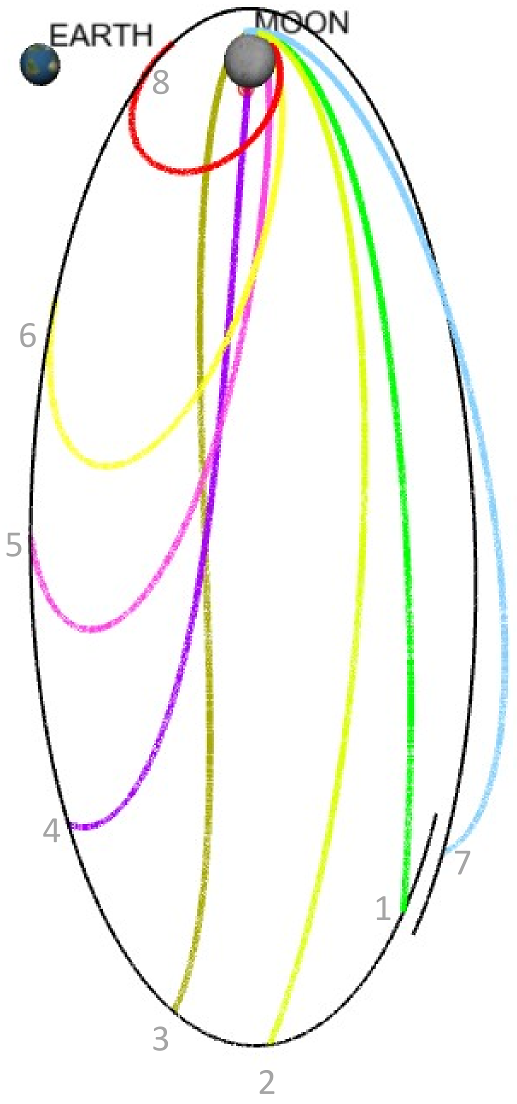
- **Abort Delta-V Limited to 850 m/s**
- **1 < Abort TOF < 3.8 d**
- **3 < Mission Duration < 9 d**
- **For aborts after 5 days of surface stay, faster transfers from LOD to NRI with similar Delta-V can be found by decreasing the transfer time below 12 hr in some cases.**



Abort Transfer Time and Mission Duration vs Abort Time



Minimum-Time Surface Abort Transfers Trajectories
In-space Delta-V Limited to 1554.5 m/s (w/ RPOD window constraint)



Key	Surface Stay Duration (days)	Abort Transfer Time (days)
1	0.0	1.9
2	0.5	2.7
3	1.0	3.0
4	2.0	3.0
5	3.0	3.6
6	4.0	2.6
7	5.0	3.0
8 (9 hr transfer)	5.5	1.1

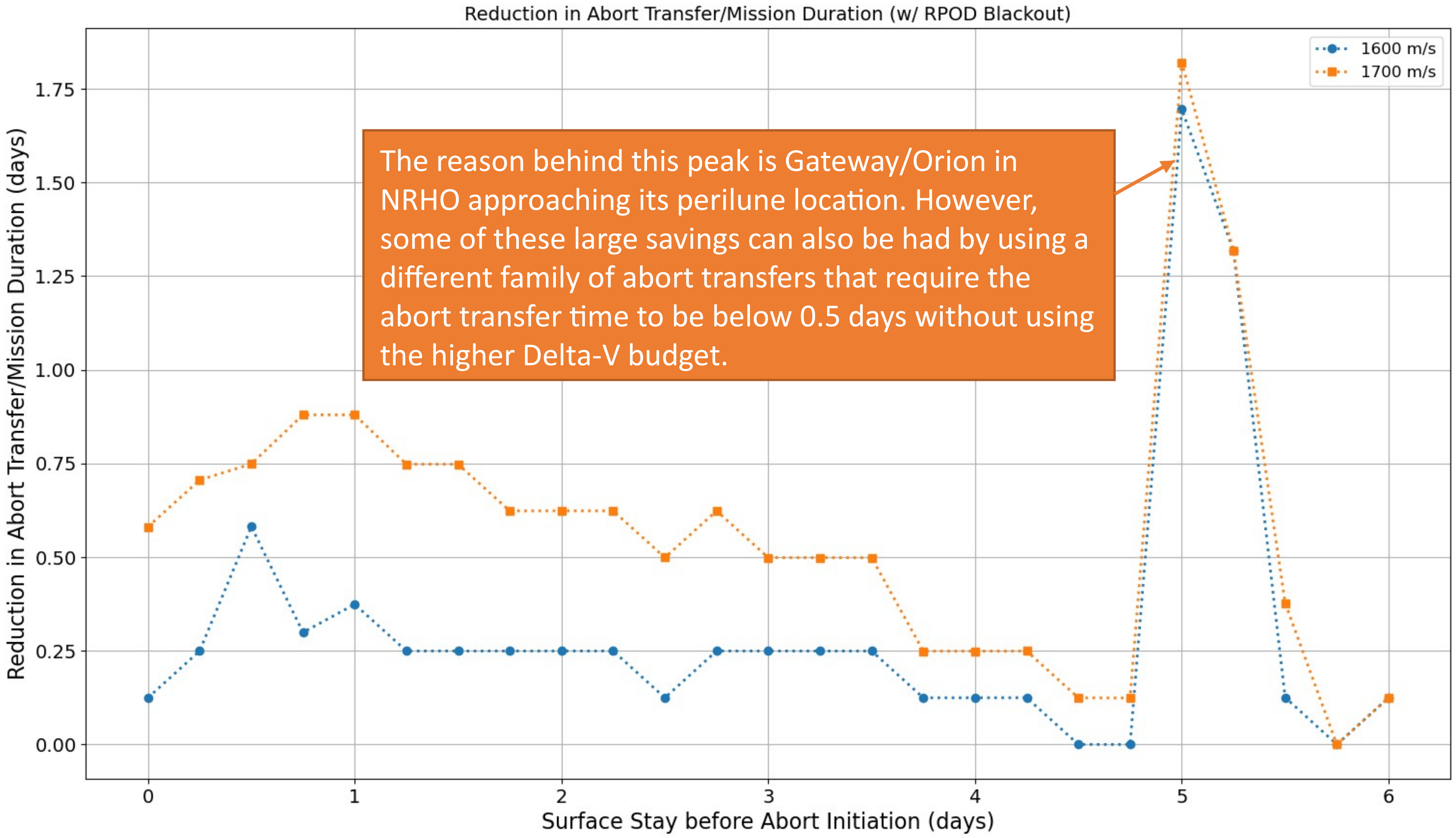
2

Savings in Abort Transfer Time with Higher In-space Delta-V Budget

- **Baseline case: Min-Time Abort Transfers with in-space Delta-V < 1554 m/s with Abort Delta-V < 850 m/s**

- **Max reduction in abort transfer time by ~1.75 days for 1600 m/s**

- **For aborts before 4 days of surface stay, max saving is 0.6 day for 1600 m/s budget**



Summary & Future Work

- Summary
  - Min-Time surface abort transfers with In-Space Delta-V < 1500 m/s may require up to 9 days of total mission duration. With using only 2-burn transfer type, there are gaps in abort coverage for some surface stay durations.
  - Min-Time surface abort transfers with In-Space Delta-V < 1554 m/s (850 m/s for LOD to NRI transfer for the selected nominal mission) may require up to 9 days of total mission duration with no gaps in abort coverage
  - Surface aborts initiated within 5-6 days of surface stay have high sensitivity to abort time. Faster transfers with similar Delta-V requirements exist in some cases if the transfer time is allowed to drop below 12 hours.

- Future Work
  - HLS surface abort performance scans for a range of mission epochs
  - Use of HLS Integrated Ideck (with powered descent and ascent segments) for surface abort analysis
  - Use of non-coplanar ascent (yaw steering) to improve HLS surface abort performance

Agenda

- HLS In-Space and Powered-Flight Trajectory Design
- Fast Trajectory Scans using Initial Guess Generator
- End-to-End Optimization of the HLS Integrated Mission
- HLS-Orion Return RPOD Performance Analysis
- HLS Surface Abort Analysis
- **Orion-Assisted Rescue of HLS Ascent Element**

Abort Scenario

Nominal sequence of events during ascent phase:

Ascent from surface → 100 km circular loiter orbit (3-4 revs) → Transfer back to NRHO → ~~Insertion into NRHO (NRI)~~

Ascent Element (AE) fails NRI

- **Failed (HLS AE) NRI**

- **Orion intercepts AE, performs RPOD, transfers crew, and coasts to departure burn.**
  - **Similar to nominal mission, the return sequence includes a NRHO departure burn and a return powered flyby.**

- **Abort addresses performance constraints (ΔV) and ECLSS lifetime constraints (crew-time)**
  - **These constraints will vary based on the outbound mission chosen.**
  - **In general, faster return missions cost more in ΔV.**

Options Considered

- Orion Ascent Element Rescue Abort Modes
  - Return Through Gateway
  - Return Direct to Earth
    - Return to Altitude/Flight Path Angle at E.I. (“global” optimal trajectories)
    - Return to Target Line (daily optimal trajectories)

Orion Rescue Trajectory, Direct Return to Earth

Gateway

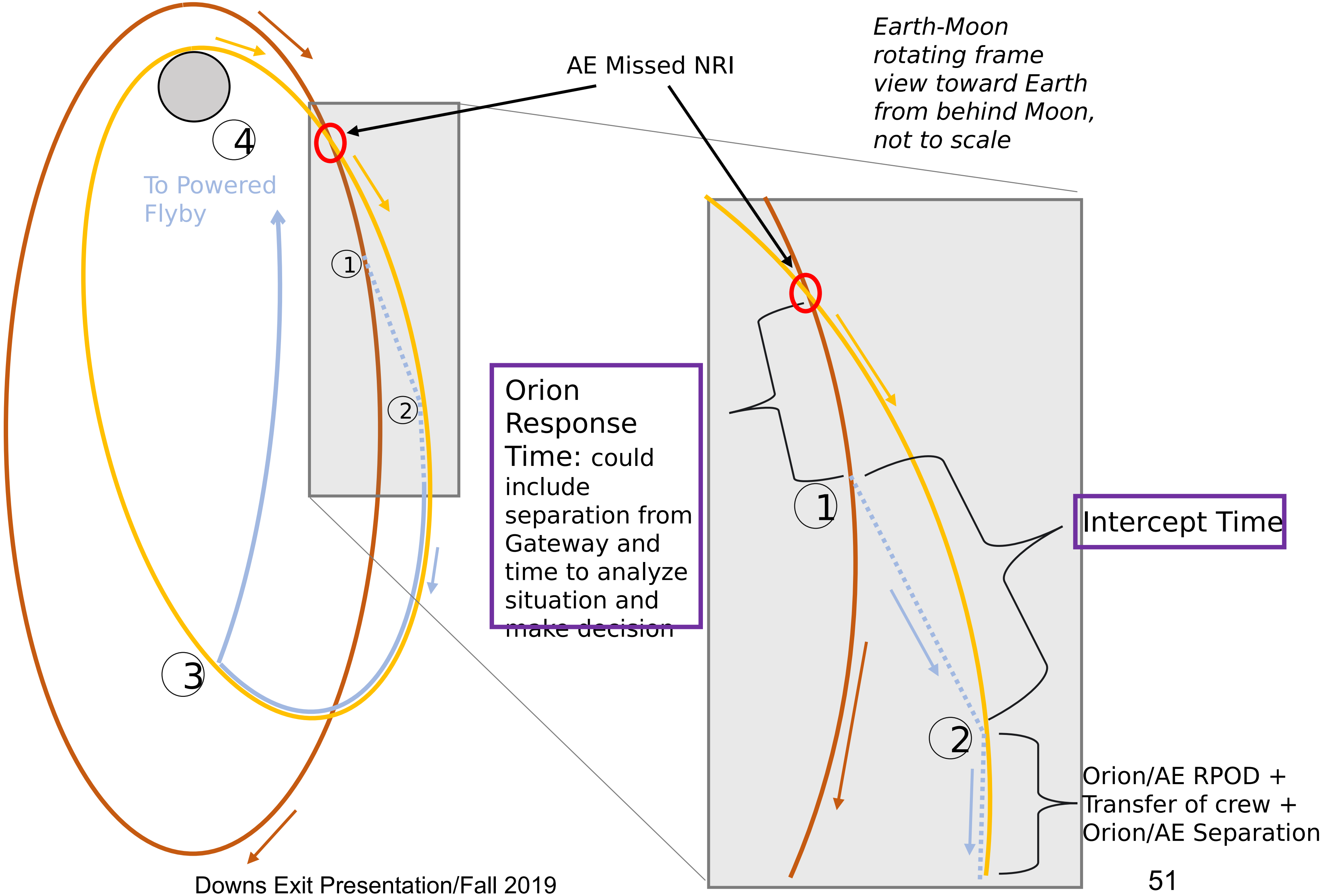
Ascent Element

Orion (4 crew)

Orion (2 crew)

Burns:

1. Orion departs Gateway and begins to chase down ascent element
2. Orion reaches AE and performs burn to match AE velocity
3. "NRD" burn to depart AE orbit
4. Return powered lunar flyby



Target Line – Earth Entry Target

- Orion Ascent Element Rescue Abort Modes
  - Return Through Gateway
  - Return Direct to Earth
    - Return to Altitude/Flight Path Angle at E.I. (“global” optimal trajectories)
    - Return to Target Line (daily optimal trajectories)

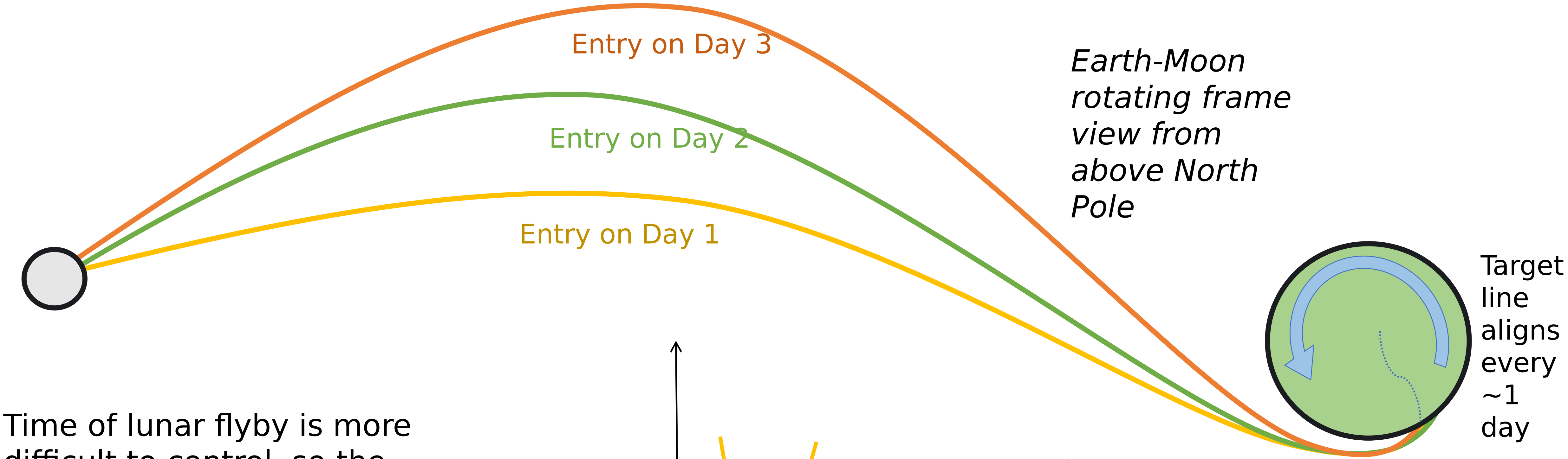
Target Line Approach

- **Target line return trajectory geometry repeats with each rotation of the Earth**
  - **EI targets on approximately 24 hour centers**

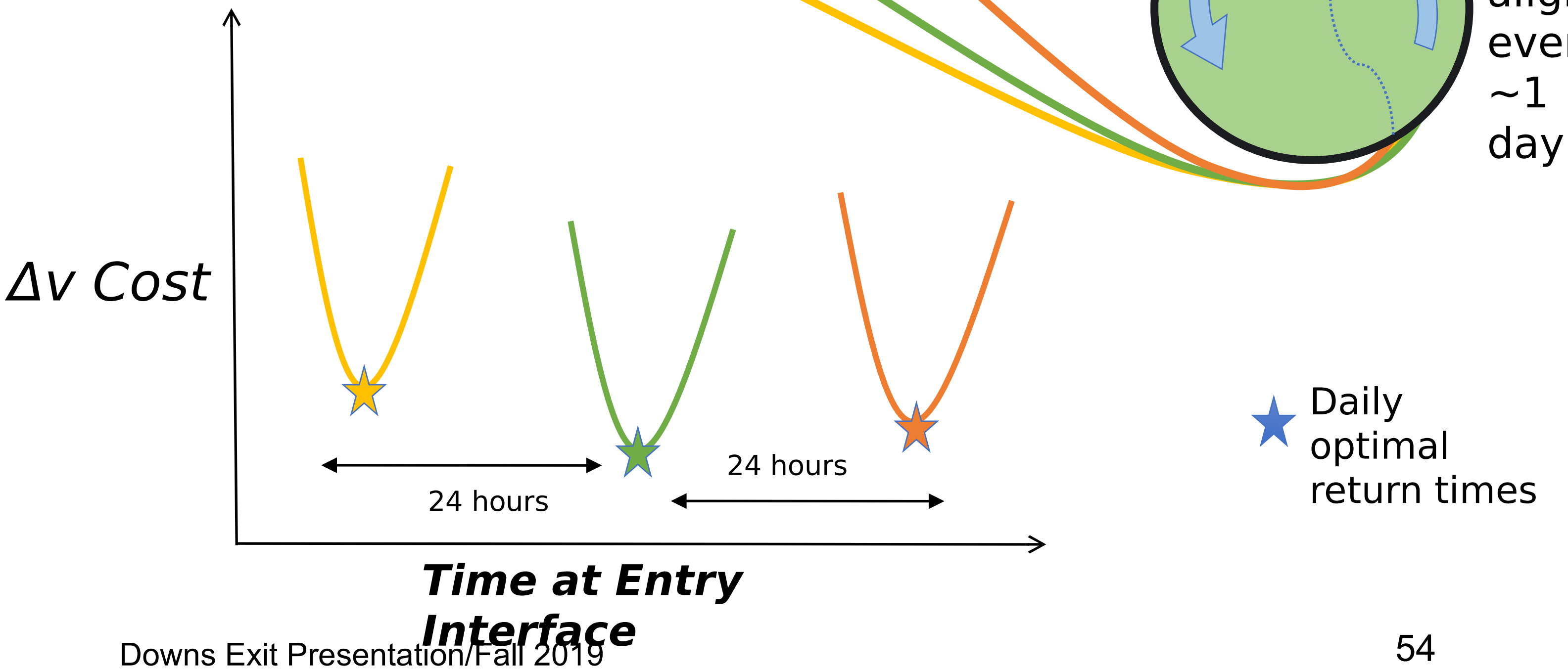
- **Approach: Find solutions for each arrival day and post-process to find the “global” optimal in terms of performance (Δv)**

- **Orion ECLSS vehicle lifetime constraint checked in post-processing (84 crew days total)**

Geometry of Return Missions to Target Line



Time of lunar flyby is more difficult to control, so the **optimal trajectories on each day vary mostly in Moon-relative RAAN** of the flyby segment to create geometries like those above.



Altitude/Flight Path Angle (FPA) – Earth Entry Target

Orion Ascent Element Rescue Abort Modes

- Return Through Gateway
- Return Direct to Earth
  - Return to Altitude/Flight Path Angle at E.I. (“global” optimal trajectories)
  - Return to Target Line (daily optimal trajectories)

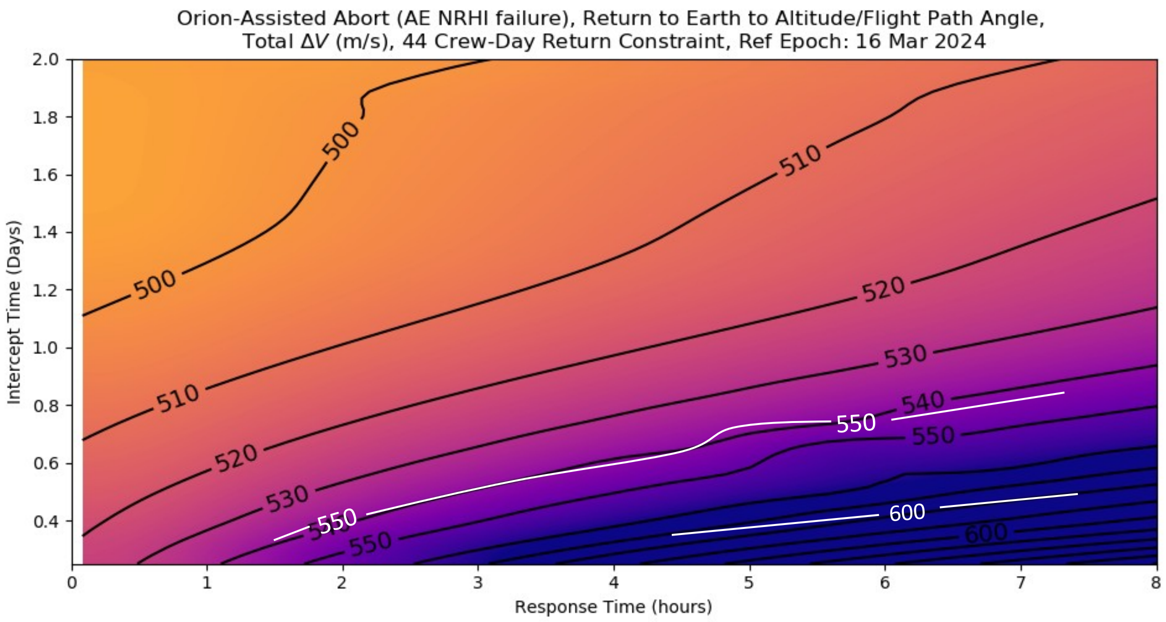
Altitude/Flight Path Angle Target

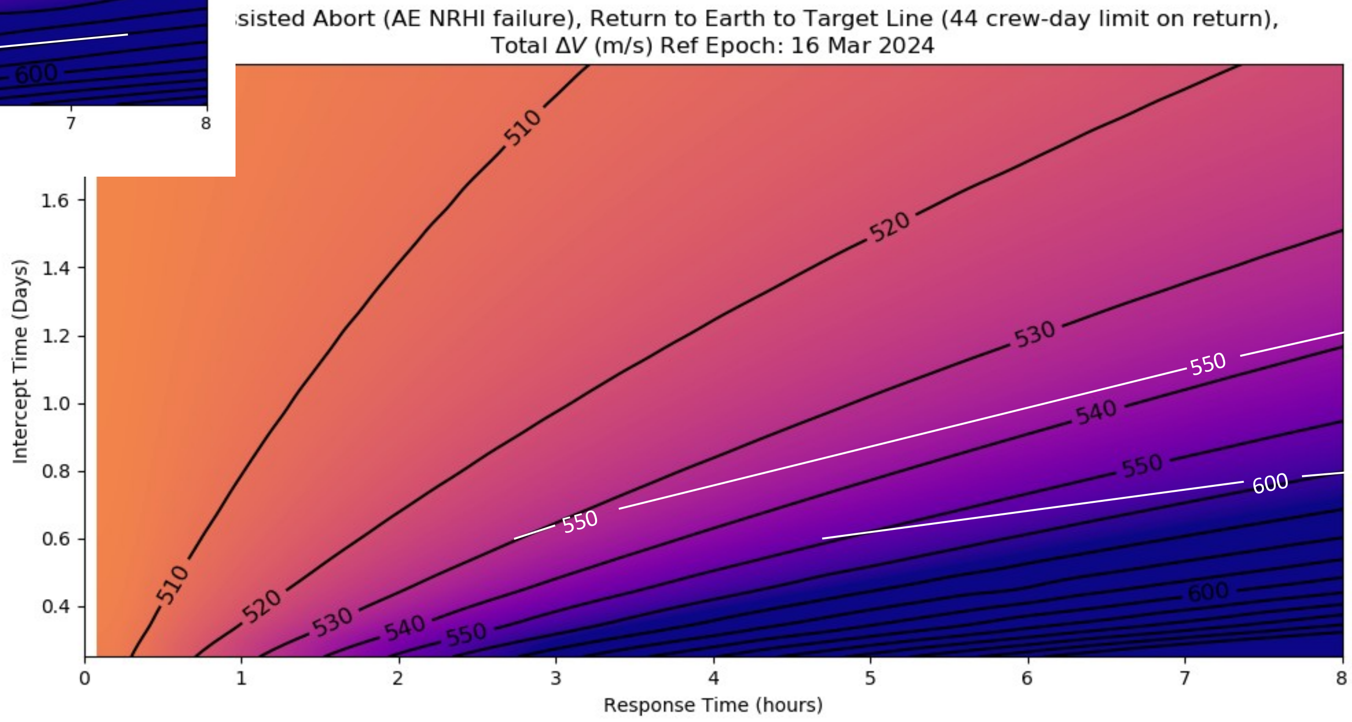
- **In order to relax as many constraints as possible, a study was done to simply target a valid flight path angle at Entry Interface.**
  - **Assumed range between -5.8 and -6.2 degrees for valid flight path angles**

- **<u>Global optimal solutions</u> can be found in this case because there are no constraints on longitude at EI**
  - **No consideration here for whether Orion lands on land or water.**
  - **Small changes in the shape/duration of the return trajectory can shift landing area**

- **We have two figures of interest when looking at these missions**
  - **Performance (ΔV) -- Minimize**
  - **ECLSS consumable usage (crew-time on Orion) -- constrain**

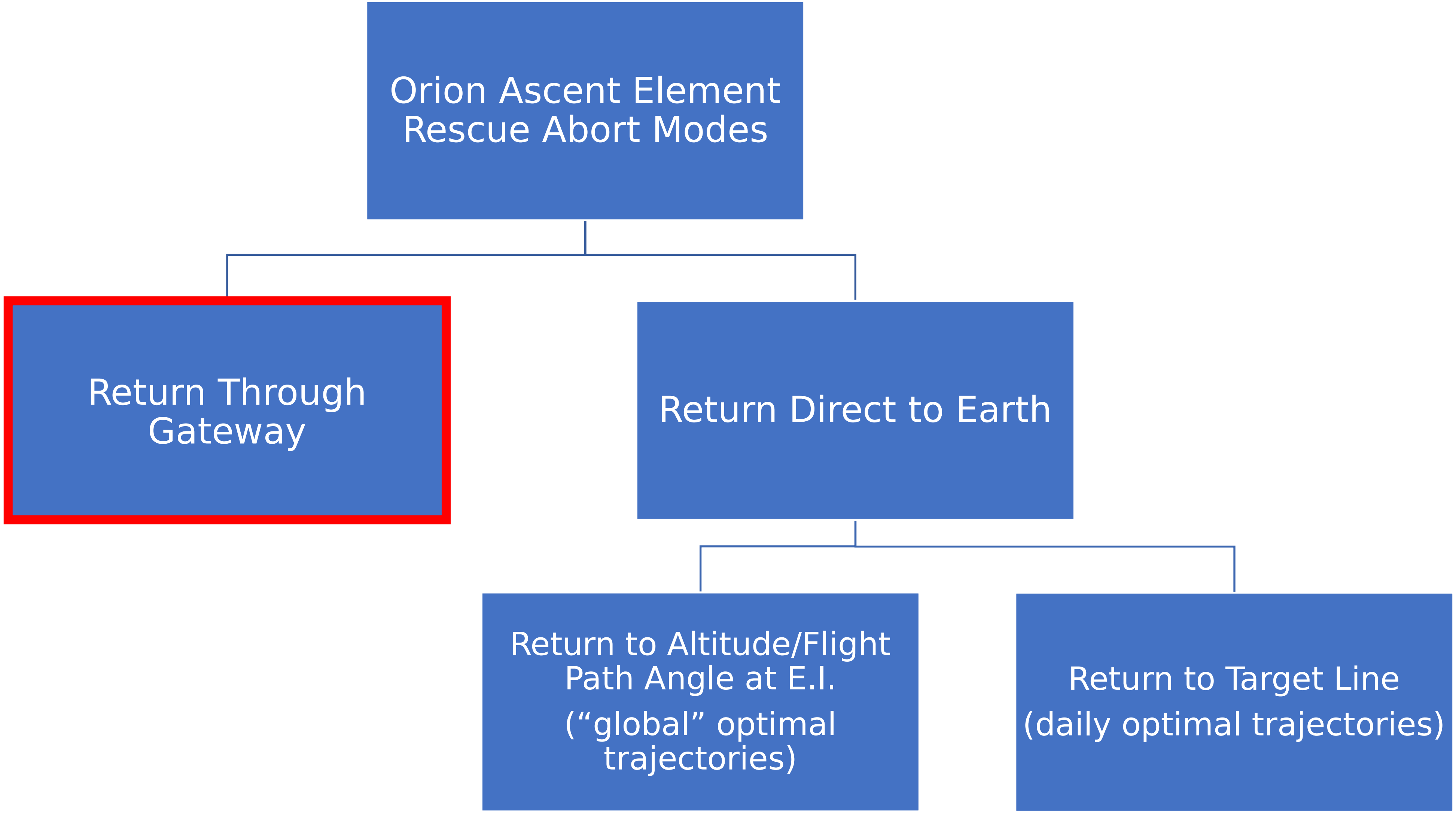
Results: Alt/FPA vs Target Line



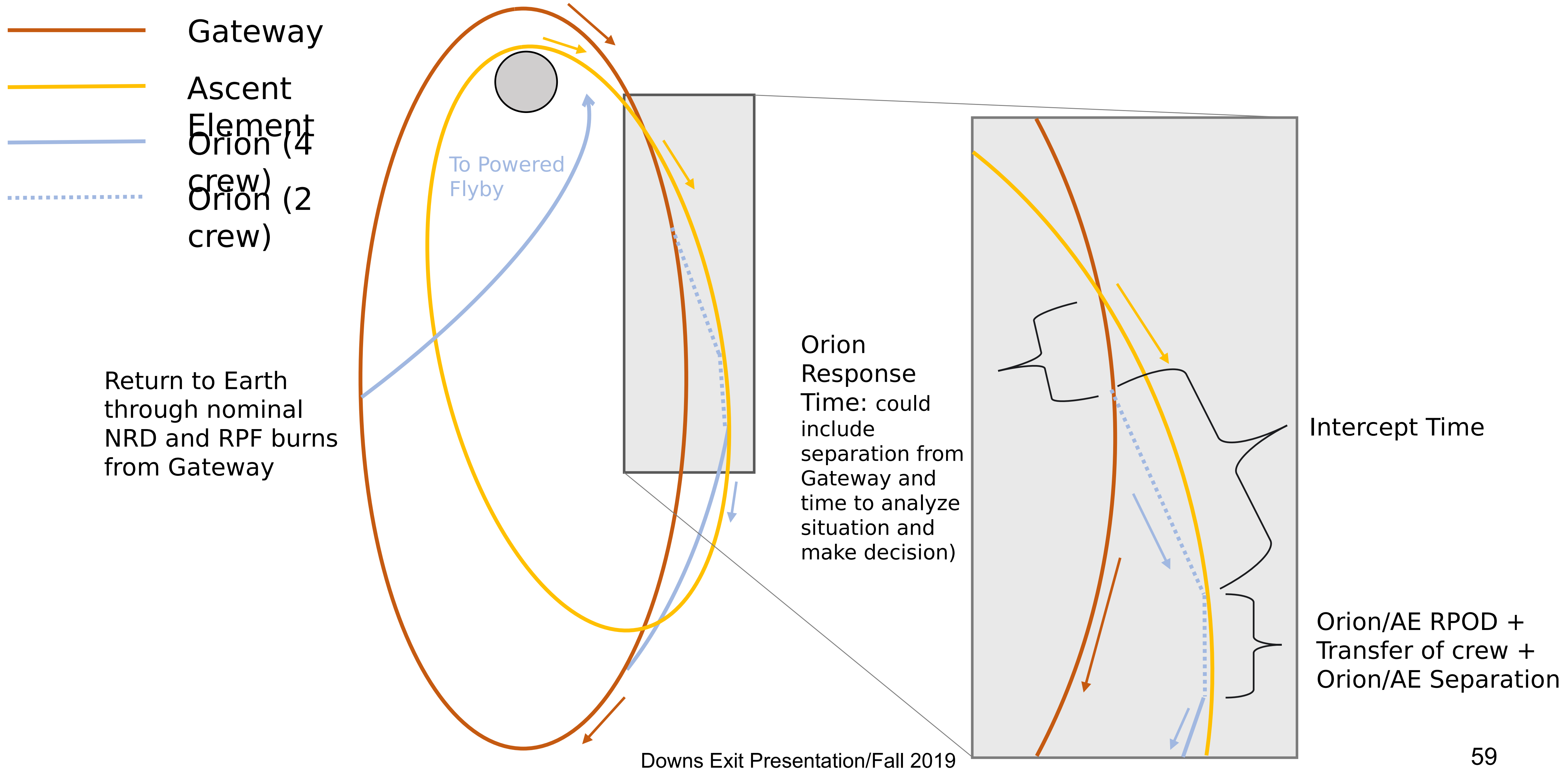


Alt/FPA target results in savings of ~10 m/s for this epoch compared to target line

Gateway – NRHO Target

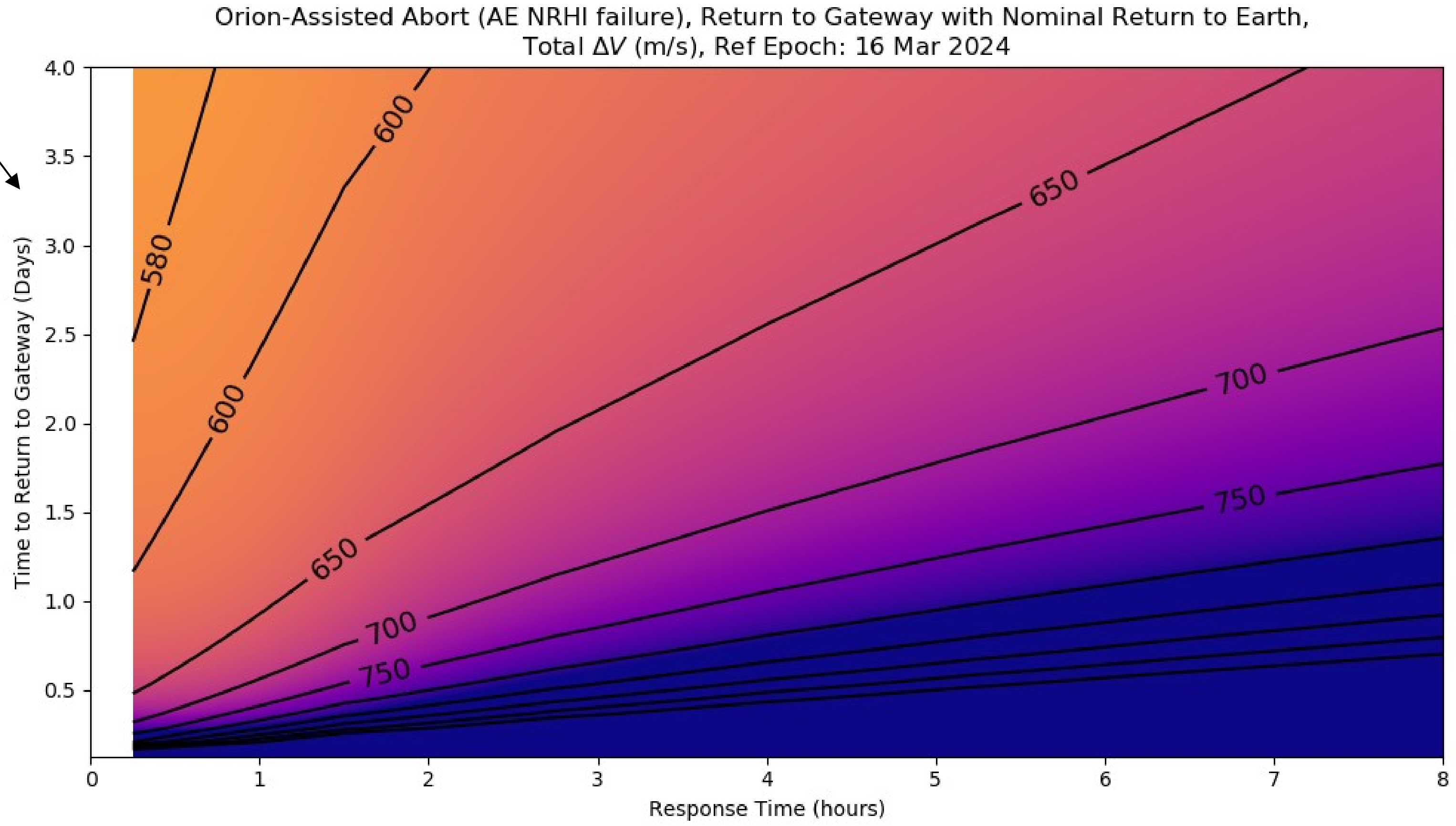


Orion Rescue Trajectory, Return through Gateway



Return Through Gateway Results

Different here: Time to complete rescue and return to Gateway



Assumed here:

409 m/s nominal return Δv for March 16, 2024 ref. mission

In general, returning back to Gateway before performing NRD costs **170+ m/s additional ΔV**

This option is therefore **infeasible in most cases**

Summary & Future Work

- Summary
  - Orion assisted HLS rescue aborts are possible with the greatest opportunity for a viable abort using a direct Earth return targeting (alt., FPA)
    - For an Earth return to a target-line (off the coast of San Diego, CA), there were some, but fewer opportunities overall.
    - There exists a possibility for an Orion rescue with return to the Gateway, but generally with out possibility of subsequent return to Earth.
      - The conclusion of the abort would require a second Orion or return vehicle to take the crew from the Gateway back to Earth
  - Currently working epoch scans for direct Earth return cases

- Future Work
  - Evaluate other Orion rescue modes (e.g., partial LOD, partial NRI)

References

- DAC-2 Final Report, Flight Mechanics Team, August 1, 2019.
- Bharat Mahajan, Gerald L. Condon, END-TO-END PERFORMANCE OPTIMIZATION OF A CREWED LUNAR LANDING MISSION STAGED FROM A NEAR RECTILINEAR HALO ORBIT, 44th Annual AAS Guidance, Navigation and Control Conference, 2022.
- Gerald L. Condon , C. Clark Esty , Christopher F. Berry‡ and Sean P. Downs, Cesar Ocampo and Bharat Mahajan, Laura M. Burkem, Mission and Trajectory Design Considerations for a Human Lunar Mission Originating from a Near Rectilinear Halo Orbit, AIAA Scitech 2020 Forum, AIAA 2020-1921 , 2020.
- Bharat Mahajan, Gerald L. Condon, and Srinivas R. Vadali, Semianalytic Computation of Ballistic Transfers in the Restricted Three-Body Problem, AIAA Scitech 2020 Forum, AIAA 2020-0960, 2020.
- Sean Downs, NASA-JSC Internship Exit Presentation, Fall 2019.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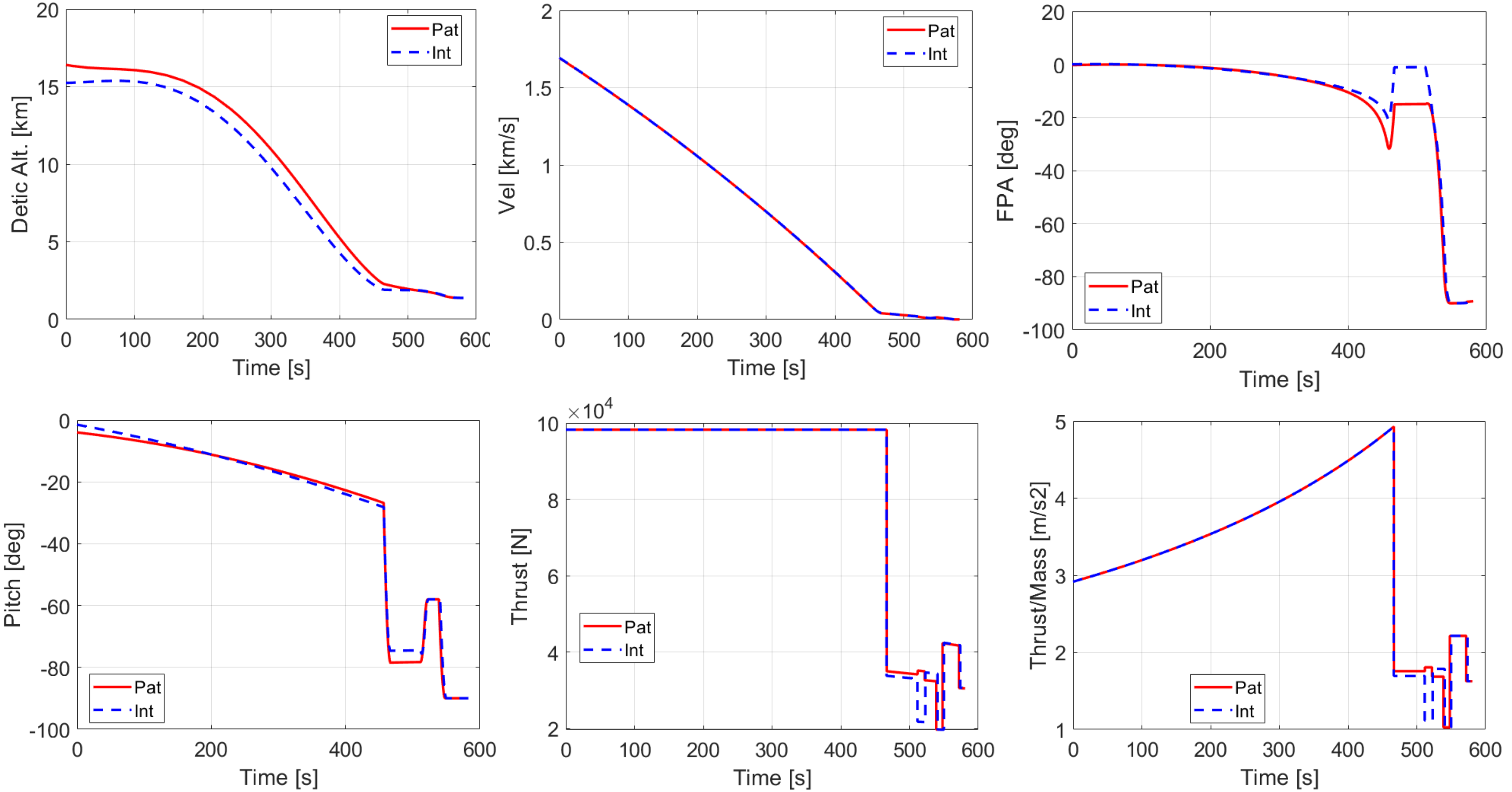
Sim Results: Patched vs End-to-End Optimization (PD)
Mission scenario: Optimal Surface Stay duration (~5.9 days)

- Mission epoch: Jan 12, 2025
- Landing site= -84.17 deg lat, 59.80 deg lon



End-to-end optimized solution's PDI occurs at lower altitude that that of the patched sim and as a result, has slightly better performance

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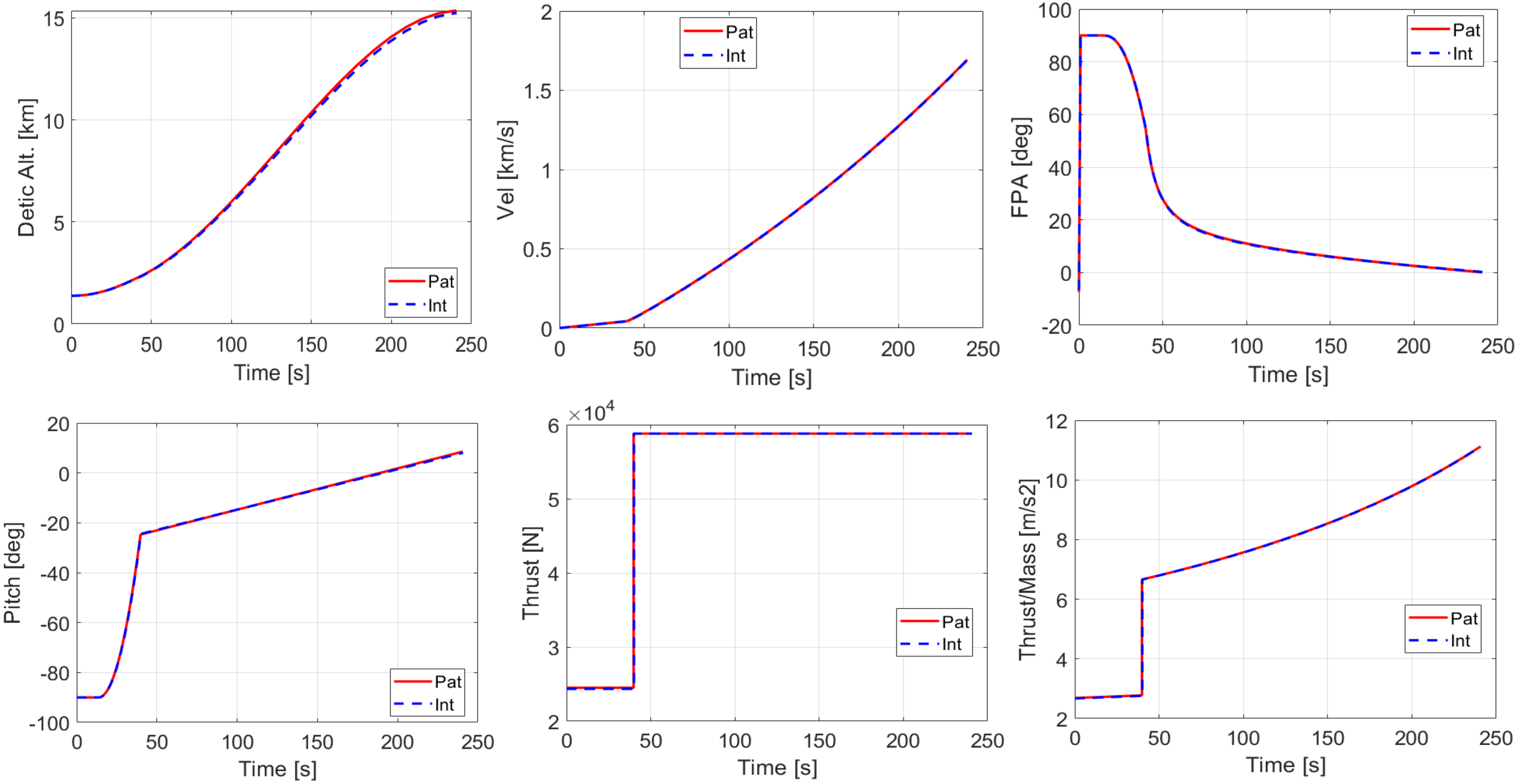
Sim Results: Patched vs End-to-End Optimization (PA)
Mission scenario: Optimal Surface Stay duration (~5.9 days)

- Mission epoch: Jan 12, 2025
- Landing site= -84.17 deg lat, 59.80 deg lon



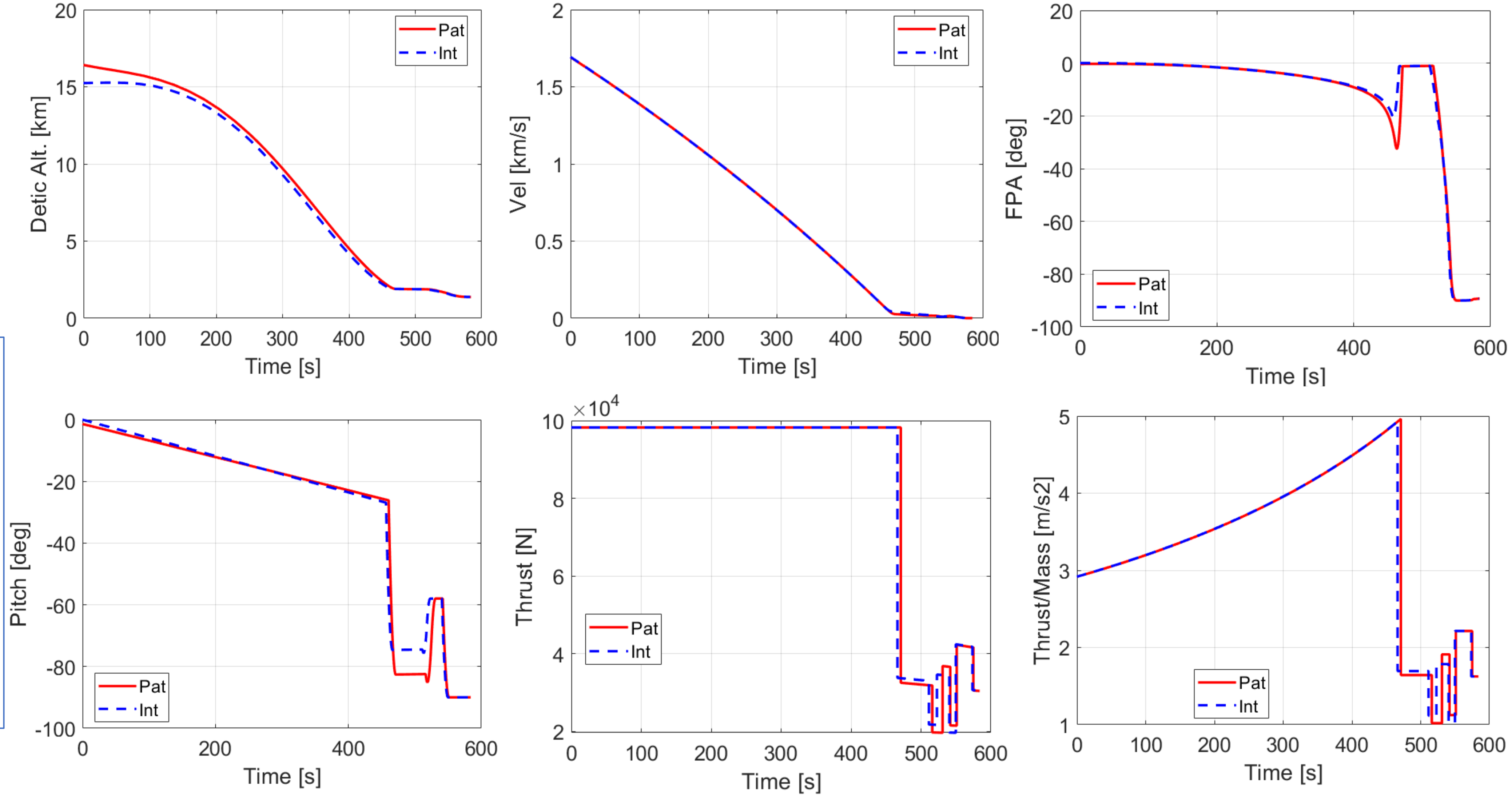
End-to-end optimized solution has almost the same performance as that of the patched sim.

65

Sim Results: Patched vs End-to-End Optimization (PD)
Mission scenario: Fixed Surface Stay duration (Optimal+6 hrs=6.1 days)

- Mission epoch: Jan 12, 2025
- Landing site= -84.17 deg lat, 59.80 deg lon

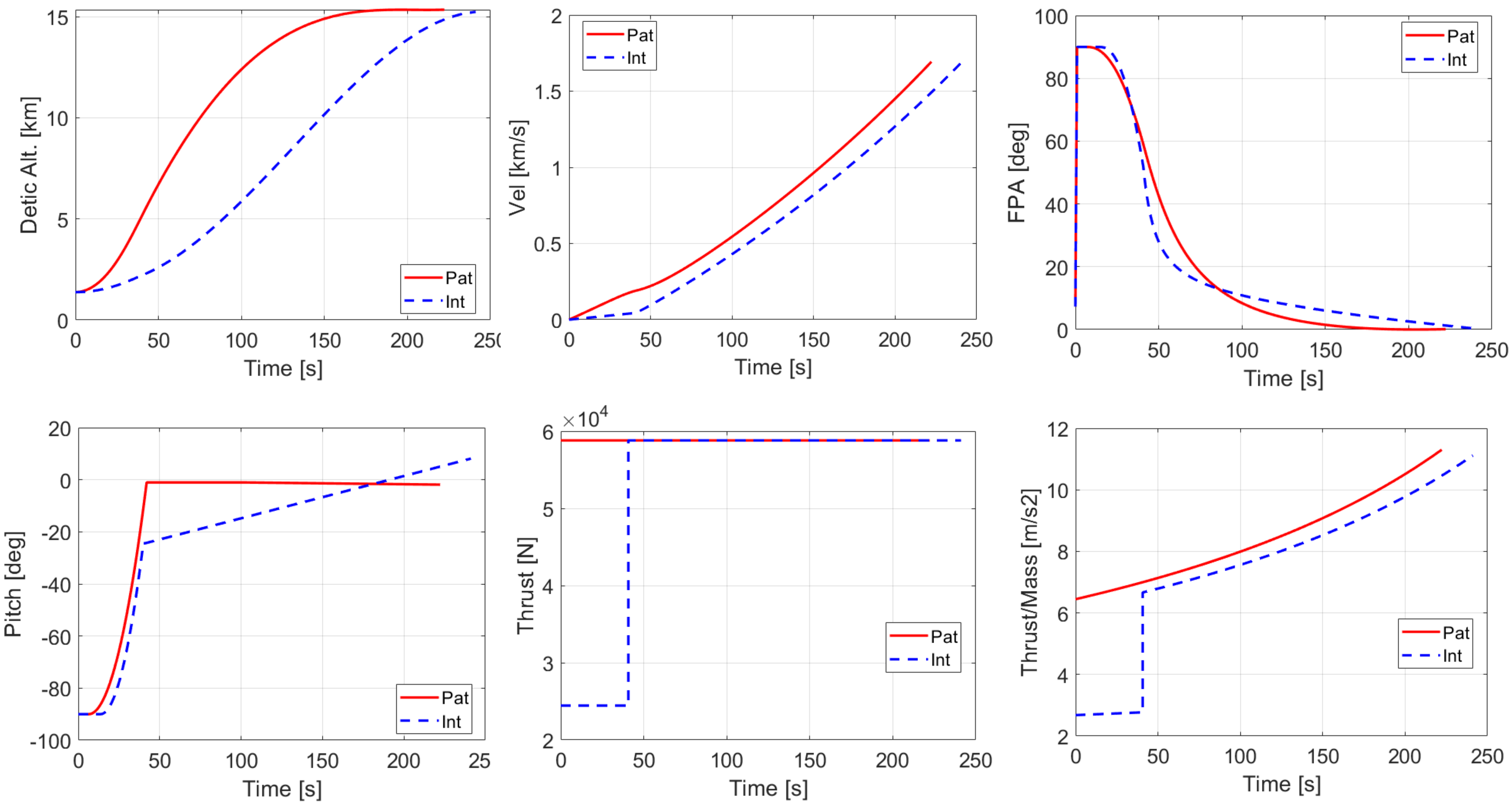
End-to-end optimized solution's PDI occurs at lower altitude that that of the patched sim and as a result, has better performance by ~80 kg of prop mass



66

Sim Results: Patched vs End-to-End Optimization (PA)
Mission scenario: Fixed Surface Stay duration (Optimal+6 hrs=6.1 days)

- Mission epoch: Jan 12, 2025
- Landing site= -84.17 deg lat, 59.80 deg lon



Powered ascent in the end-to-end optimized solution has longer duration by 20 sec than that of the patched sim and as a result, has lower prop mass usage by ~87 kg

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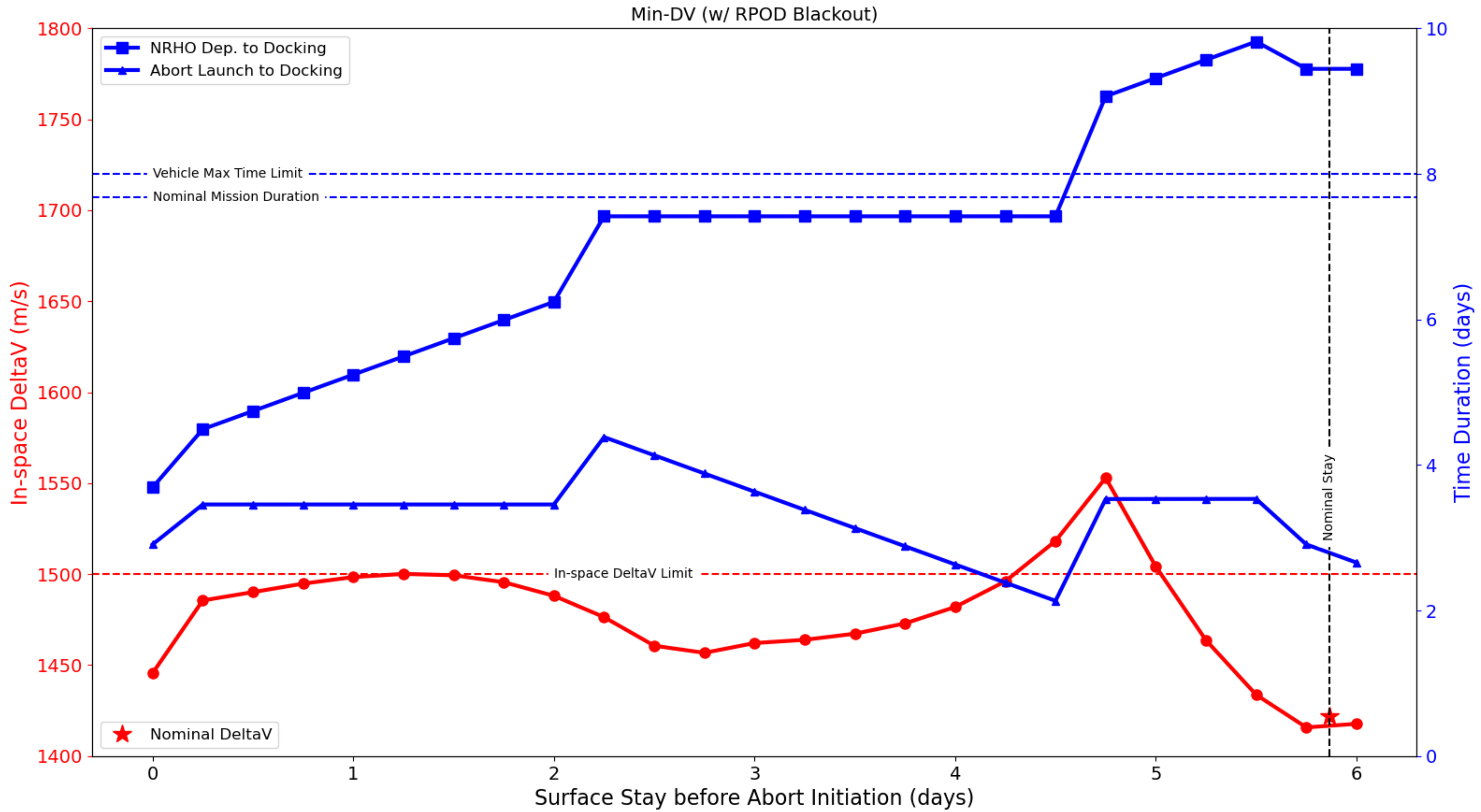
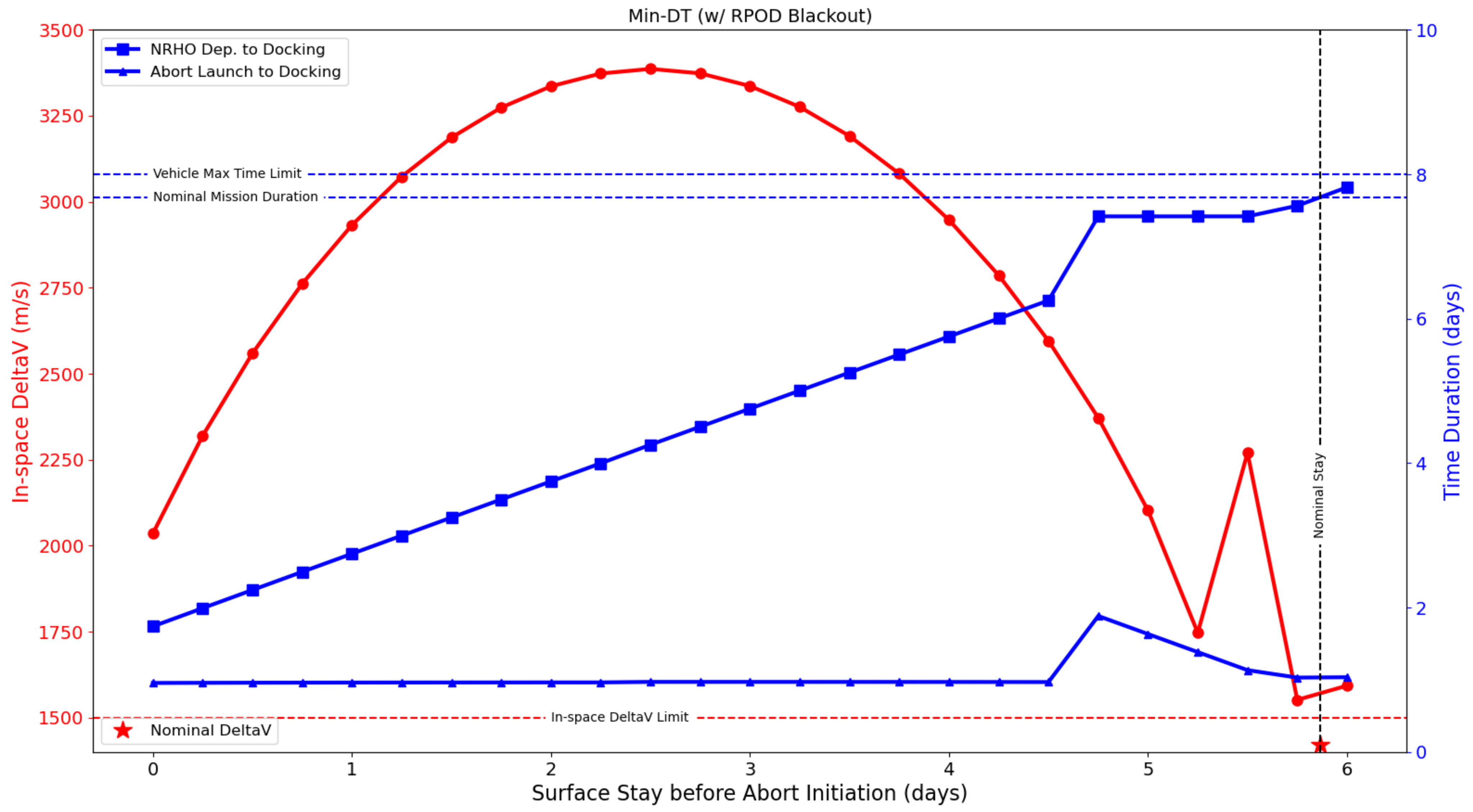
Minimum Delta-V Surface Abort Transfers (w/ RPOD constraint)

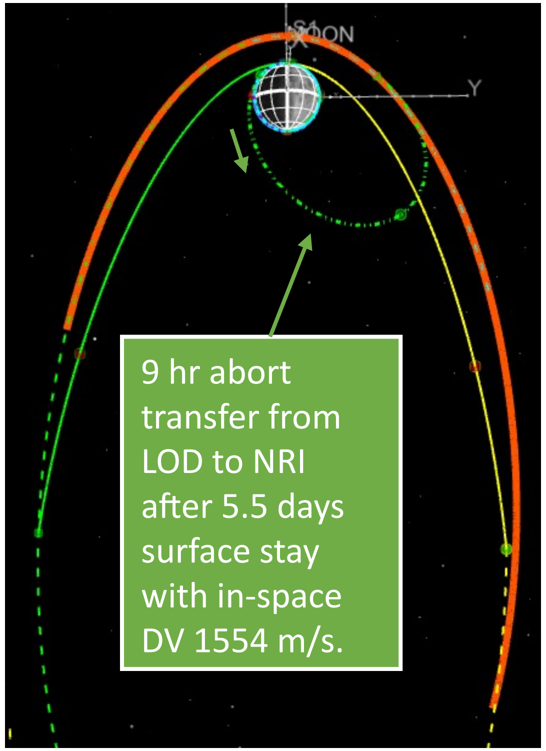


Minimum-Time Surface Abort Transfers

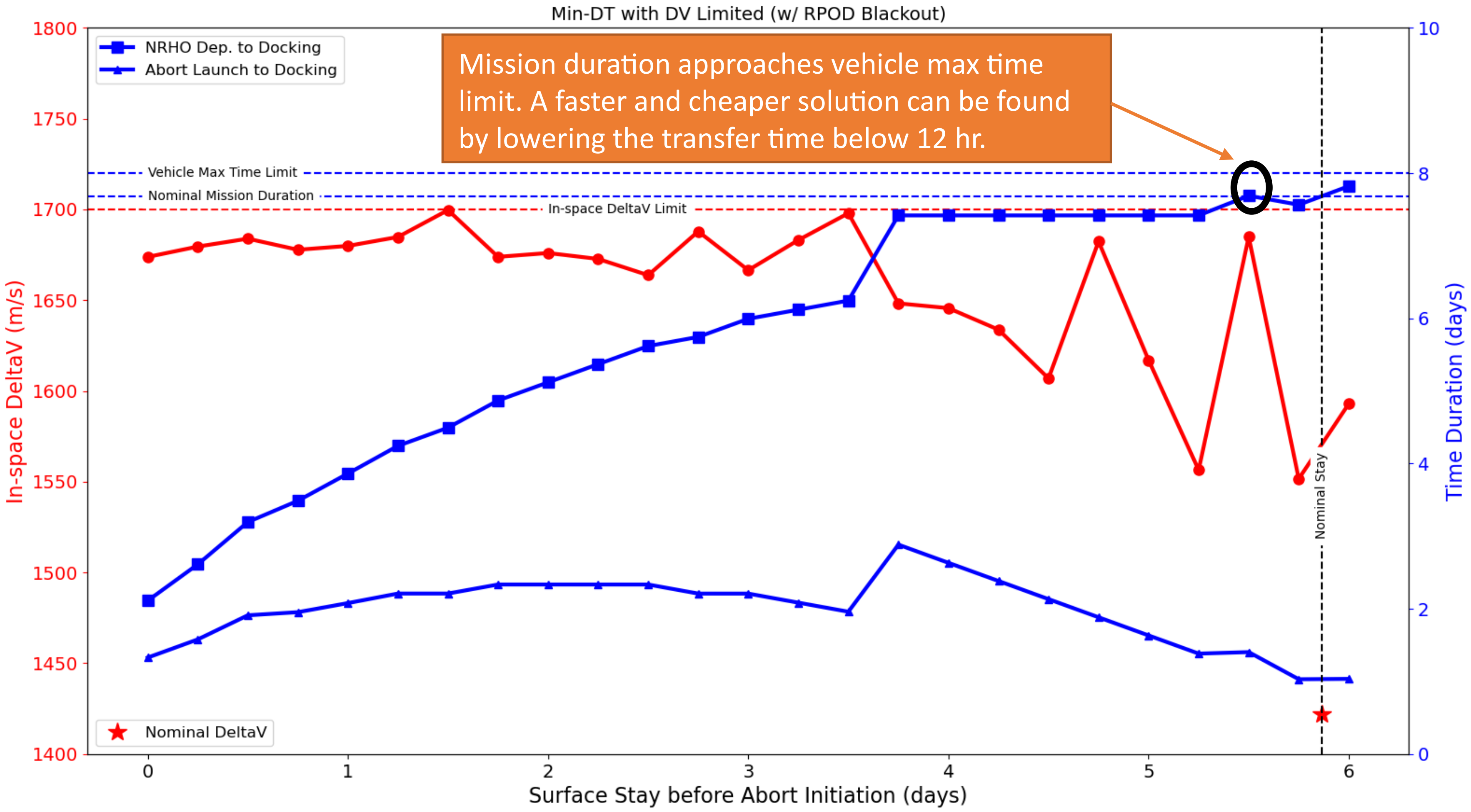


Minimum-Time Surface Abort Transfers
Delta-V Limited to 1700 m/s (w/ RPOD window constraint)

- **1 < Abort TOF < 3 d**
- **2.1 d < Mission Duration < 7.5 d**
- **For aborts after 5 days of surface stay, faster transfers from LOD to NRI with lower Delta-V can be found by decreasing the transfer time below 12 hr in some cases.**

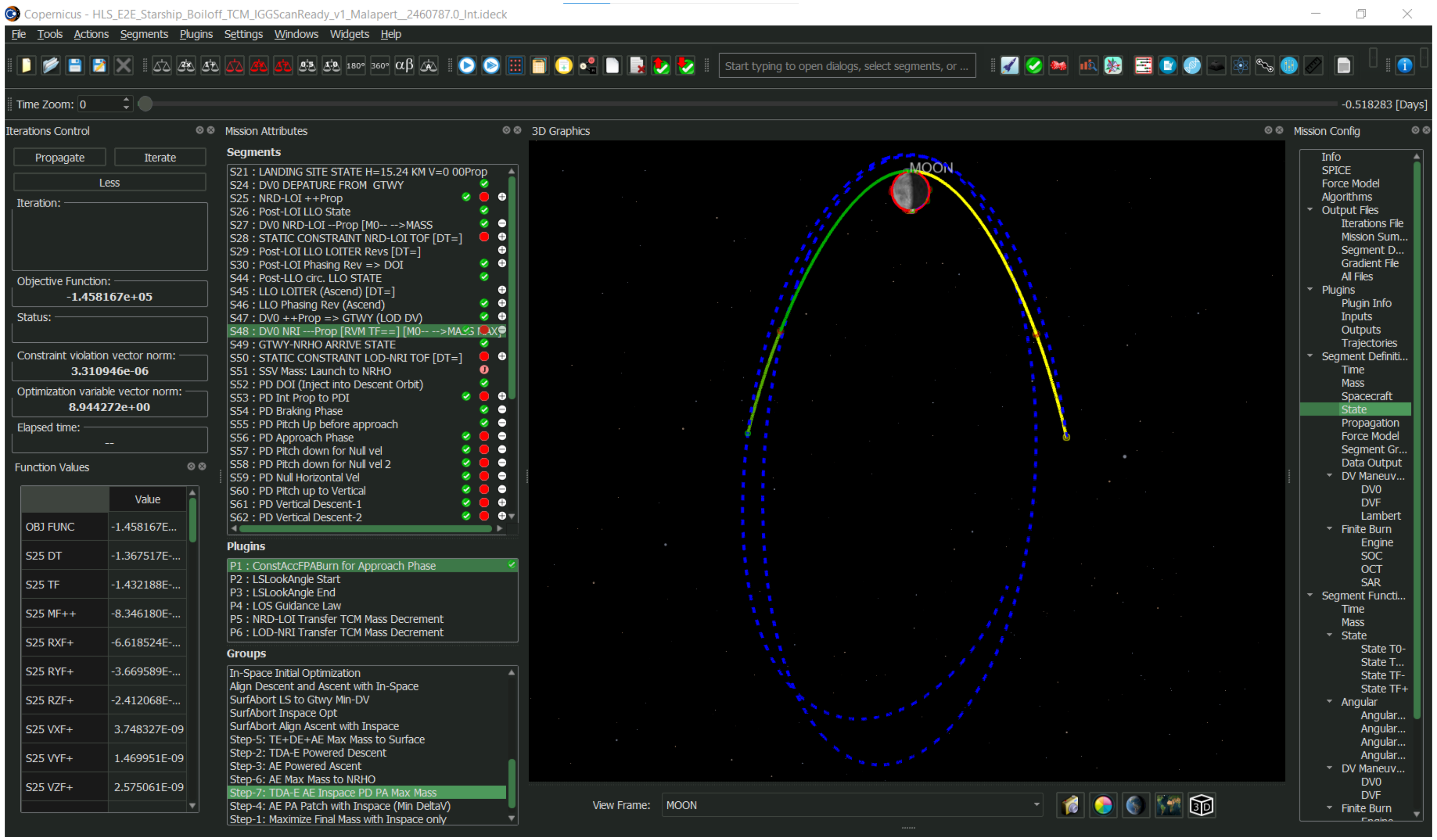


Abort Transfer Time and Mission Duration vs Abort Time



Performance Optimization using Copernicus

- **Copernicus: A generalized 3-DOF trajectory design and optimization tool maintained at NASA-JSC**
- **Extensively used for nominal and abort in-space trajectory optimization for the Artemis program**
- **Has High-fidelity Force Models for Gravity, Third-Body perturbations, SRP, and atmospheric drag**
- **Uses multiple-shooting direct method for transcription of the optimal control problem. Indirect method is also available**
- **The transcripted control problem is numerically solved using state-of-the-art optimizers, such as, Sparse Nonlinear Optimizer (SNOPT)**



For HLS mission, Copernicus is used for minimizing In-space Delta-V and prop mass used for powered descent/ ascent, and for satisfying the mission-specific constraints simultaneously

Epoch Scan

- **In order to gain an accurate understanding of what the availability of this abort mode will be, it is important to know the DV values at each epoch.**
  - **The amount of DV available on Orion will be dependent on epoch: Some outbound missions use more DV than others.**
- **Mission availability will be used in this analysis**
  - **Other constraints applied: Lighting at any site, 3-day loiter, and 8-day max Orion outbound duration**
  - **After these constraints: 42 Orion mission opportunities available, 13 HLS missions accessible**
- **The epoch scan considers only a return to the altitude/flight path angle E.I. target**
- **Investigated epoch range March 16, 2024 – August 25, 2025**
  - **80 nominal HLS missions in this range**