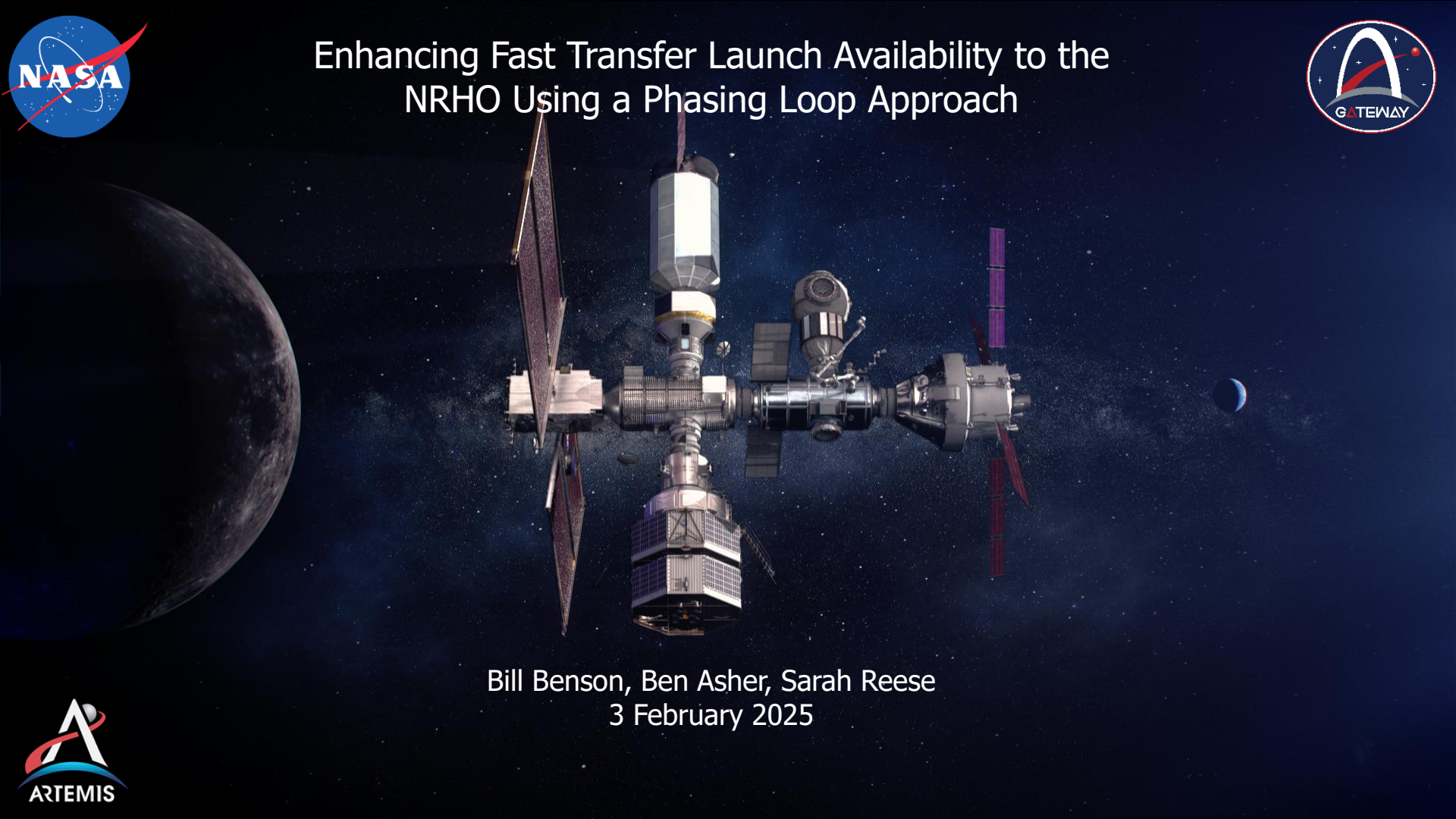
Enhancing Fast Transfer Launch Availability to the NRHO Using a Phasing Loop Approach



Bill Benson, Ben Asher, Sarah Reese

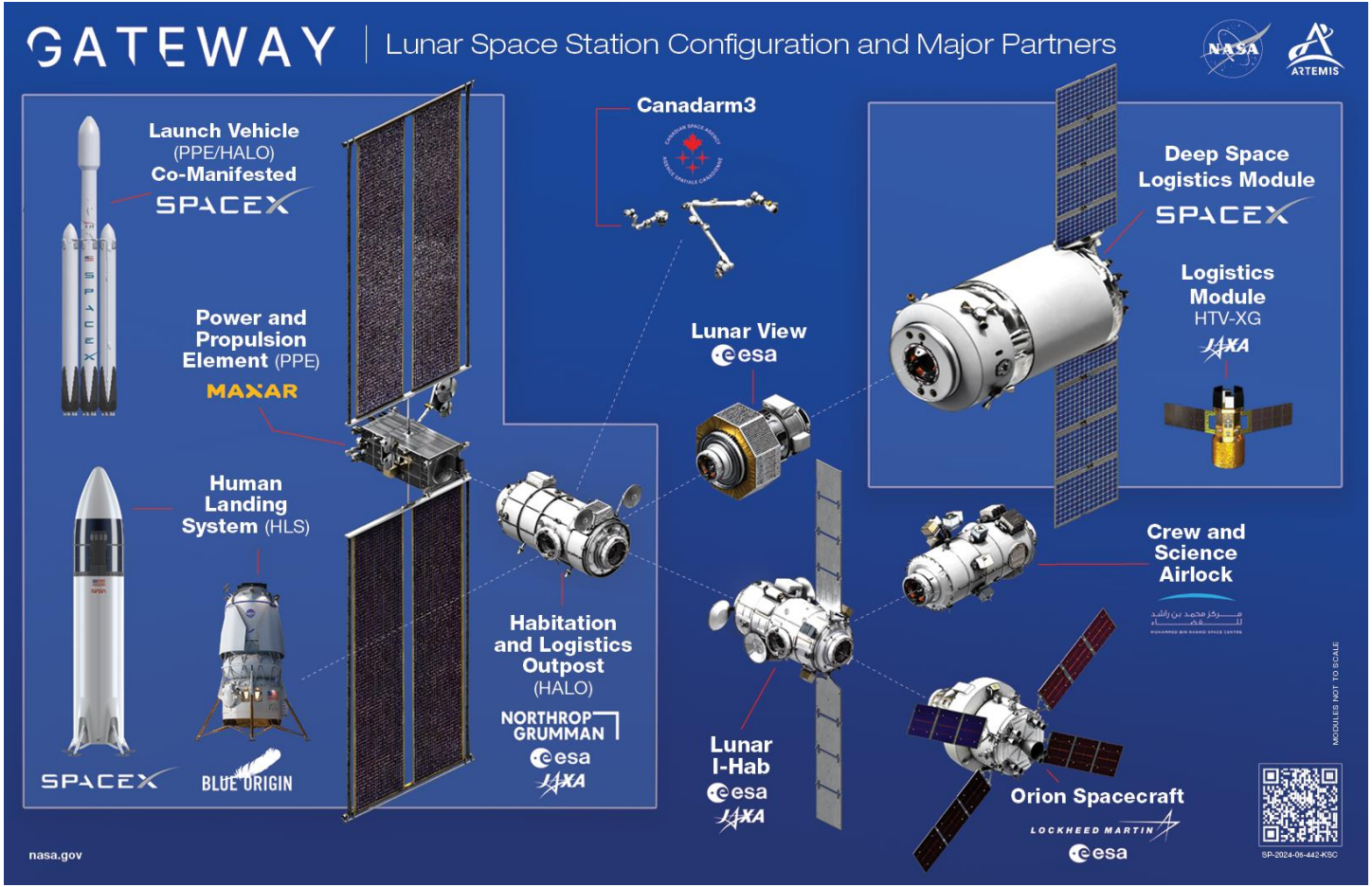
3 February 2025

Purpose and Scope

Design a methodology to maximize the launch availability for a logistics resupply mission to Gateway in support of any given Artemis campaign.

- An Artemis campaign is primarily dependent on the limited launch availability of the crewed SLS/Orion system.
- The logistics module (LM) is scheduled to be the first component arriving at Gateway for any given Artemis campaign; followed by the Human Landing System (HLS) and then the crew.
- Maximizing the LMs launch availability is crucial for the success of an Artemis mission
  - The LM's launch availability is limited by a delta-V budget restriction of 440 m/s for all deterministic maneuvers
  - Delta-V for Trajectory Correction Maneuvers (TCM's), Proximity Operations or Docking is not considered for the purposes of this study

Gateway and Major Partners



Deep Space Logistics Project

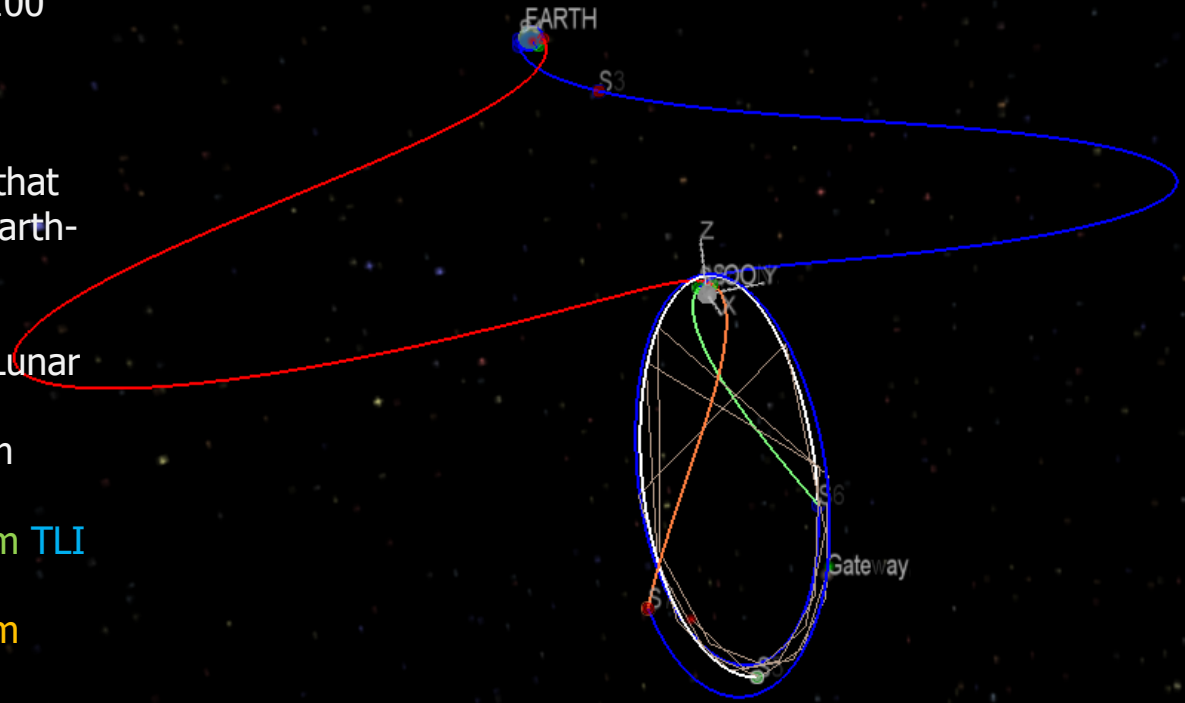
Deep Space Logistics (DSL), a project within the Gateway Program, is responsible for leading the commercial supply chain in deep space by procuring services for transporting cargo, equipment, and consumables to enable exploration of the Moon and Mars starting with logistics resupply to Gateway.

The DSL team seeks to understand the launch availability assuming a "Fast Transit", which is contractually defined as a *maximum 30-day interval* from liftoff to arrival at Gateway.

Near-Rectilinear Halo Orbit (NRHO) In 2B Earth-Moon Rotating Frame

- Center: Earth-Moon L2
- Period: 6.56 days
- Mean radius: 3250 x 71,100 km
- Inclination: ~Polar
- Quasi-periodic orbit that maintains an orbit plane that is always normal to the Earth-Moon vector
- Continuous LOS w/Earth
- Near Continuous LOS w/Lunar South Pole
- "Easy" access to and from Earth:
  1. 400 – 450 m/s from TLI to NRHO
  2. 400 – 450 m/s from NRHO back to TEI

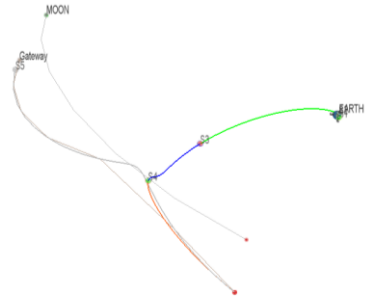
- Each Rev of the NRHO is incremented at perilune starting with Rev 1 on 1/2/2020



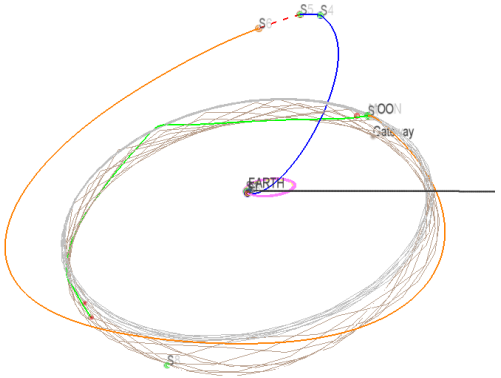
Fast vs. Slow Transits

- "Fast" transits are contractually defined as any transit less than 30 days as measured between liftoff and hard-capture at Gateway.
- The DSL contract also permits "Slow" transit missions that could include options such as low-thrust transits or BLTs. Previous work by Parker et al.* has shown 100% launch availability for BLTs and will not be considered in this study.

*J. Parker, "Monthly Variations of Low-Energy Ballistic Transfers to Lunar Halo Orbits," AAIA/AAS Astrodynamics Specialist Conference, Aug. 2010.



Direct (Fast) in J2000 Frame



BLT (Slow) in J2000 Frame

Launch Opportunity vs. Launch Window

- *Launch Opportunity* – The span of days over which a LM may be launched that supports a particular Orion/SLS launch date that satisfies constraints on the earliest/latest arrival at Gateway as specified by the Artemis program

- *Launch Window* – The interval on a specific day in the Launch Opportunity where a mission may be launched.
  - Instantaneous launch windows are a single launch time per day that satisfies the ascending node requirement for TLI
  - Some launch days may have several instantaneous windows that satisfy multiple ascending node targets
  - Finite launch windows occur over a continuous period lasting minutes or hours where the LV conducts out-of-plane steering to satisfy the ascending node target

Analysis Approach

- Phase 1 will establish the baseline by considering the launch availability for a single Artemis Campaign using straightforward approaches such as direct insertion from a fast transit.
- Phase 2 will explore, alternative approaches, such as phasing loops, to assess different operational strategies for the same Artemis Campaign as in Phase 1.
- Phase 3 will generalize the results from Phases 1 and 2 to apply to any Artemis Campaigns throughout the year to validate the methodology and characterize the required vehicle capability.

Phase 1

- **ESTABLISH THE BASELINE USING DIRECT INSERTION FROM A FAST TRANSIT**

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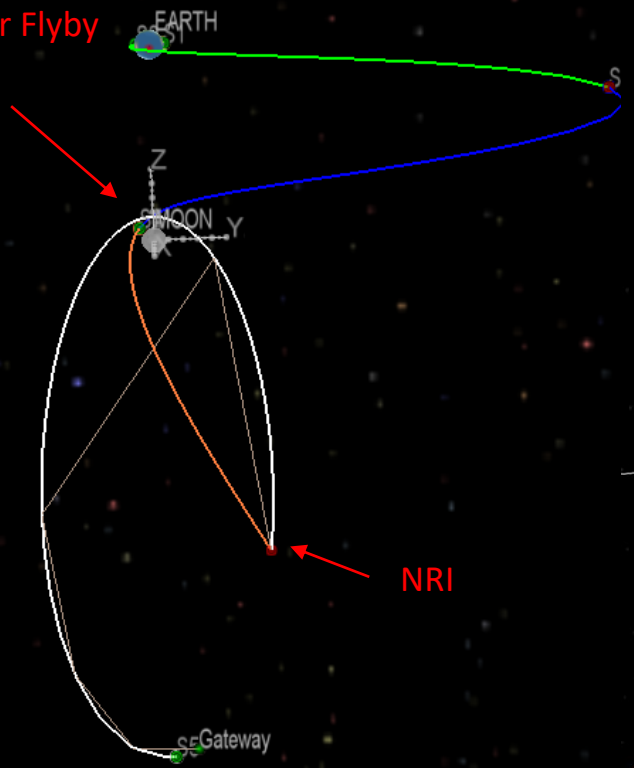
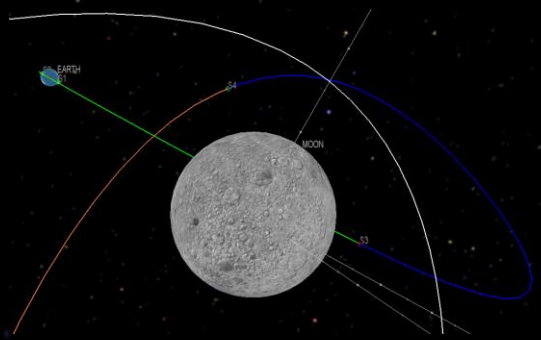
Direct Transfer

- Five Segments
  1. Park Orbit
  2. LV TLI Outbound
  3. Perilune Approach
  4. NRHO Approach and Gateway Rendezvous
  5. NRHO Ephemeris

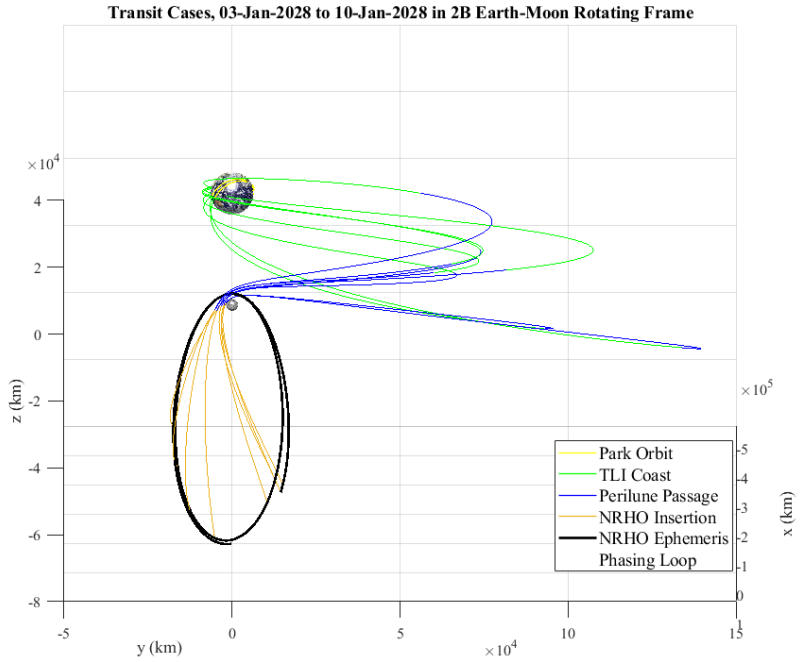
Powered Lunar Flyby (PLF)

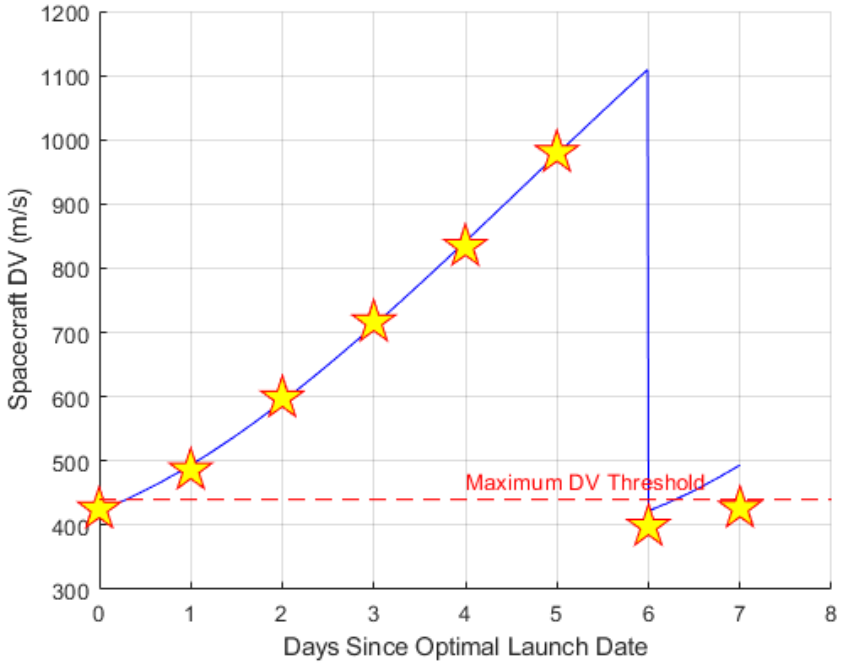




Optimal case shown here such that the Gateway and the LM are at the same location in the NRHO at the LM's NRI maneuver where spacecraft DV is minimized

Short TLI Coast Direct Transfer Overplots

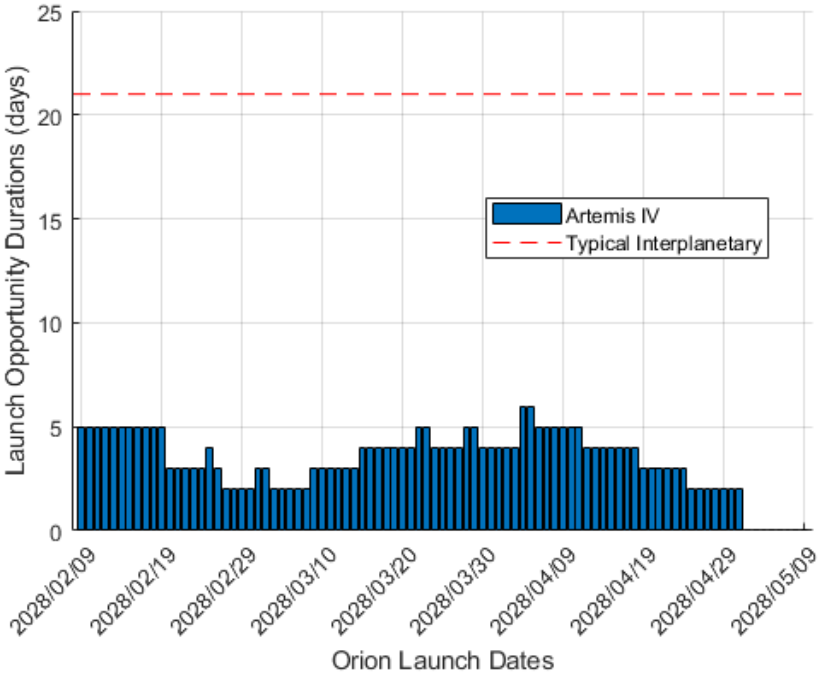




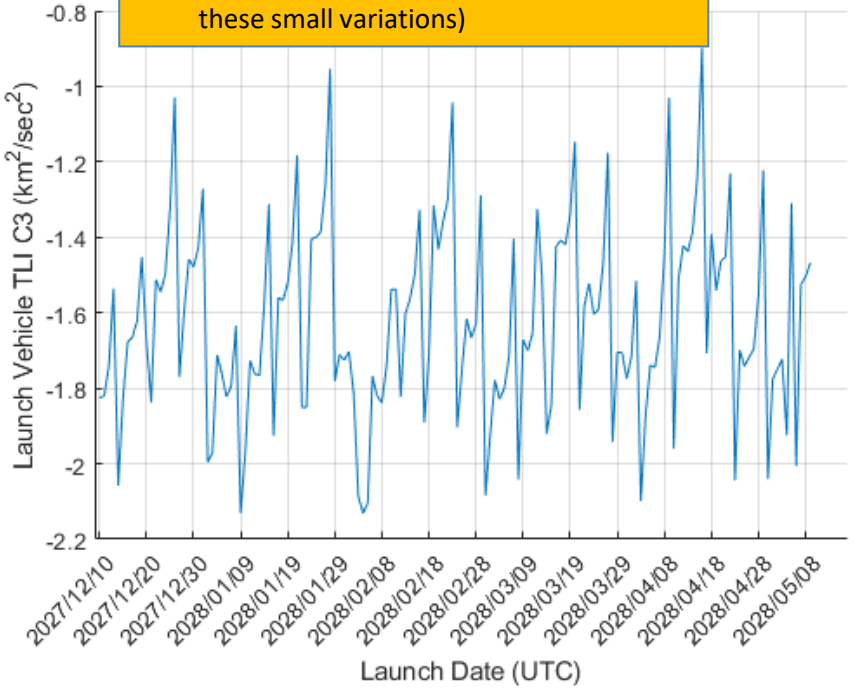
Example Launch Opportunity with Short TLI Coast Direct Transfer for the 2/9/2028 Orion Launch Date

Up to 2 contiguous launch days may be available and 5 days total when constrained by both the 440 m/s DV threshold and a minimized mission duration

Launch Opportunities over a 3-Month Interval of Orion Launch Dates with Short TLI Coast Direct Transfer

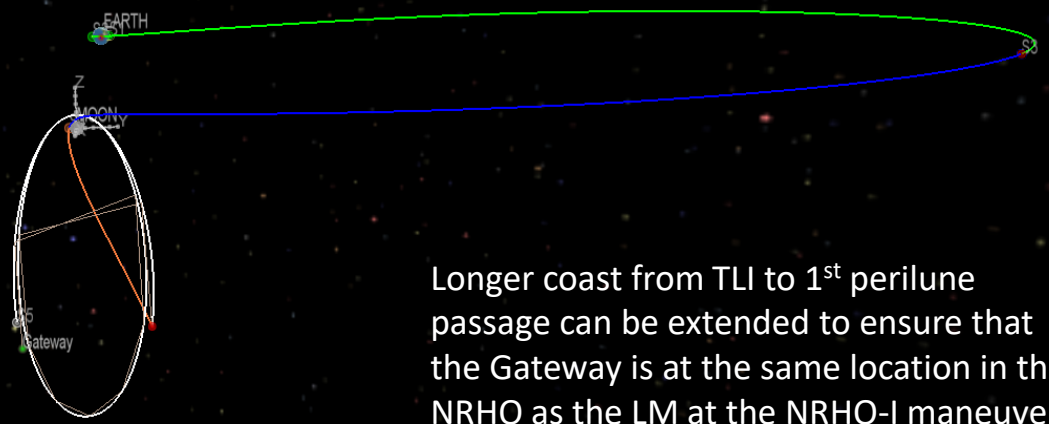


- Launch Opportunity is insensitive to TLI (LV capability should be insensitive to these small variations)



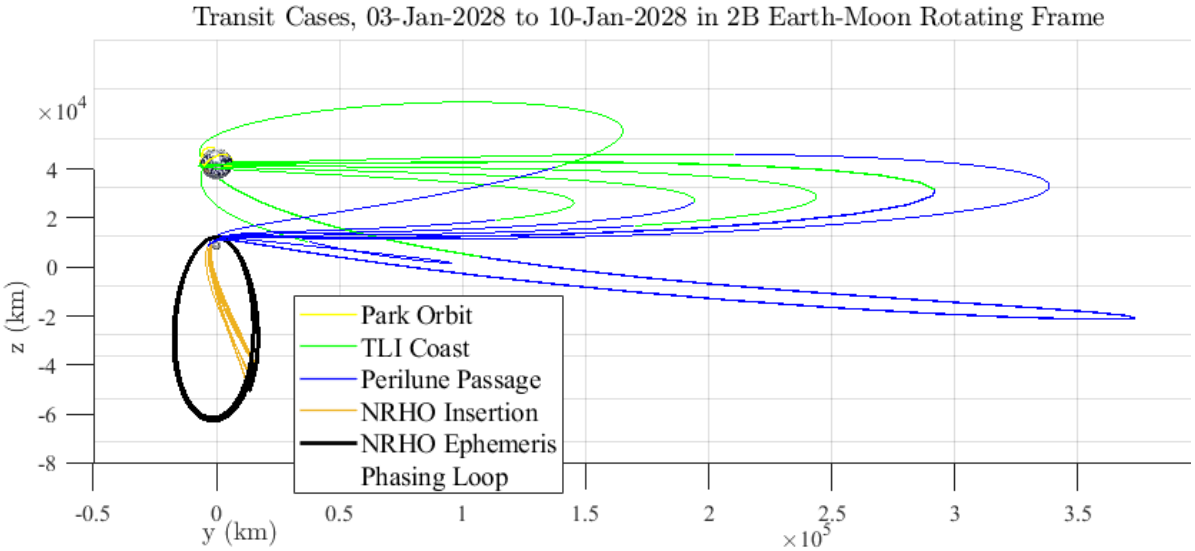
Variable TLI Coast Direct Transfer

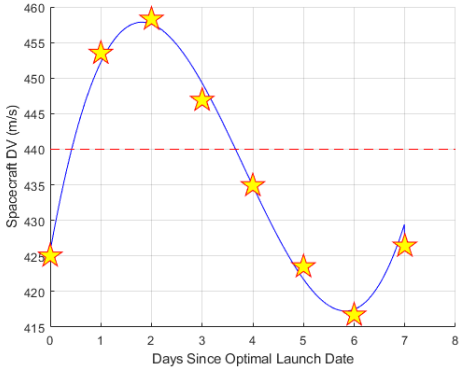
- Five Segments
  1. Park Orbit
  2. LV TLI Outbound
  3. Perilune Approach
  4. NRHO Approach and Gateway Rendezvous
  5. NRHO Ephemeris

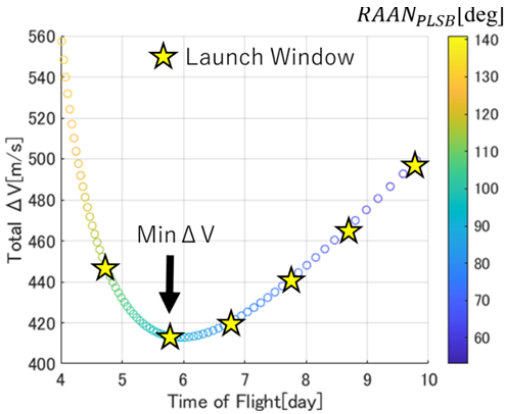


Longer coast from TLI to 1st perilune passage can be extended to ensure that the Gateway is at the same location in the NRHO as the LM at the NRHO-I maneuver

Variable TLI Coast Direct Transfer Overplots







J, Kikuchi., N, Murakami., Y, Matsumoto., and S, Ueda.: "Trajectory Design of NRHO Transfer with Continuous Launch Window for Logistics Resupply Mission to Gateway", IAF 75th International Astronautical Congress, Milan, Italy, C1.IP.33, 2024. Ref Kikuchi et. al

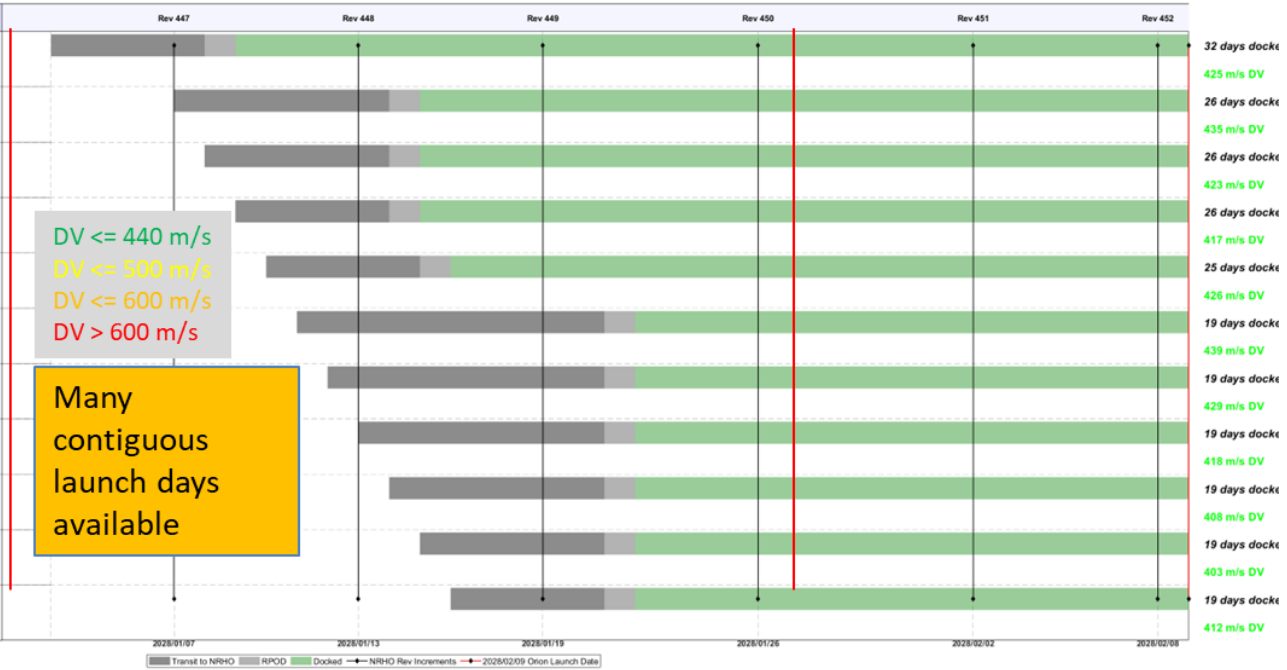
Example Launch Opportunity with *Variable* TLI Coast Direct Transfer for the 2/9/2028 Orion Launch Date

Earliest Arrival

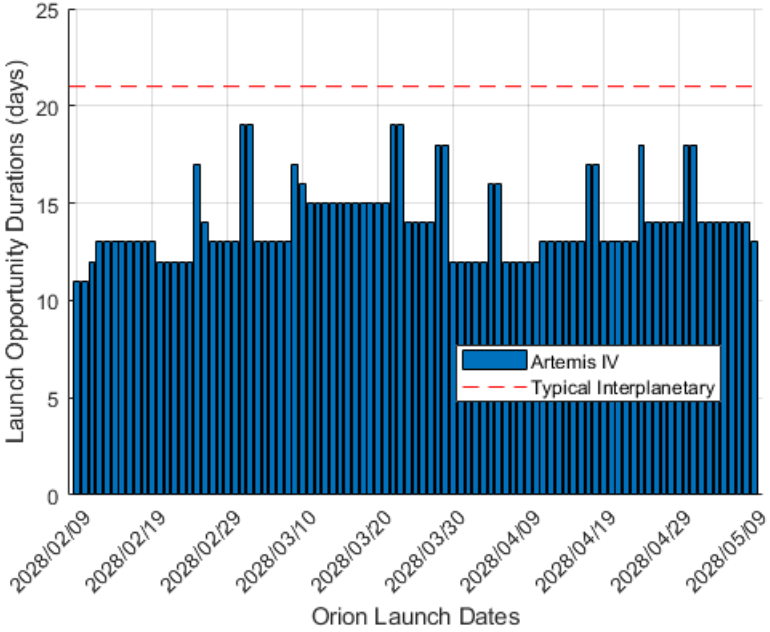
Latest Arrival

MISSION TYPE	LAUNCH DATE	DUR
Direct (Short TLI Coast)	2028/01/03	6
Direct (Short TLI Coast)	2028/01/07	8
Direct (Short TLI Coast)	2028/01/08	7
Direct (Short TLI Coast)	2028/01/09	6
Direct (Short TLI Coast)	2028/01/10	6
Direct (Variable TLI Coast)	2028/01/11	11
Direct (Variable TLI Coast)	2028/01/12	10
Direct (Variable TLI Coast)	2028/01/13	9
Direct (Variable TLI Coast)	2028/01/14	8
Direct (Variable TLI Coast)	2028/01/15	7
Direct (Variable TLI Coast)	2028/01/16	6

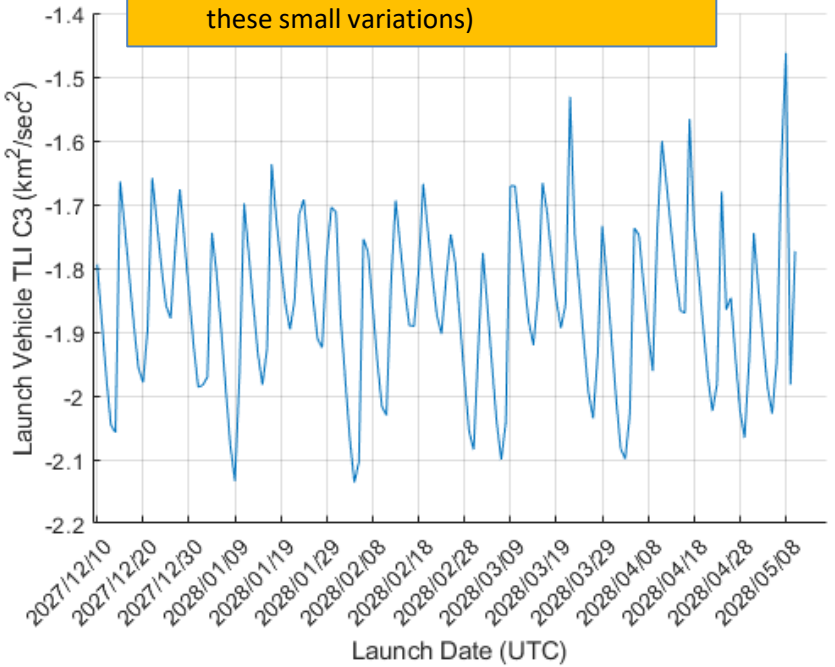
Launch Opportunity: 11 days



Launch Opportunities over a 3-Month Interval of Orion Launch Dates with *Variable* TLI Coast Direct Transfer



- Launch Opportunity is insensitive to TLI (LV capability should be insensitive to these small variations)

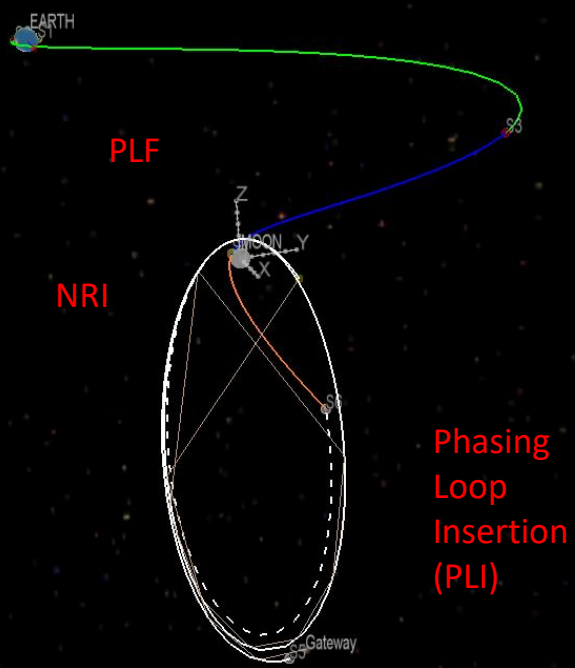


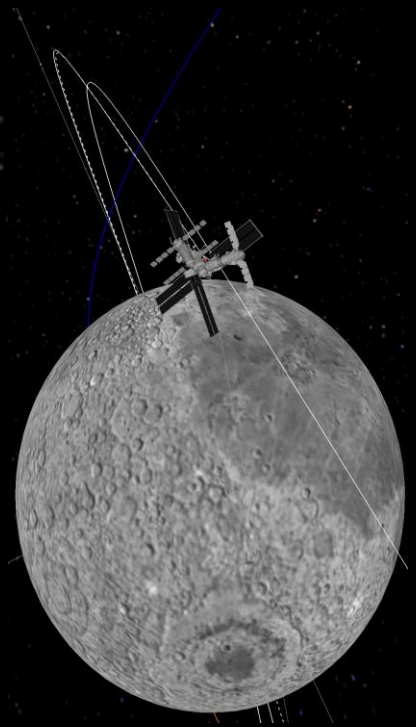
Phase 2

- **EXPLORE ALTERNATIVE APPROACHES SUCH AS PHASING LOOPS**

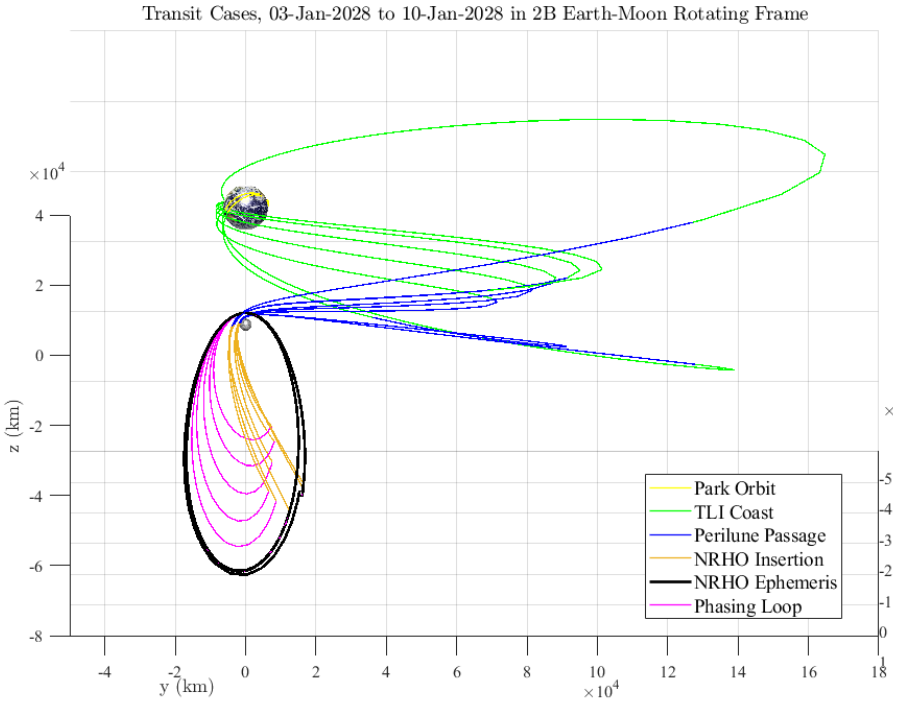
Single Phasing Loop Transfer

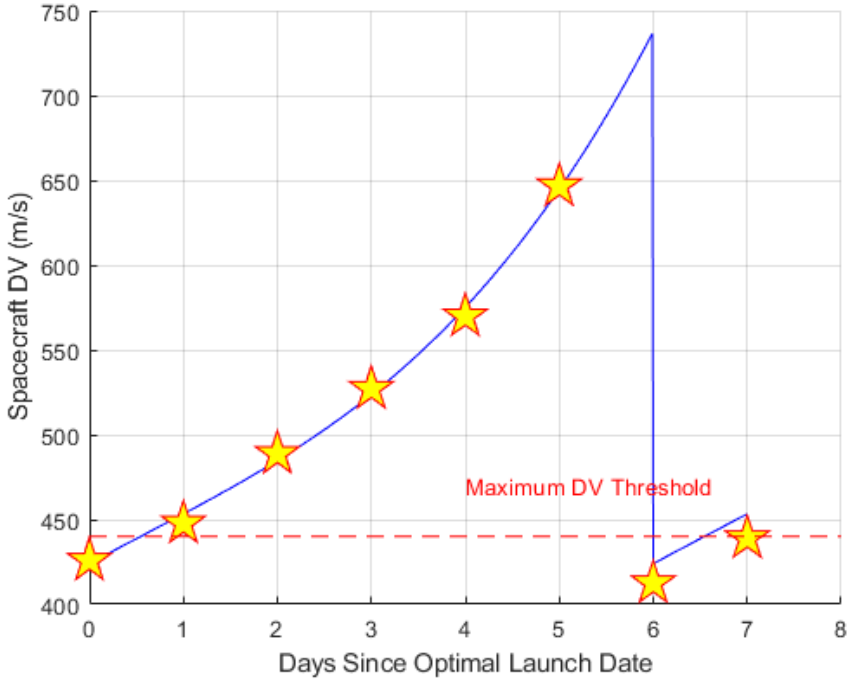
- Six Segments
  1. Park Orbit
  2. LV TLI Outbound
  3. Perilune Approach
  4. NRHO Approach
  5. NRHO Ephemeris
  6. NRHO Single Phasing Loop and Gateway Rendezvous (---)





Single Phasing Loop Transfer Overplots

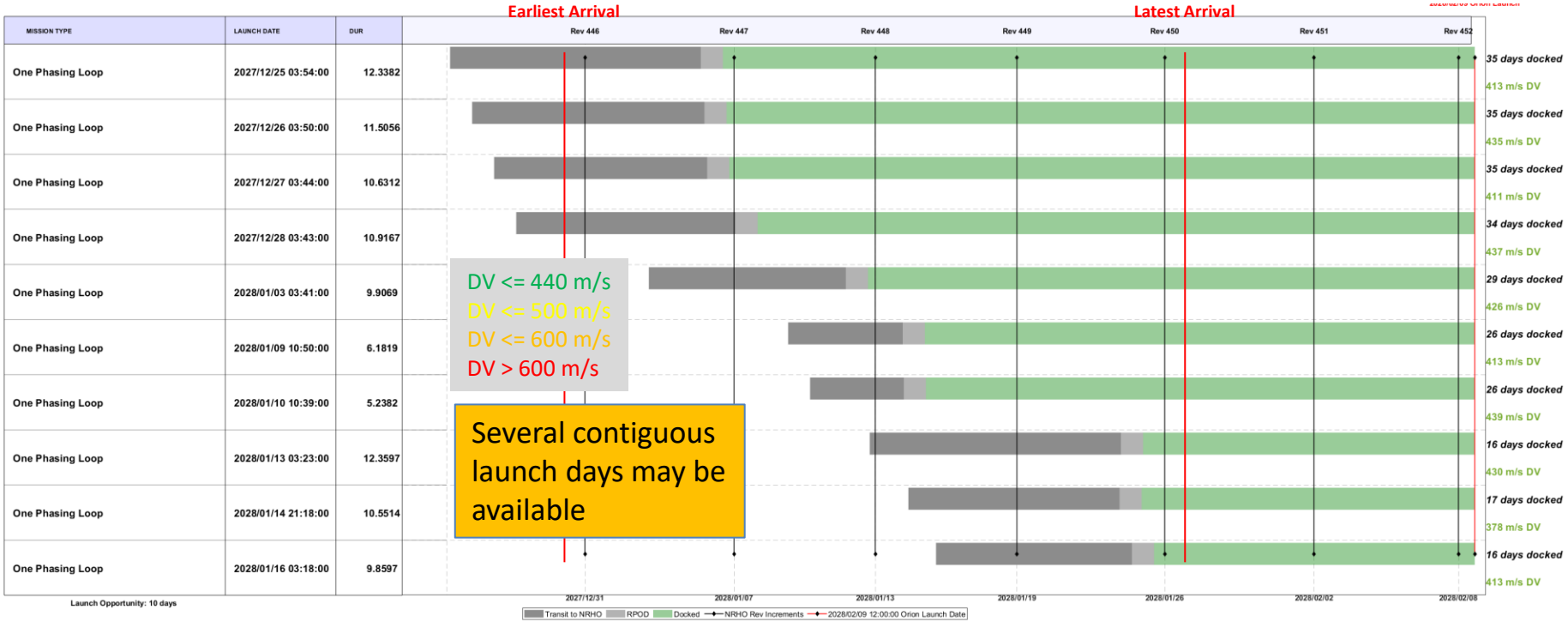




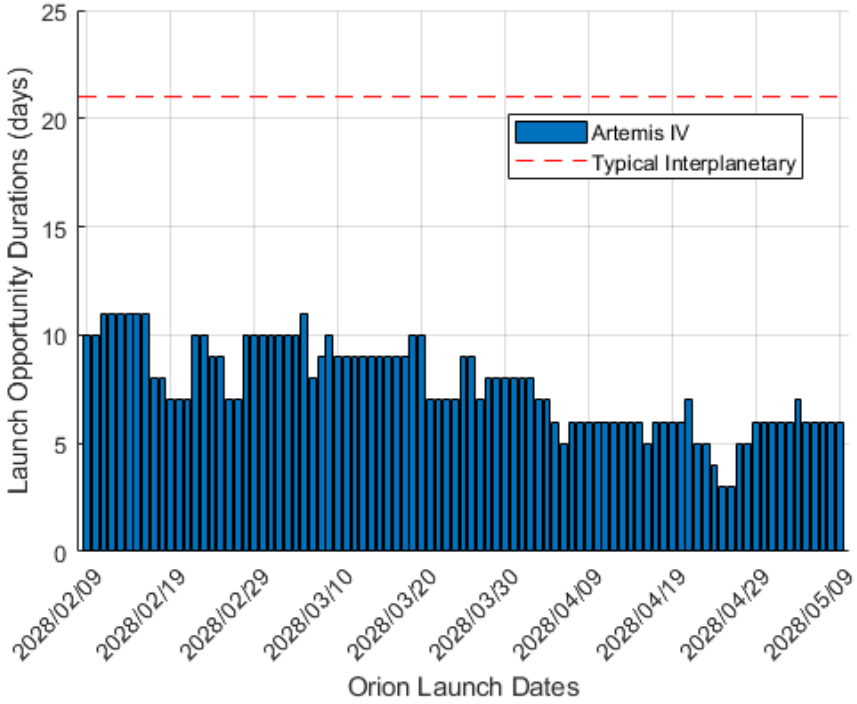
Example Launch Opportunity with *Single Phasing Loop* Transfer for the 2/9/2028 Orion Launch Date

MISSION TYPE	LAUNCH DATE	DUR
One Phasing Loop	2027/12/25 03:54:00	12.3382
One Phasing Loop	2027/12/26 03:50:00	11.5056
One Phasing Loop	2027/12/27 03:44:00	10.6312
One Phasing Loop	2027/12/28 03:43:00	10.9167
One Phasing Loop	2028/01/03 03:41:00	9.9069
One Phasing Loop	2028/01/09 10:50:00	6.1819
One Phasing Loop	2028/01/10 10:39:00	5.2382
One Phasing Loop	2028/01/13 03:23:00	12.3597
One Phasing Loop	2028/01/14 21:18:00	10.5514
One Phasing Loop	2028/01/16 03:18:00	9.8597

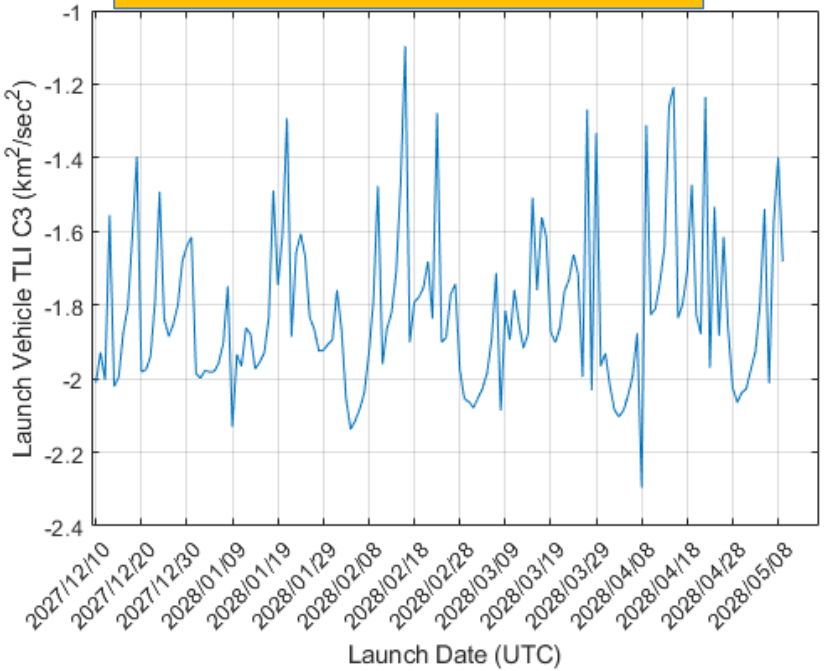
Launch Opportunity: 10 days



Launch Opportunities over a 3-Month Interval of Orion Launch Dates with *One-Phasing Loop* Transfer

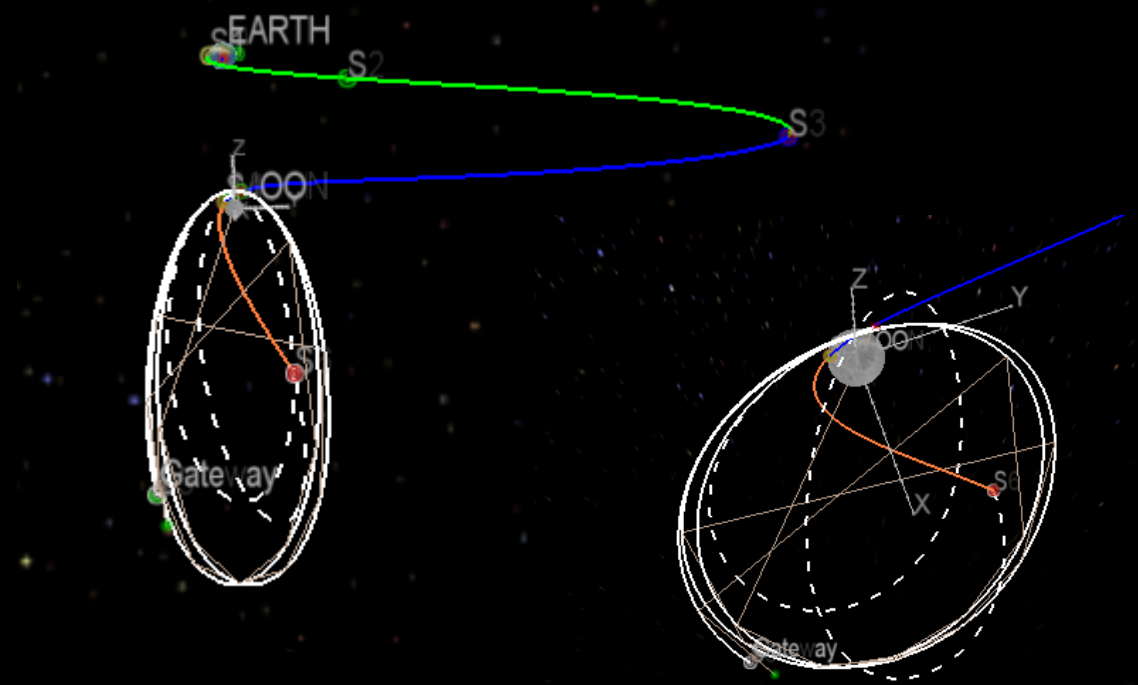


- Launch Opportunity is insensitive to TLI (LV capability should be insensitive to these small variations)

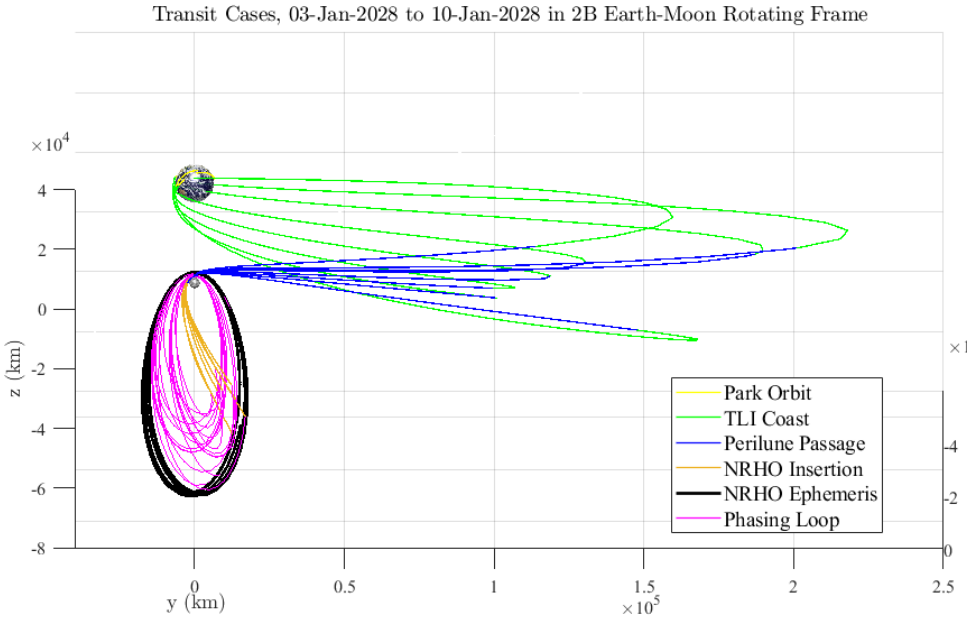


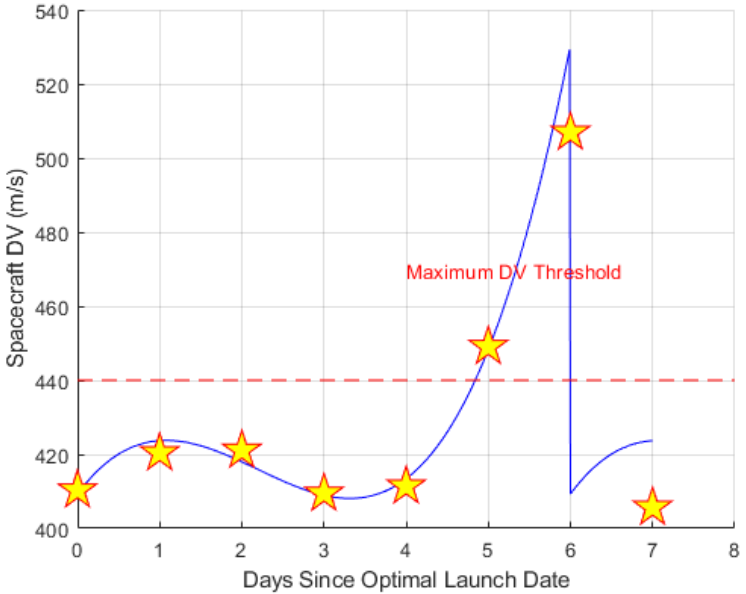
Double Phasing Loop Transfer

- Six Segments
  1. Park Orbit
  2. LV TLI Outbound
  3. Perilune Approach
  4. NRHO Approach
  5. NRHO Ephemeris
  6. NRHO Single Phasing Loop and Gateway Rendezvous (---)



Double Phasing Loop Transfer Overplots

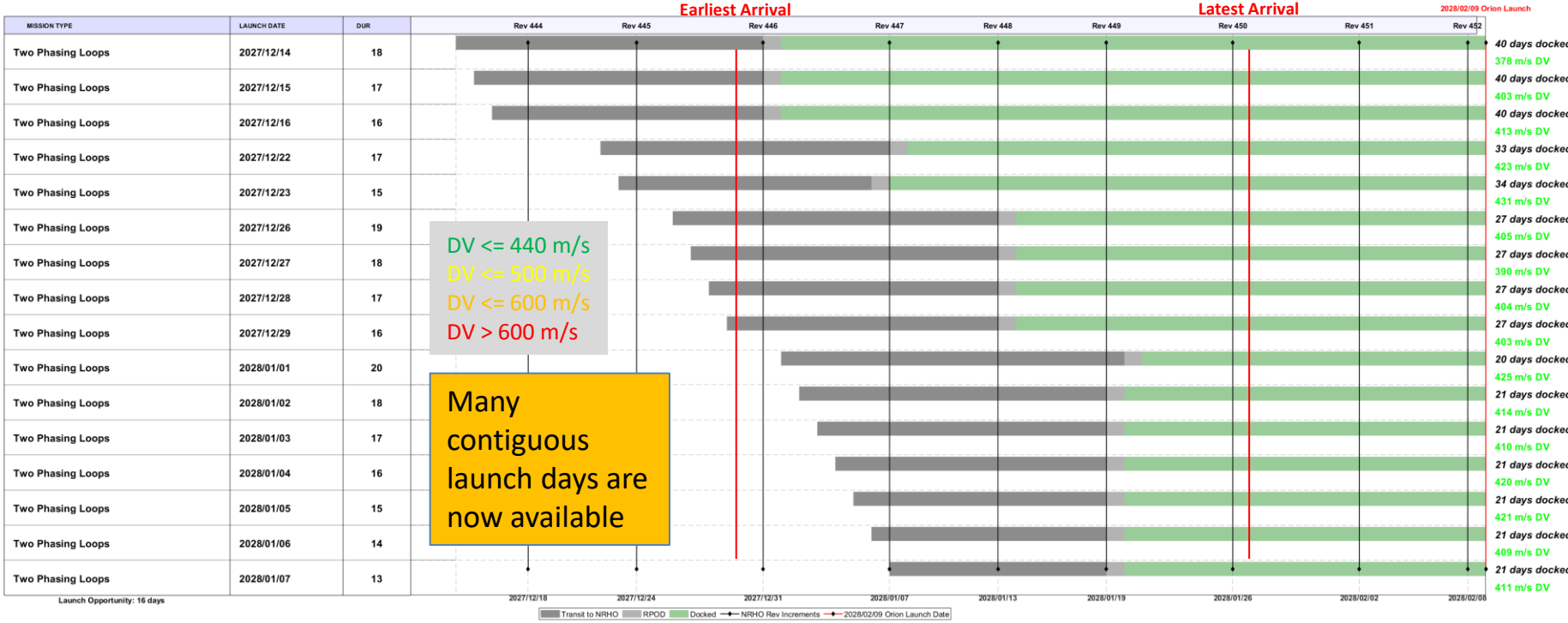




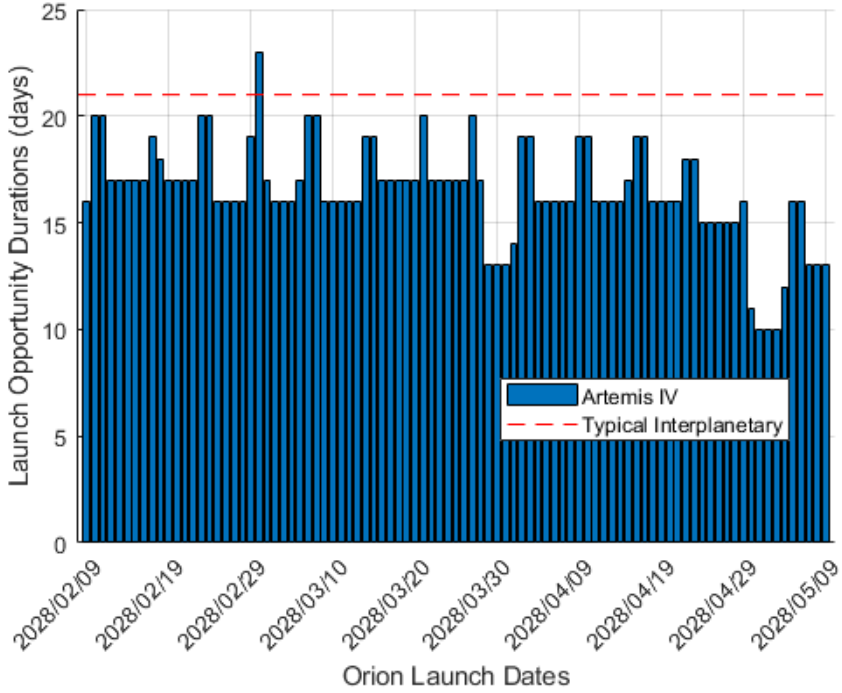
Example Launch Opportunity with *Two*-Phasing Loops Transfer for the 2/9/2028 Orion Launch Date

MISSION TYPE	LAUNCH DATE	DUR
Two Phasing Loops	2027/12/14	18
Two Phasing Loops	2027/12/15	17
Two Phasing Loops	2027/12/16	16
Two Phasing Loops	2027/12/22	17
Two Phasing Loops	2027/12/23	15
Two Phasing Loops	2027/12/26	19
Two Phasing Loops	2027/12/27	18
Two Phasing Loops	2027/12/28	17
Two Phasing Loops	2027/12/29	16
Two Phasing Loops	2028/01/01	20
Two Phasing Loops	2028/01/02	18
Two Phasing Loops	2028/01/03	17
Two Phasing Loops	2028/01/04	16
Two Phasing Loops	2028/01/05	15
Two Phasing Loops	2028/01/06	14
Two Phasing Loops	2028/01/07	13

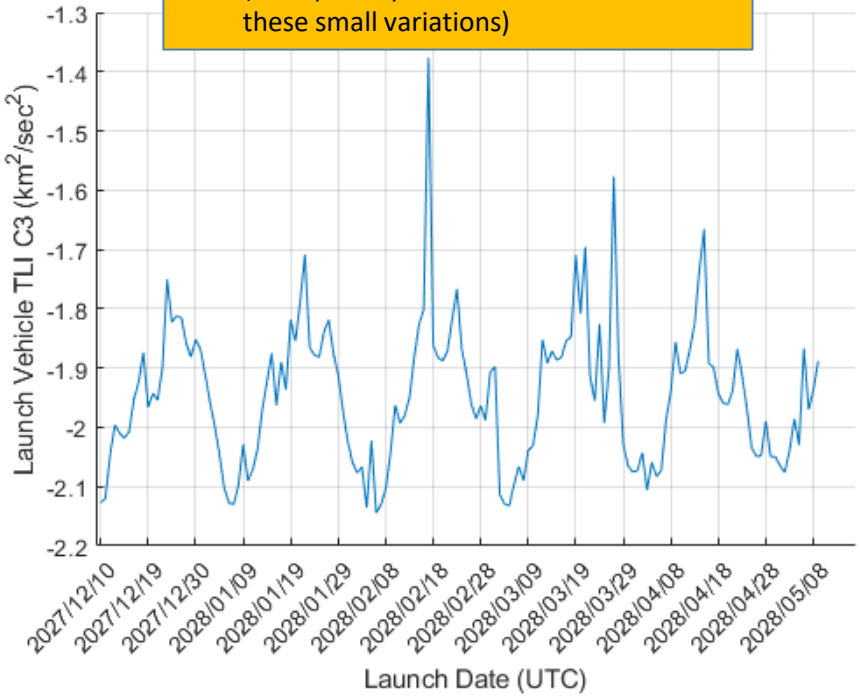
Launch Opportunity: 16 days



Launch Opportunities over a 3-Month Interval of Orion Launch Dates with *a Double* Phasing Loops Transfer



- Launch Opportunity is insensitive to TLI (LV capability should be insensitive to these small variations)

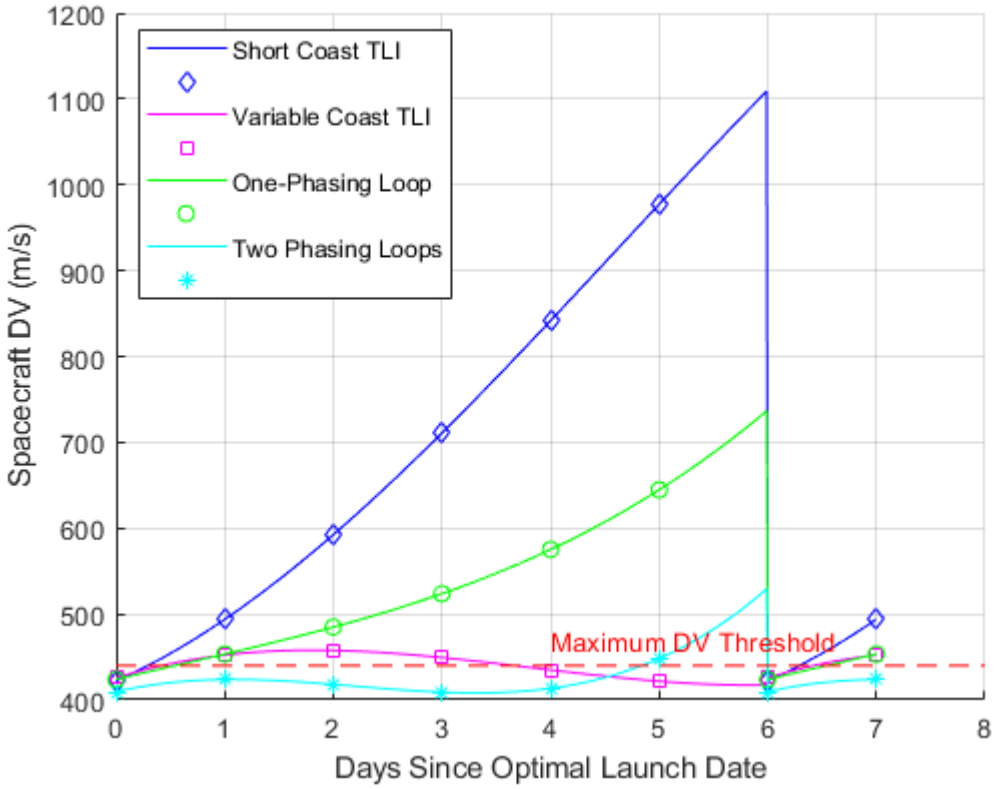


Phase 3

- **GENERALIZE THE RESULTS FROM PHASES 1 AND 2 TO APPLY TO ANY ARTEMIS CAMPAIGNS THROUGHOUT THE YEAR TO VALIDATE THE METHODOLOGY**

One-Week Launch Availability using all Methods

Combining methods should allow a near continuous launch opportunity

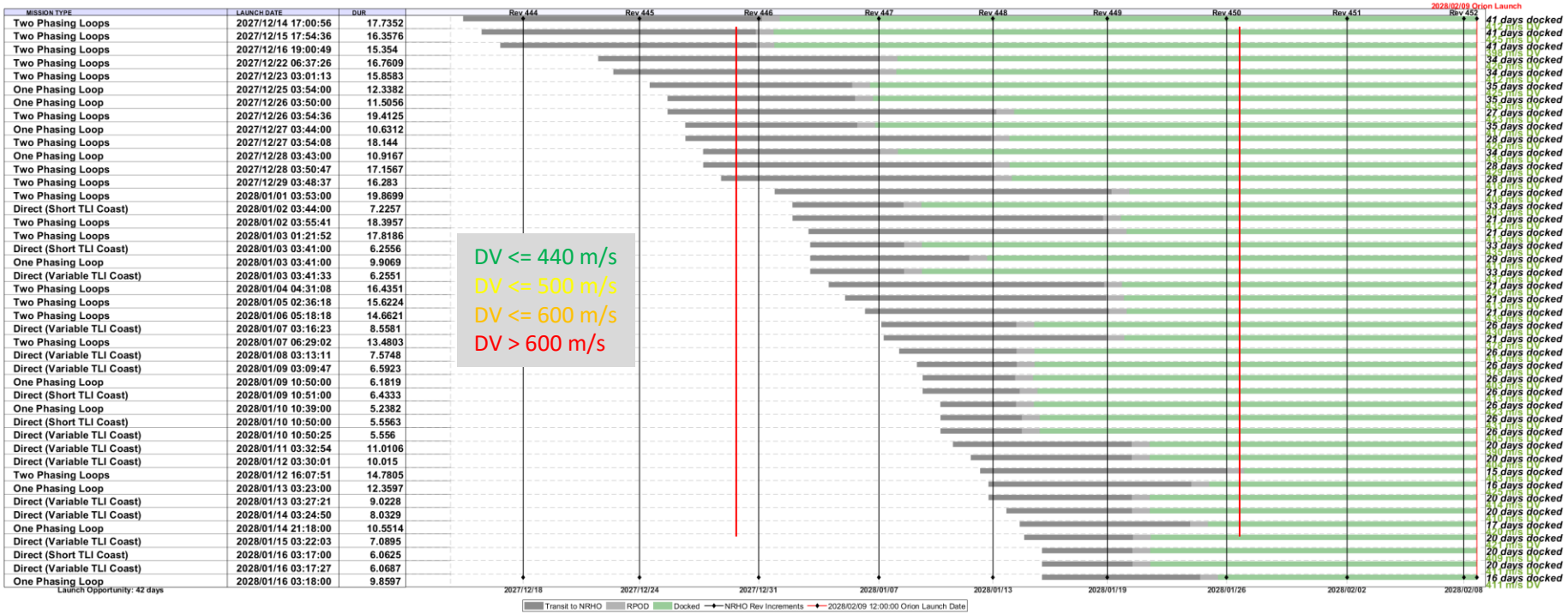


Example Logistics Module Launch Opportunity to Support a 9 February 2028 Artemis IV Campaign

Earliest Arrival

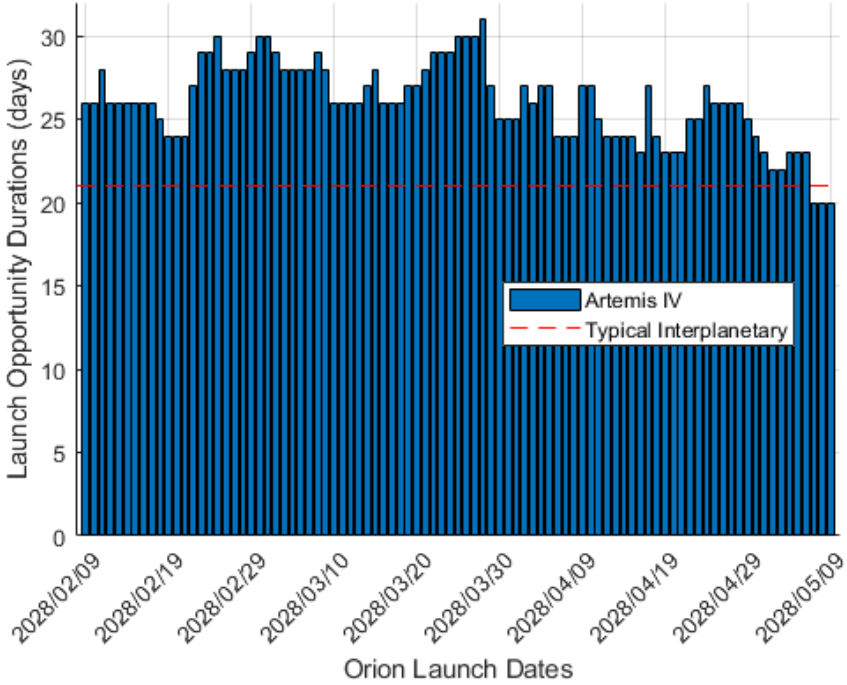
Latest Arrival

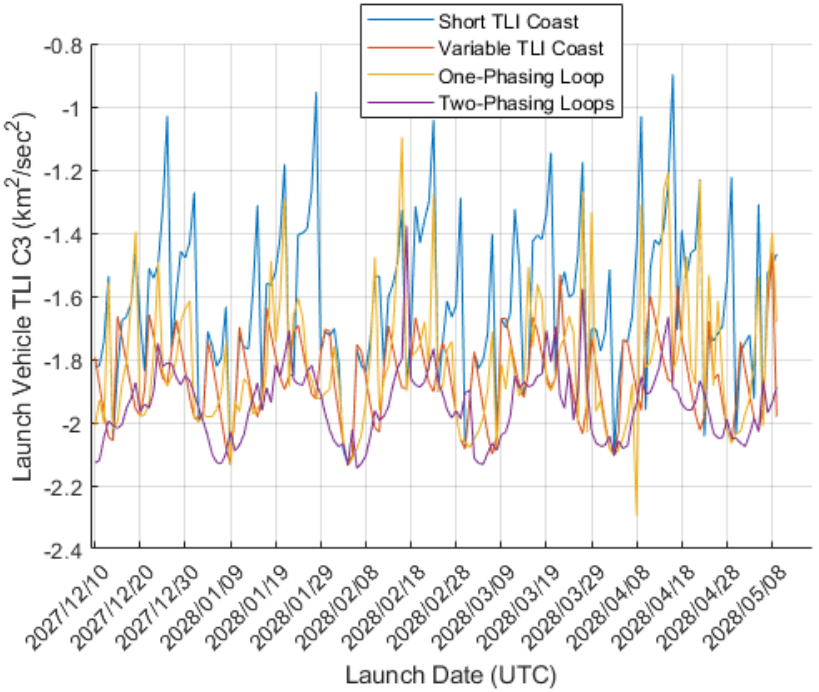
MISSION TYPE	LAUNCH DATE	DUR
Two Phasing Loops	2027/12/14 17:00:56	17.7352
Two Phasing Loops	2027/12/15 17:54:36	16.3576
Two Phasing Loops	2027/12/16 19:00:49	15.354
Two Phasing Loops	2027/12/22 06:37:26	16.7609
Two Phasing Loops	2027/12/23 03:01:13	15.8583
One Phasing Loop	2027/12/25 03:54:00	12.3382
One Phasing Loop	2027/12/26 03:50:00	11.5056
Two Phasing Loops	2027/12/26 03:54:36	19.4125
One Phasing Loop	2027/12/27 03:44:00	10.6312
Two Phasing Loops	2027/12/27 03:54:08	18.144
One Phasing Loop	2027/12/28 03:43:00	10.9167
Two Phasing Loops	2027/12/28 03:50:47	17.1567
Two Phasing Loops	2027/12/29 03:48:37	16.283
Two Phasing Loops	2028/01/01 03:53:00	19.8699
Direct (Short TLI Coast)	2028/01/02 03:44:00	7.2257
Two Phasing Loops	2028/01/02 03:55:41	18.3957
Two Phasing Loops	2028/01/03 01:21:52	17.8186
Direct (Short TLI Coast)	2028/01/03 03:41:00	6.2556
One Phasing Loop	2028/01/03 03:41:00	9.9069
Direct (Variable TLI Coast)	2028/01/03 03:41:33	6.2551
Two Phasing Loops	2028/01/04 04:31:08	16.4351
Two Phasing Loops	2028/01/05 02:36:18	15.6224
Two Phasing Loops	2028/01/06 05:18:18	14.6621
Direct (Variable TLI Coast)	2028/01/07 03:16:23	8.5581
Two Phasing Loops	2028/01/07 06:29:02	13.4803
Direct (Variable TLI Coast)	2028/01/08 03:13:11	7.5748
Direct (Variable TLI Coast)	2028/01/09 03:09:47	6.5923
One Phasing Loop	2028/01/09 10:50:00	6.1819
Direct (Short TLI Coast)	2028/01/09 10:51:00	6.4333
One Phasing Loop	2028/01/10 10:39:00	5.2382
Direct (Short TLI Coast)	2028/01/10 10:50:00	5.5563
Direct (Variable TLI Coast)	2028/01/10 10:50:25	5.556
Direct (Variable TLI Coast)	2028/01/11 03:32:54	11.0106
Direct (Variable TLI Coast)	2028/01/12 03:30:01	10.015
Two Phasing Loops	2028/01/12 16:07:51	14.7805
One Phasing Loop	2028/01/13 03:23:00	12.3597
Direct (Variable TLI Coast)	2028/01/13 03:27:21	9.0228
Direct (Variable TLI Coast)	2028/01/14 03:24:50	8.0329
One Phasing Loop	2028/01/14 21:18:00	10.5514
Direct (Variable TLI Coast)	2028/01/15 03:22:03	7.0895
Direct (Short TLI Coast)	2028/01/16 03:17:00	6.0625
Direct (Variable TLI Coast)	2028/01/16 03:17:27	6.0687
One Phasing Loop	2028/01/16 03:18:00	9.8597



29

Launch Opportunities over a 3-Month Interval of Orion Launch Dates applying all Methods





Conclusions and Future Work

- Conclusions
  - A method of rapidly developing LV targets to support future Artemis campaigns has been developed
  - Combining methodologies increases launch opportunity and launch windows
  - A minimum 20-day launch opportunity exists for any Orion launch date over the 3-month interval analyzed
  - Launch Vehicle targets are insensitive to the various approaches/methods
  - Shorter duration missions drive higher spacecraft DV costs
- Future Work
  - Continue to refine methodology for LM mission design and LV target generation
  - Examine feasibility of multiple instantaneous windows for a given launch date
  - Expand the one-Rev analysis over 2 lunar months (8-Revs) to better understand relationship to 9:2 NRHO:Lunar Synodic Period resonance
  - Investigate combining two-phasing loop method with variable TLI coast to achieve a single approach that satisfies all possible launch dates
  - Examine implications to other disciplines (power, thermal, comm, radiation, etc.)
  - Incorporate JAXA methodology (see next slide)

Late Breaking Research

- The JAXA Research and Development Directorate published new research* on this topic at the 2024 International Astronautical Congress (IAC) approximately one month following the commencement of our study
  - Research showed an alternate approach they called the “Perilune Rendezvous Method” (PRM).
  - The PRM also increased launch availability compared to the direct approach while also decreasing the total mission ΔV by up to ~33%
  - The trade is an increase in transfer duration as well as mission complexity.
- Forward work to replicate JAXA’s results and design an additional methodology to increasing launch availability and mission capability

*J, Kikuchi., N, Murakami., Y, Matsumoto., and S, Ueda.: “Trajectory Design of NRHO Transfer with Continuous Launch Window for Logistics Resupply Mission to Gateway”, IAF 75th International Astronautical Congress, Milan, Italy, C1.IP.33, 2024.