Jet Propulsion Laboratory
California Institute of Technology

KPLO Supporting Trajectory Analysis

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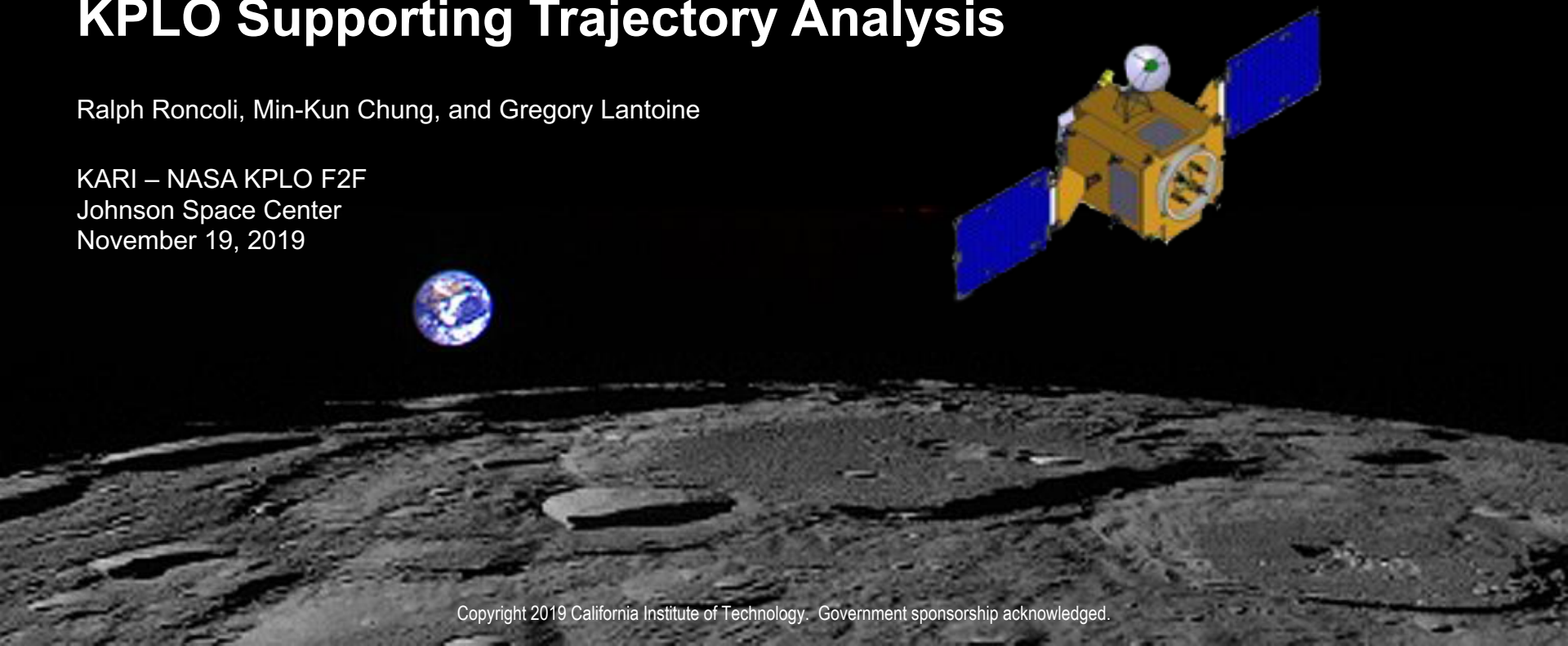
KARI – NASA KPLO F2F
Johnson Space Center
November 19, 2019



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Analysis Objectives

- Investigate two types of low energy trajectory options to reduce the lunar transfer ΔV requirements
  - GRAIL-like trajectory options (analysis performed by Min-Kun Chung)
    - Assumes launch vehicle can deliver KPLO to a C3 of ~ -0.6 km^2/s^2
  - Lunar-assisted low energy trajectory options (analysis performed by Gregory Lantoine)
    - Assumes launch vehicle can only deliver KPLO to an apoapsis of ~ 300,000 km
- Objective
  - Identify lowest ΔV extended launch period (≥ 20 days) that satisfies all constraints
    - Same constraints as used by JSC
    - Launch in July 2022 (with assumed parking orbit characteristics)
    - Orbit beta angle within 25 deg of zero on lunar summer southern solstice (03-Feb-2023)
    - Capture into 12 hour period orbit about the Moon with an inclination of 90º
    - Final orbit: 100 km circular

ΔV Budget from KARI F2F in October 2019

Reference Point

	KARI F2F (Oct 2019)		Description
	Maneuver	ΔV (m/s)	
	Coast	Short	
Deterministic	AM1	0.	
	PM1	1.72	Perigee maneuver
	PM3	26.75	Perigee maneuver
	LOI1	300.79	Lunar orbit insertion (capture orbit period 12 hours)
	LOI2	266.17	Period reduction (post ΔV period 3.5 hours)
	LOI3	0.65	Period reduction (post ΔV 100x1822 km)
	LOI4	205.99	Period reduction (post ΔV 100x300 km)
	SKM	40.42	Period reduction (post ΔV 100x100 km)
		842.49	**Sub-Total ΔV**
Statistical	LW Extension	0.	
	LV Error	16.7	
	TCM (PM/LOI)	26.87	
	OMT	0.	
	LEO Inc Corr	0.	
		43.57	**Sub-Total ΔV**
		886.06	**Total ΔV**

KARI F2F (Oct 2019)	
Maneuver	ΔV (m/s)
Coast	Short
AMx+PMx+LOI1	329.26
LOI2+LOI3+LOI4	472.81
SKM	40.42
	842.49
LV Error +TCM	43.57
	43.57
	886.06

KARI F2F (Oct 2019)	
Maneuver	ΔV (m/s)
Coast	Short
AMx+PMx+LOI1	329
LOI2+LOI3+LOI4	473
SKM	40
	842
LV Error +TCM	44
	44
	886

ΔV Budget

New Starting Point

KARI F2F (Oct 2019)	
Maneuver	**ΔV (m/s)**
Coast	Short
AMx+PMx+LOI1	329
LOI2+LOI3+LOI4	473
SKM	40
	842
LV Error +TCM	44
	44
	886

New

New Starting Point for ΔV Budget		
Maneuver	**ΔV (m/s)**	**Description**
Coast		Parking orbit coast strategy
TCM + LOI1	??	Trans-lunar cruise ΔV (capture orbit period 12 hours)
LOI2+LOI3+LOI4	513	Period reduction (from 12 hours to 100x100 km)
SKM	75	Orbit maintenance for 1 year
	588	**Sub-Total ΔV**
LV Error +TCM	44	
	44	**Sub-Total ΔV**
	??	**Total ΔV**

The objective of the analysis is to find the lowest ΔV option

and then compare these two numbers

The Two Best GRAIL-Like Low Energy Trajectory Options

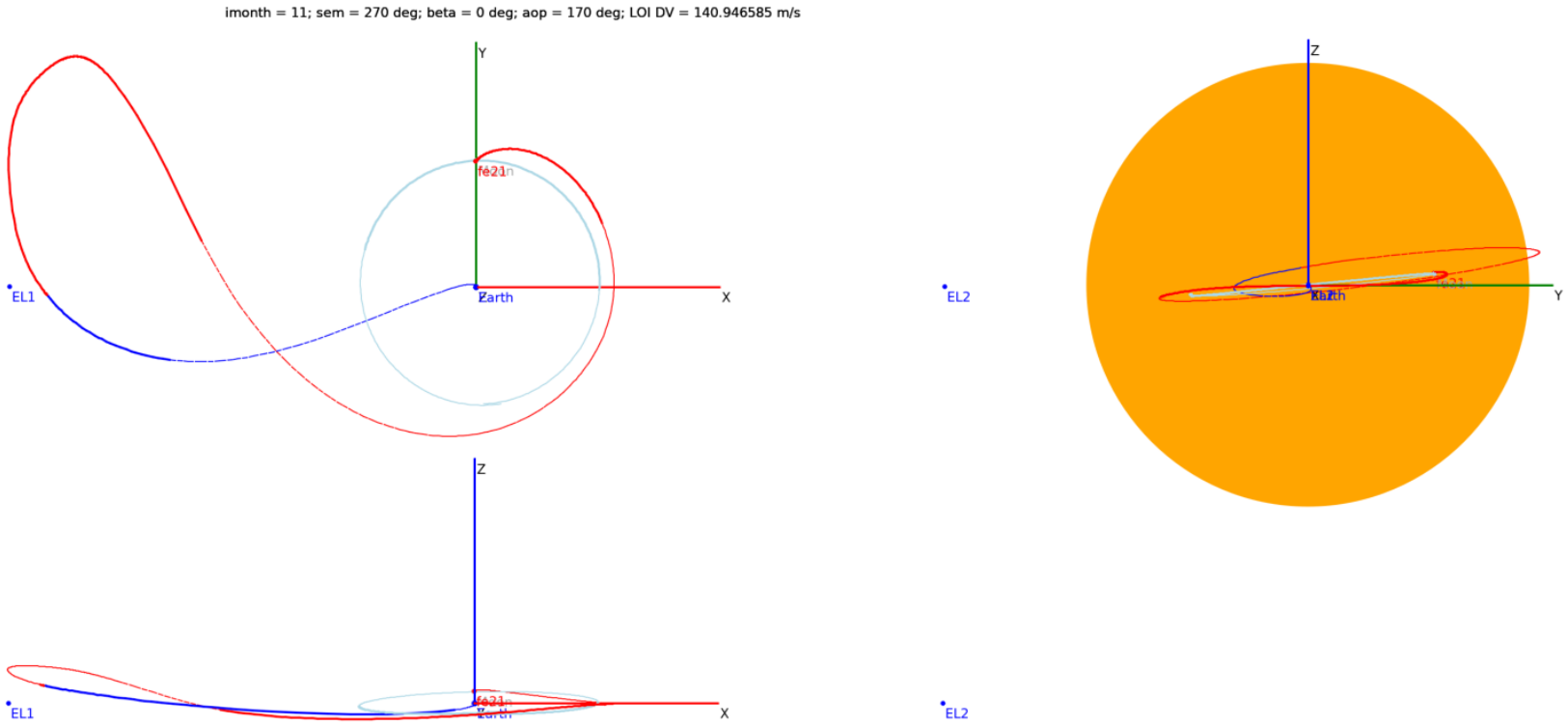
Additional promising opportunities also exist

KARI F2F (Oct 2019)	
Maneuver	**ΔV (m/s)**
Coast	Short
AMx+PMx+LOI1	329
LOI2+LOI3+LOI4	473
SKM	40
	842
LV Error +TCM	44
	44
	886

	GRAIL-like Option 1	GRAIL-like Option 2
Maneuver	**ΔV (m/s)**	**ΔV (m/s)**
Coast	**Short**	**Short**
TCM + LOI1	**170**	**170**
LOI2+LOI3+LOI4	513	513
SKM	75	75
Sub-Total ΔV	**758**	**758**
LV Error +TCM	44	44
Sub-Total ΔV	**44**	**44**
Total ΔV	**802**	**802**

- Option 1
  - Provides launch opportunities throughout the entire month of July
  - Targets a beta angle of 0º on the lunar solstice (03-Feb-2023)
  - LOI on November 16, 2022
  - LOI ΔV includes 10 m/s for gravity losses (> 5%)
- Option 2
  - Provides launch opportunities for about 20 days from mid July to early August
  - Targets a beta angle of 0º on the lunar solstice (03-Feb-2023)
  - LOI on November 29, 2022
  - LOI ΔV includes 10 m/s for gravity losses (> 5%)

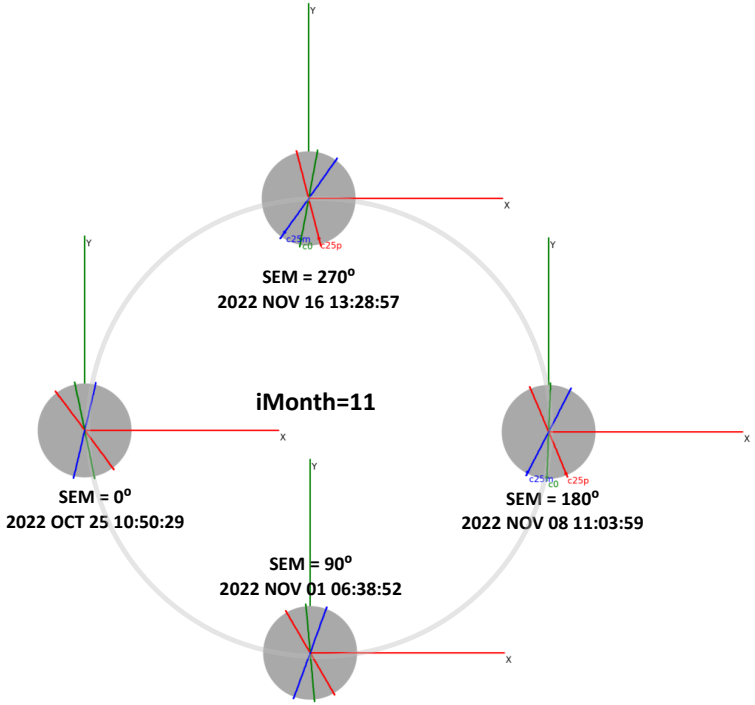
GRAIL-like Low Energy Trajectory – Option 1

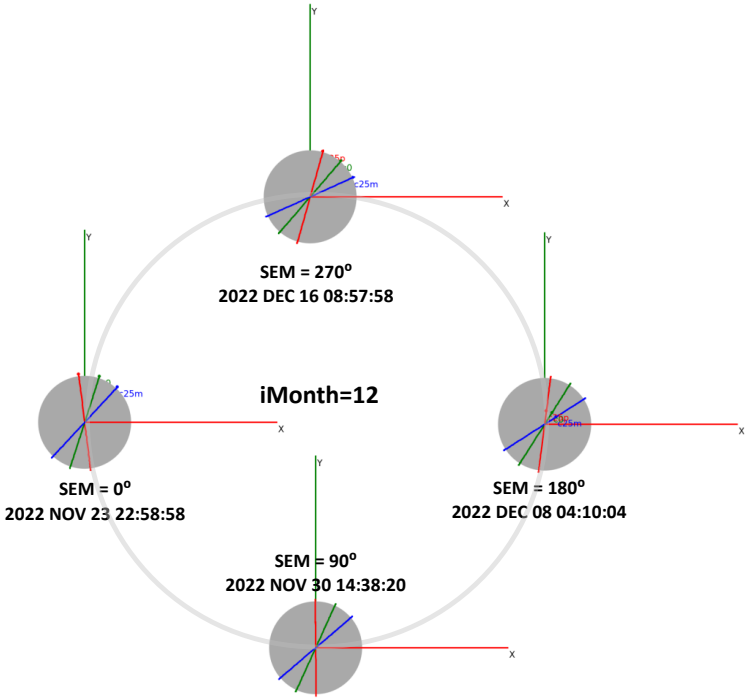


GRAIL-like Low Energy Trajectory – Option 2

Analysis Process – Setting up the LOI Arrival Geometry

Beta Angle Constraint at iMonth = 11 and 12





Optimization Strategy

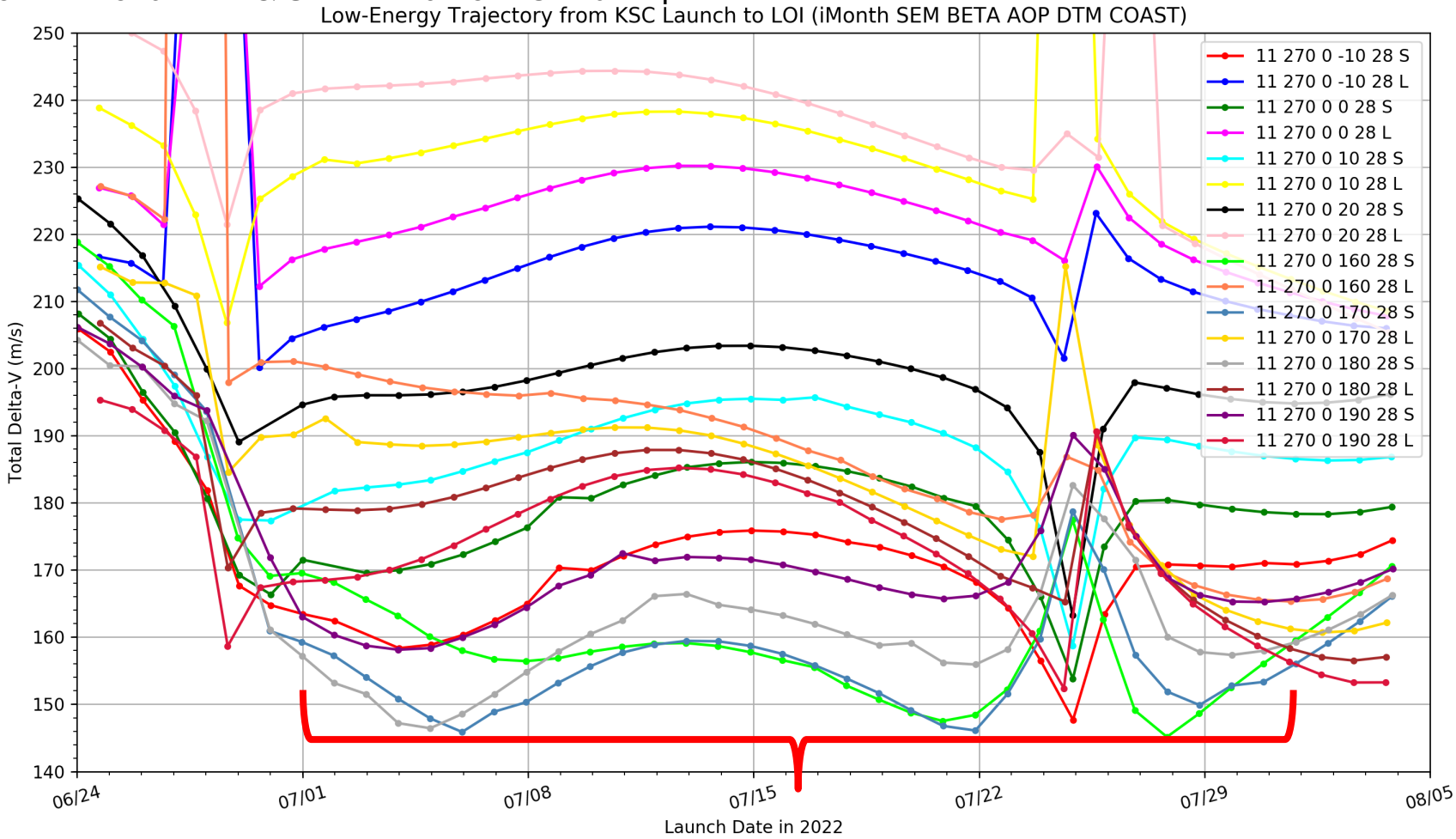
- The GRAIL-like, low energy trajectory from KSC to LOI is optimized as follows:
  - Controls:
    - C3 / Injection ΔV
    - RAV (Right Ascension of the Apoapsis Vector
    - DAV (Declination of the Apoapsis Vector)
    - LOI ΔV at LOI
  - Cost: Total ΔV = LOI ΔV + TCM ΔV
  - Constraints:
    - The LOI condition is propagated backwards from LOI, and the KSC launch condition is propagated forward to the TCM time for a position continuity
    - The velocity discontinuity at TCM of the above two propagated trajectories is the TCM ΔV, and it is added to the cost above

Parametric Study

Targeting a beta angle of 0º on 03-Feb-2023

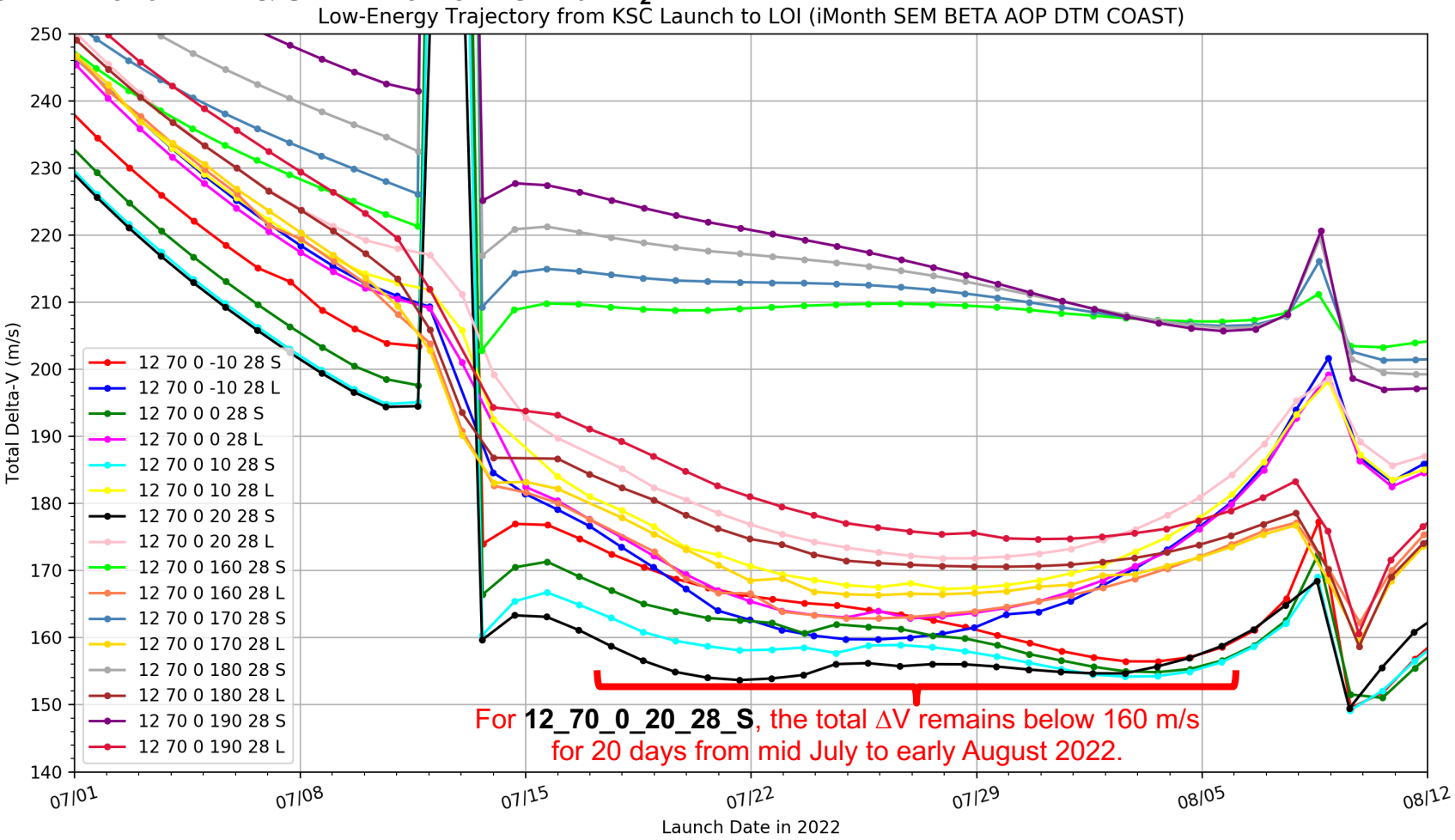
- Many preliminary parametric runs were made initially to scope the ΔV trade space, covering a broad range of SEMs, Beta angles, AOPs, and TCM times
- More refined runs were made around the three SEM regions: (1) iMonth = 11 & SEM = 270º; (2) iMonth = 12 & SEM = 90º; (3) iMonth = 12 & SEM = 270º:
  - SEM for LOI date: 270, 260, & 250º for via EL_1; and 90, 80, & 70º for via EL_2
  - Beta angle for LOI node: 0º on 03-FEB-2023
  - AOP for LOI orbit state: -10, 0, 10, & 20º for Southern approach; and 160, 170, 180, & 190 for Northern approach
  - TCM time: 28 days from launch
  - Launch Coast Options: Short and Long
- Two best options are presented here

Option 1: iMonth = 11 & SEM = 270º for LOI via EL_1



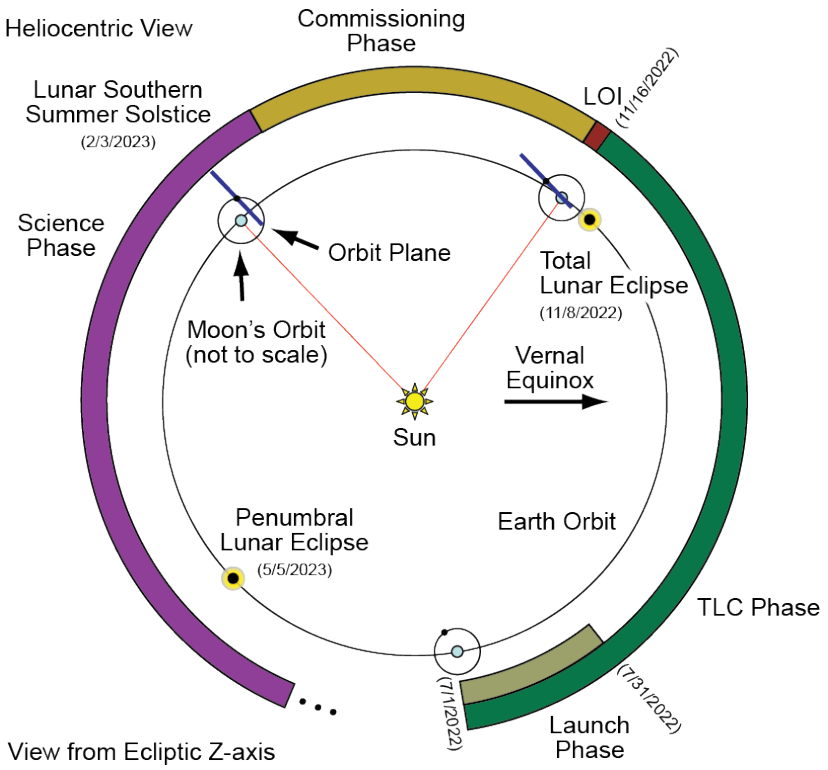
For **11_270_0_170_28_S**, the total ΔV remains below 160 m/s almost the whole month.

Option 2: iMonth = 12 & SEM = 70º for LOI via EL_2



Mission Timelines – for GRAIL-Like Low Energy Trajectory Options

Option 1



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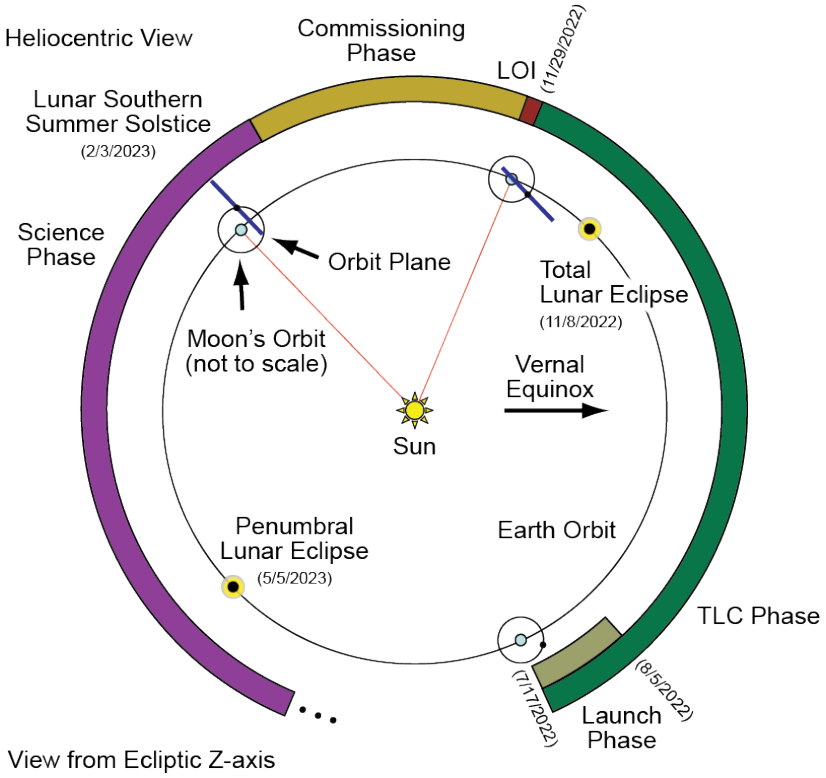


Lunar Assisted – Low Energy Trajectory Option

Assumptions

- Same as GRAIL-like low energy trajectory analysis except for the assumed launch vehicle injection capability
  - Launch vehicle injection: 290,000 km apoapsis (fixed launch C3 of -2.69 km^2/s^2)
- Launch geometry
  - Inclination of 28.5 deg
  - Launch site not considered
- Lunar orbit
  - 100-km circular, polar (RAAN & phase optimized)
  - Enforce beta angle of ~0 deg at south pole summer solstice (Feb 3, 2023)
- LOI
  - Ensure that 1st LOI burn can be viewed from Earth
  - LOI burn split not modeled
  - Finite burns and gravity losses not modeled
  - 5% ΔV penalty is added to account for gravity losses

The Best Lunar Assisted – Low Energy Trajectory Option

Comparison of Options

KARI F2F (Oct 2019)	
Maneuver	**ΔV (m/s)**
Coast	Short
AMx+PMx+LOI1	329
LOI2+LOI3+LOI4	473
SKM	40
	842
LV Error +TCM	44
	44
	886

	GRAIL-like Option 1	GRAIL-like Option 2
Maneuver	**ΔV (m/s)**	**ΔV (m/s)**
Coast	**Short**	**Short**
TCM + LOI1	**170**	**170**
LOI2+LOI3+LOI4	513	513
SKM	75	75
Sub-Total ΔV	**758**	**758**
LV Error +TCM	44	44
Sub-Total ΔV	**44**	**44**
Total ΔV	**802**	**802**

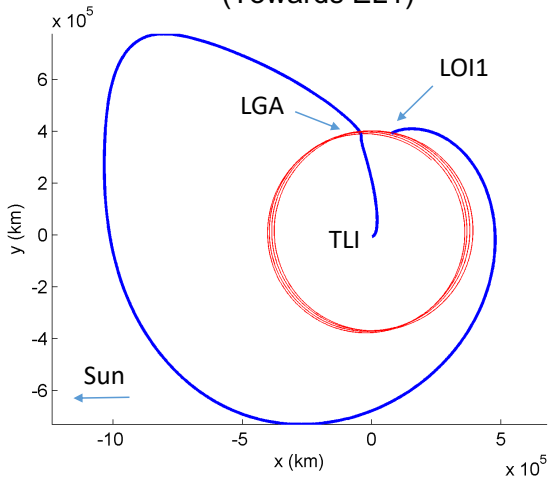
	LA-LET Option 3
Maneuver	**ΔV (m/s)**
Coast	**-**
PMs	**39**
LOIs	**670**
SKM	75
Sub-Total ΔV	**784**
LV Error +TCM	44
Sub-Total ΔV	**44**
Total ΔV	**828**

- Option 3
  - Provides launch opportunities throughout the month of July - assuming “no LV AOP constraints”
  - LV AOP constraints may create 10-day gap in launch period – additional solutions may exist
  - Uses 2-4 phasing loops and three arrival dates
  - Includes 5% ΔV penalty for gravity losses

Lunar Assisted – Low Energy Trajectories

LGA + 4-month low energy trajectory families (”backbone solutions”)

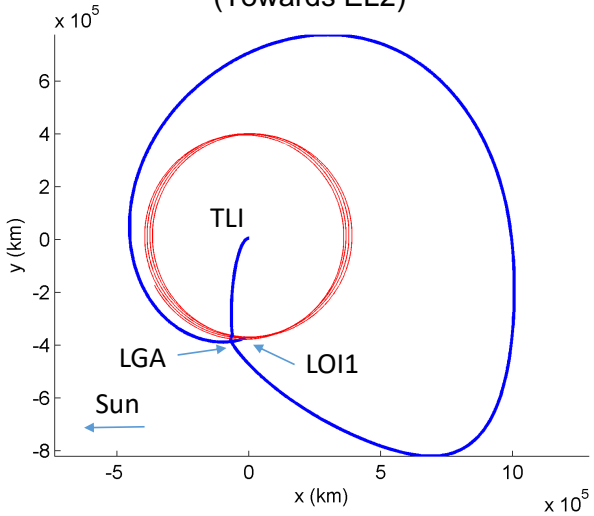
2022 Jul 17 TLI, 2022 Nov 15 arrival
(Towards EL1)



Sun-Earth rotating frame

- Flight time (from TLI to LOI1): 122 days
- Max Earth distance: 1,200,000 km
- 1 Earth eclipse: 33 min
- 1 Moon eclipse: 42 min
- No Earth occultation at LOI1

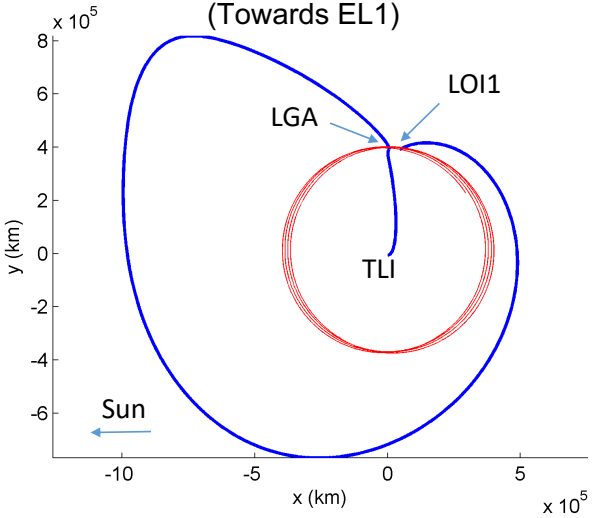
2022 Jul 31 TLI, 2022 Nov 30 arrival
(Towards EL2)



Sun-Earth rotating frame

- Flight time (from TLI to LOI1): 122 days
- Max Earth distance: 1,150,000 km
- No Earth eclipse
- 1 Moon eclipse: 6 min
- No Earth occultation at LOI1

2022 Aug 14 TLI, 2022 Dec 15 arrival
(Towards EL1)



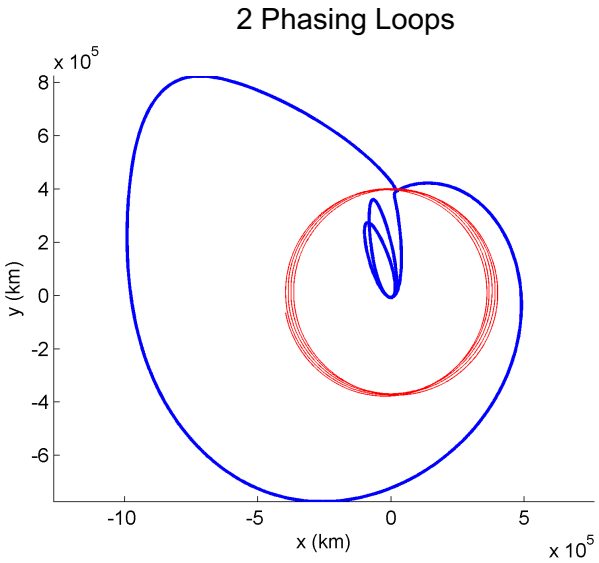
Sun-Earth rotating frame

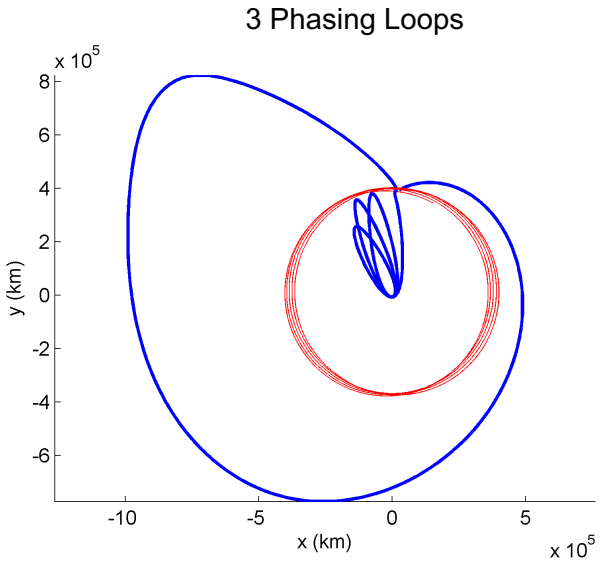
- Flight time (from TLI to LOI1): 123 days
- Max Earth distance: 1,165,000 km
- 1 Earth eclipse: 37 min
- 1 Moon eclipse: 44 min
- No Earth occultation at LOI1

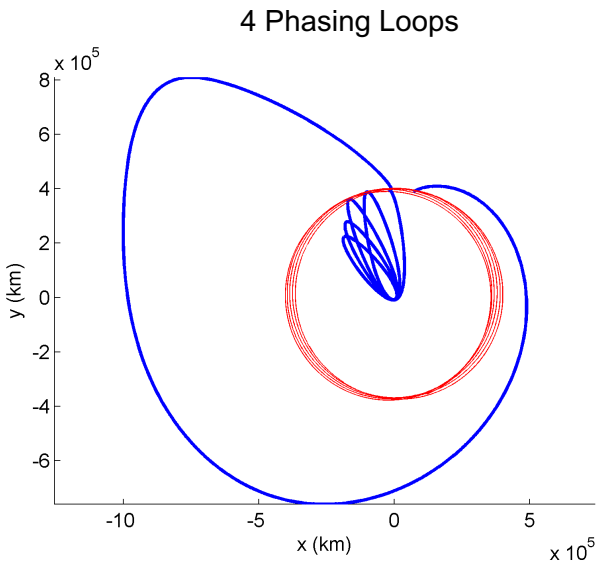
Launch Period with Phasing Loops

- Rather than launching directly towards the Moon, the spacecraft is injected into a highly elliptical orbit for several revolutions (loops) before the first lunar flyby
- Three main objectives:
  - to increase the launch period duration by inserting additional loops and varying slightly their periods according to the launch date
  - to allow for lower injection energy (i.e. C3) requirements (apoapsis of the first phasing loop can be well below the Moon)
  - to reduce the ΔV needed to correct the launch vehicle injection dispersion with maneuvers at consecutive perigee passes
- Solar and lunar perturbations are significant
  - solar perturbations may cause an increase or a decrease in the periapsis altitude – a maneuver at the first apoapsis may be necessary to raise periapsis
  - lunar resonances should be avoided

Lunar Assisted – Low Energy Trajectories with Phasing Loops

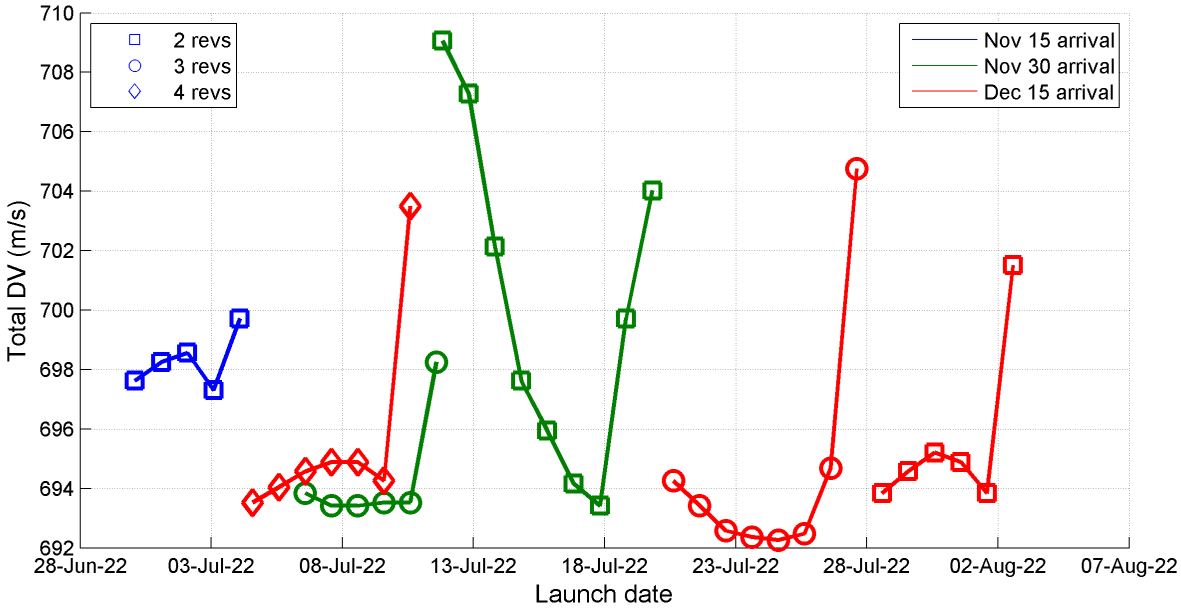






July 2022 Launch Period

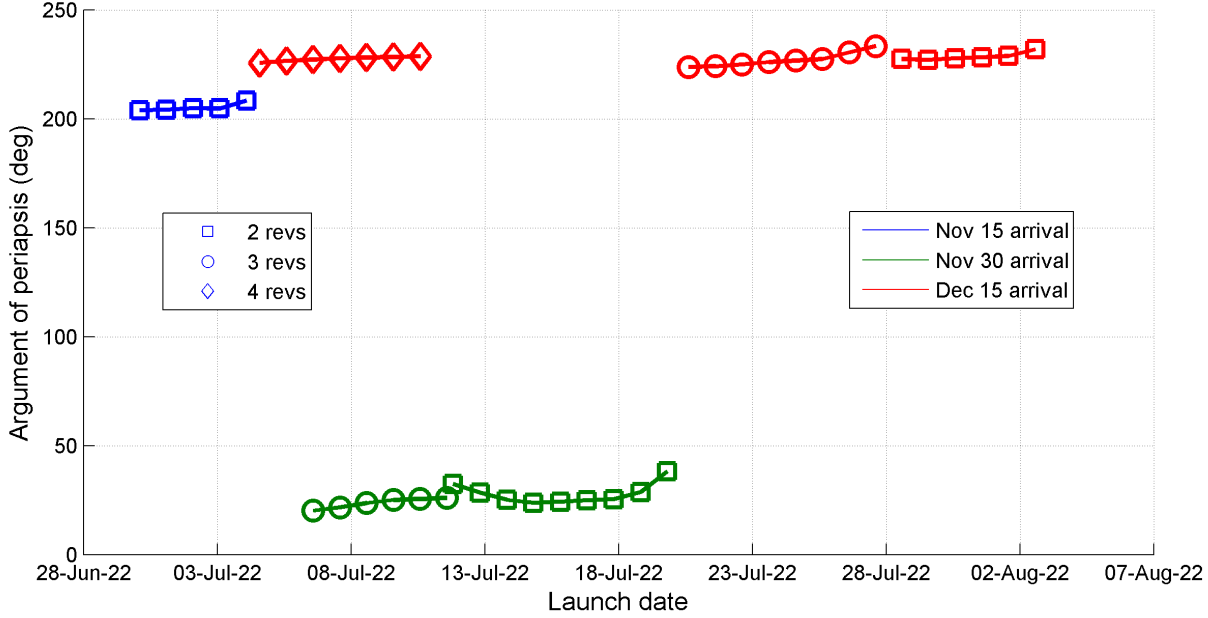
- A continuous 31-day launch period exists in July 2022 using phasing loops (from 2 to 4 revs) and the three trajectory families (”backbone solutions”)



- ΔV does not include
  - lunar orbit maintenance ΔV (75 m/s)
  - or statistical ΔV (44 m/s)

July 2022 Launch Period – with LV AOP Constraints

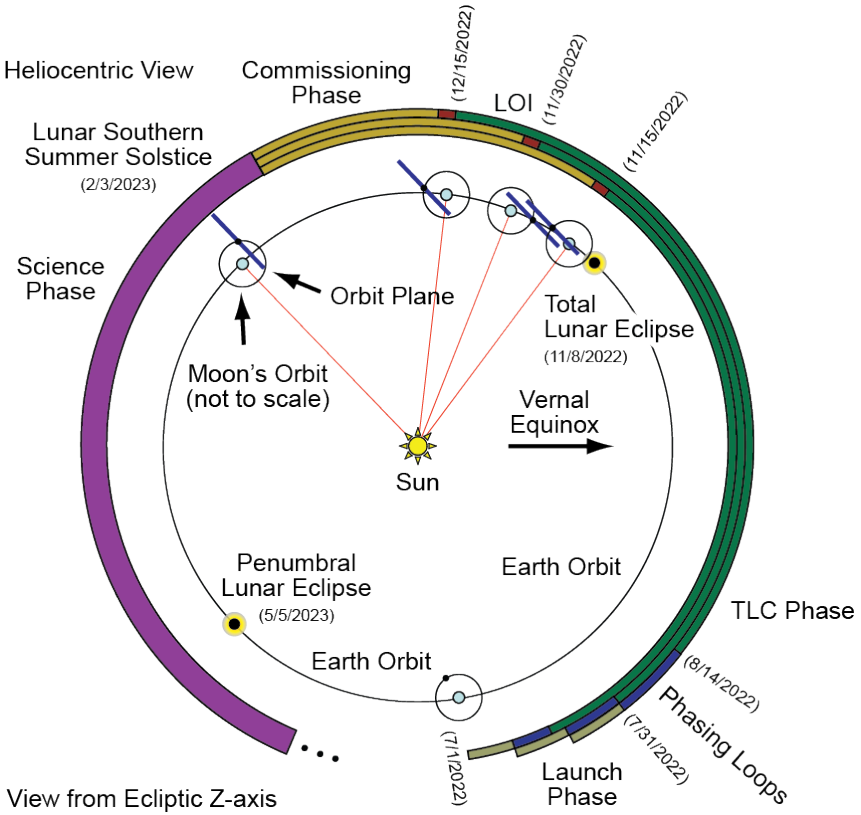
- If the launch vehicle Argument of Periapsis (AOP) constraints are real, then this would eliminate Nov 30 arrival



- LV AOP constraints would create a 10-day gap in the launch period between July 10 and July 20

Mission Timeline – for Lunar Assisted – Low Energy Trajectory Option

Option 3



Summary of Options

KARI F2F (Oct 2019)	
Maneuver	ΔV (m/s)
	886

	GRAIL-like Option 1	GRAIL-like Option 2
Maneuver	ΔV (m/s)	ΔV (m/s)
Total ΔV	802	802

	LA-LET Option 3
Maneuver	ΔV (m/s)
Total ΔV	828

- Good options exist to reduce the ΔV requirements to get to the Moon while preserving the desired orbit geometry and duration for science
- GRAIL-Like Low Energy Trajectory Options
  - Provides ~160 m/s savings over the original phasing loop design, preserves science, provides ~85 m/s margin over the existing ΔV budget, and avoids total lunar eclipse
  - Requires larger launch vehicle injection energy (C3 of ~ -0.6 km^2/s^2)
  - Maximum Earth range is ~1.56 million km
- Lunar Assisted – Low Energy Trajectory Options
  - Provides ~135 m/s savings over the original phasing loop design, preserves science, provides ~60 m/s margin over the existing ΔV budget, and avoids total lunar eclipse
  - Does not require an increase in launch vehicle injection energy requirements (C3 of ~ -2.69 km^2/s^2)
  - Maximum Earth range is ~1.2 million km
  - Introduces some complexity (variable phasing orbits, lunar flyby) to create a large, finite duration launch period

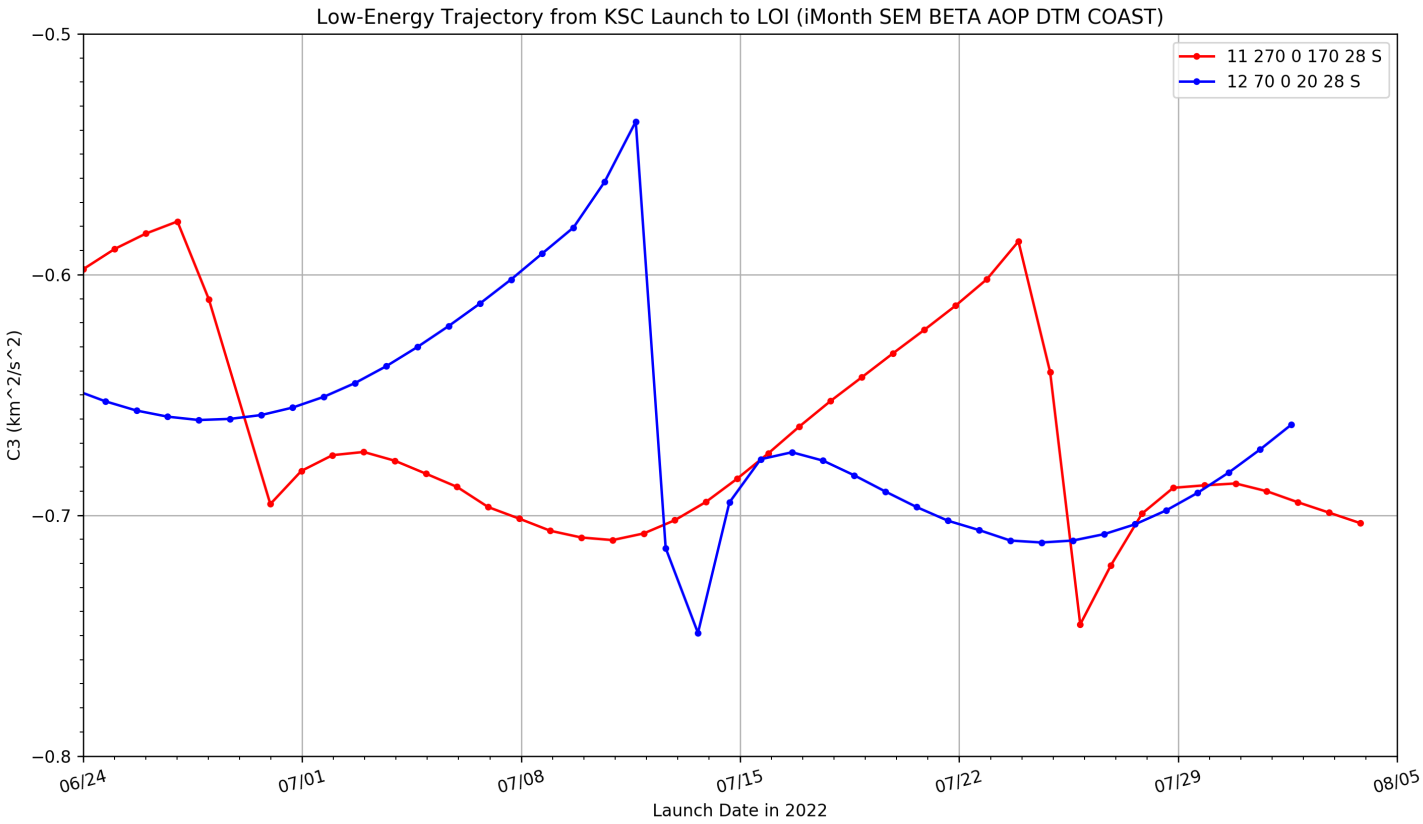
Backup Slides

For GRAIL-Like Low Energy Trajectory Options

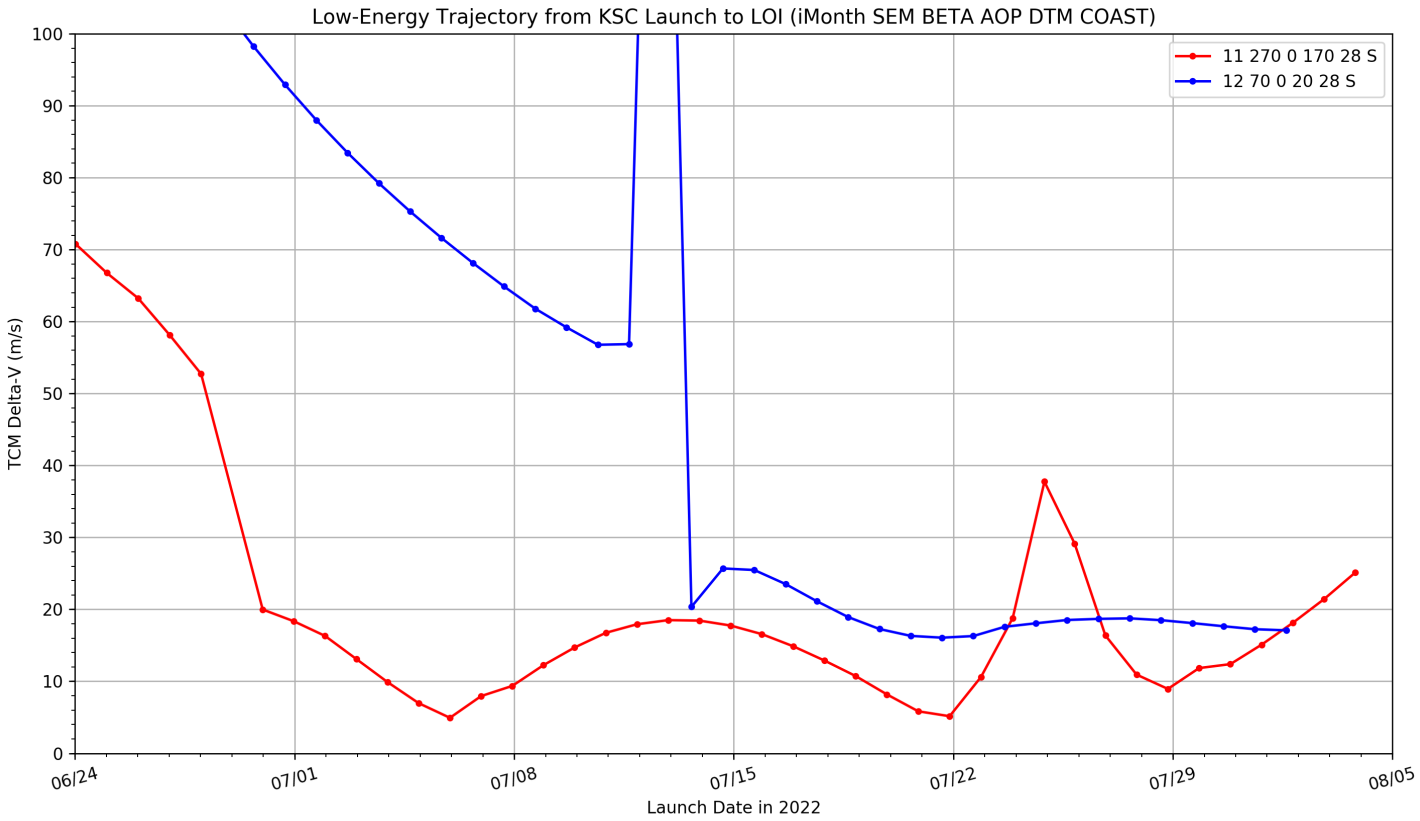
Synopsis and Assumptions

- The GRAIL-like, Low-Energy trajectory is optimized for the minimum total ΔV = LOI ΔV + a mid-course TCM ΔV from KSC launch in July, 2022 to LLO in order to find a ~20-day launch period with the lowest total ΔVs:
  - FTs considered: enough days at 1 day step from KSC to LOI to form July 2020 launch periods.
  - TCM times are parameterized: L + 28 days (TCM at L + 21 to 28 days yields good results)
- LOI occurs right after 08-NOV-2022 to avoid the total eclipse.
- The LOI LLO is assumed to be 104 x 8,706 km (from KARI KPLO documentation) polar orbit with 90º inclination. Other LLO elements are constant for a given launch period.
- KSC launch is assumed with the following condition:
  - Park orbit: altitude = 185 km; inclination = 28.5º
  - Launch vehicle ascent: arc = 15º; time = 10 minutes
  - Coast options: Short and Long
- Simple propagation model:
  - Earth J2 only and Sun & Moon as point bodies

C3 for Best Low Energy Trajectory Options



TCM ΔV for Best Low Energy Trajectory Options

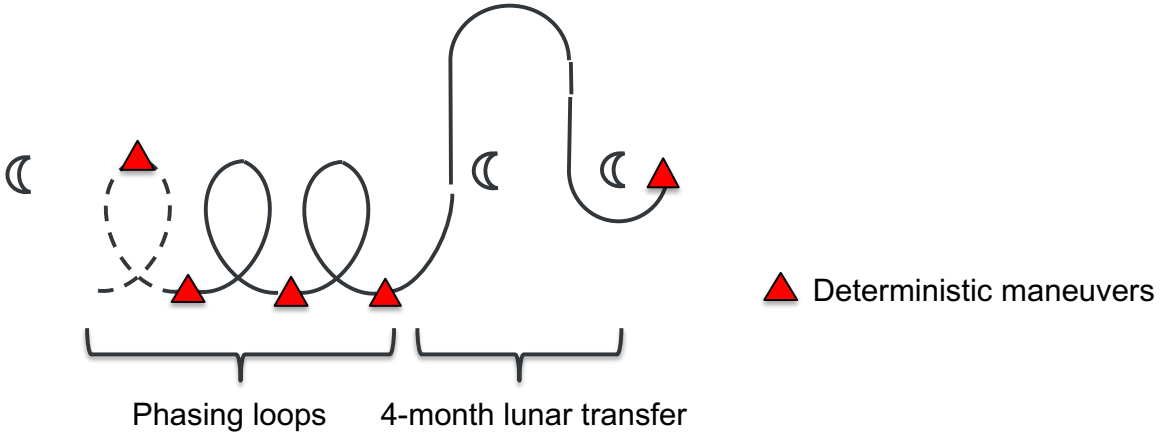


Backup Slides

For Lunar Assisted – Low Energy Trajectory Options

Phasing Loop Strategy

- Two phasing loops minimum to have enough time to correct for the launch vehicle injection dispersion and target precisely the lunar flyby
  - Corresponding flight time (~27 days) must be accounted in LGA required time
- Deterministic maneuvers at the first apogee (to raise the perigee when needed) and at the subsequent perigee passes (to control the period of the orbits, handle perturbations and perform TLI)



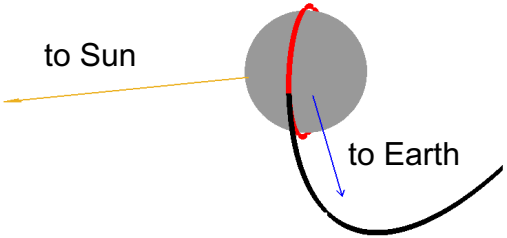
Phasing Loop Analysis

- Sensitivity to initial orbit period (or initial apoapsis altitude)
- Apoapsis below lunar orbit (290,000 km): higher launch vehicle injection capability and less sensitive to solar and lunar perturbations (and maybe launch vehicle dispersions too), but requires a maneuver to raise apoapsis to the Moon

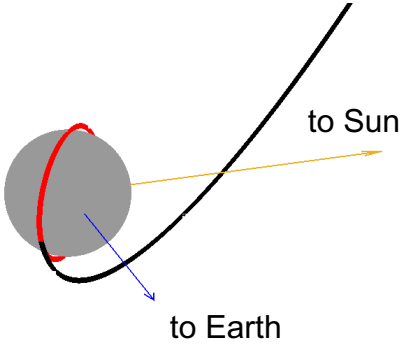
- Launch period analysis (July 2022)
  - Design phasing orbits, LGA and lunar transfer for each date of the launch period
    - A trajectory family or “backbone” solution is picked
    - Number of phasing loops are picked, and their period can be varied by the optimizer
  - Minimize ΔV for each date and target the same lunar orbit

LOI Burn Visibility

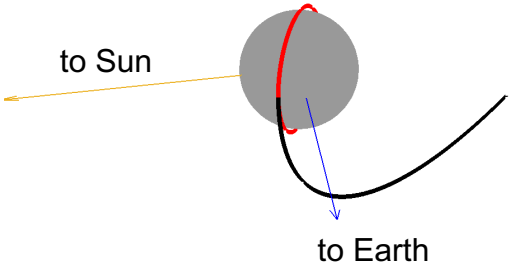
LOI can be Viewed from Earth for the Three Families



Nov 15 arrival



Nov 30 arrival

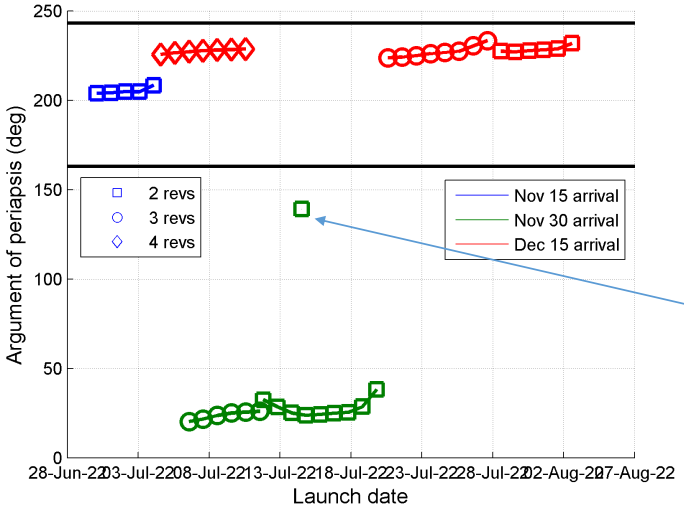


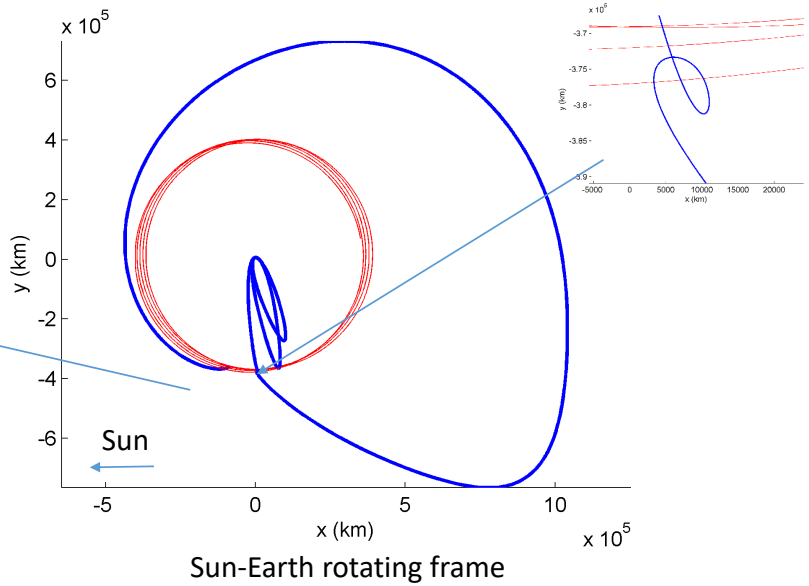
Dec 15 arrival

July 2022 Launch Period – New Nov 30 Solution

Attempting to change AOP to satisfy launch vehicle constraints (if they are real)

- Lunar flyby was modified (from outgoing to incoming) to allow for a different argument of periapsis at launch
- This new solution has an argument of periapsis of ~140 deg, closer to the LV constraints





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