Options for Staging Orbits in Cislunar Space

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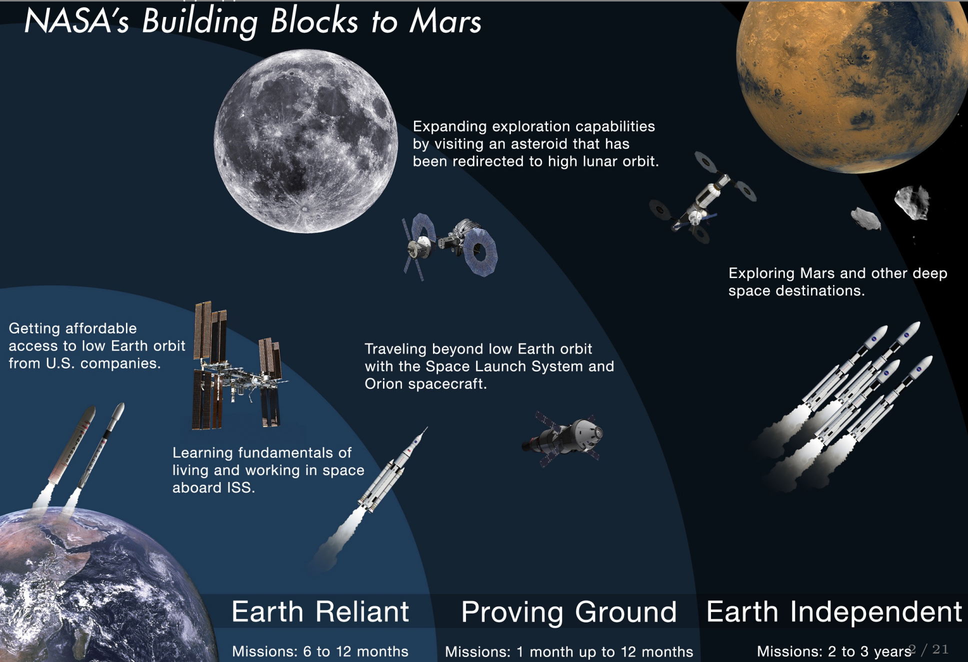
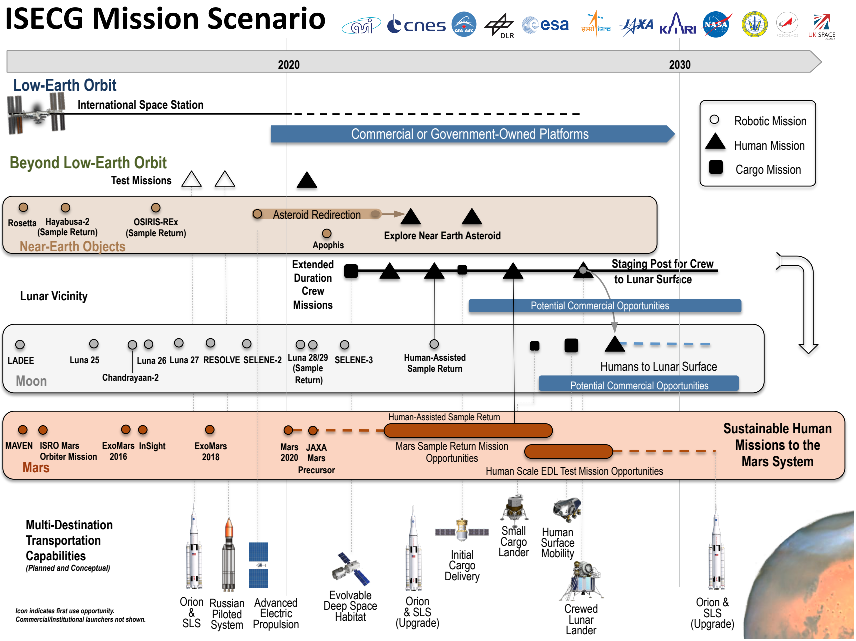
Need for Staging Orbit

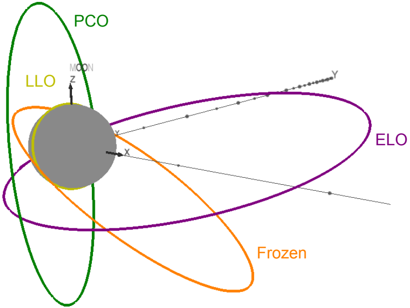


Hub for International Exploration



Smaller Cislunar (Lunar Two-body) Orbits

Orbit Type	Orbit Period	Amplitude Range	E-M Orientation
Low Lunar Orbit (LLO)	$\sim$2 hrs	100 km	Any inclination
Prograde Circular (PCO)	11 hrs	3,000 to 5,000 km	$\sim 75^\circ$ inclination
Frozen Lunar Orbit	$\sim$13 hrs	880 to 8,800 km	40° inclination
Elliptical Lunar Orbit (ELO)	$\sim$14 hrs	100 to 10,000 km	Equatorial



Low Lunar Orbit (LLO): LLO is defined as a circular orbit of an altitude around 100 km. LLOs are favorable for surface access and polar orbit inclinations offer global landing site access.

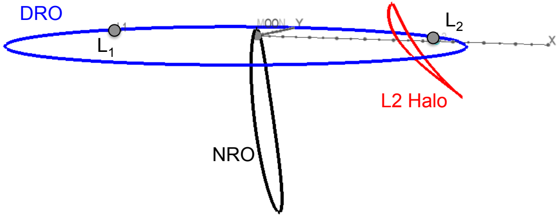
An Elliptical Lunar Orbit (ELO), such as the 100 x 10,000 km shown, trades insertion costs with transfer cost to lunar surface.

Prograde Circular Orbits (PCOs) are defined as circular orbits of various sizes that rotate in the prograde direction and are highly stable, requiring few to zero corrections to be maintained.

Frozen orbits are similar but need not be circular and have orbital parameters that oscillate around fixed values.

Larger Cislunar (Three-body) Orbits

Orbit Type	Orbit Period	Amplitude Range	E-M Orientation
Near Rectilinear Orbit (NRO)	6-8 days	2,000 to 75,000 km	Roughly polar
Earth-Moon L2 Halo	8-14 days	0 to 60,000 km (L2)	Dependent on size
Distant Retrograde Orbit (DRO)	∼14 days	70,000 km	Equatorial



Near-rectilinear halo orbits (NROs) were discovered as a bridge between L1 and L2 halos. NROs are halo orbits with large amplitudes over either the North or South poles that are fixed in the Earth-moon plane.

Halo orbits are a subset of orbits around the collinear libration points that are purely periodic but slightly unstable in the full ephemeris model.

Distant Retrograde Orbits (DROs) are relatively periodic three-body orbits that can be extremely stable, requiring zero corrective maneuvers.

All Cislunar Orbits for Consideration Summarized

Orbit Type	Orbit Period	Amplitude Range	E-M Orientation
Low Lunar Orbit (LLO)	~2 hrs	100 km	Any inclination
Prograde Circular (PCO)	11 hrs	3,000 to 5,000 km	~ 75 ° inclination
Frozen Lunar Orbit	~13 hrs	880 to 8,800 km	40° inclination
Elliptical Lunar Orbit (ELO)	~14 hrs	100 to 10,000 km	Equatorial
Near Rectilinear Orbit (NRO)	6-8 days	2,000 to 75,000 km	Roughly polar
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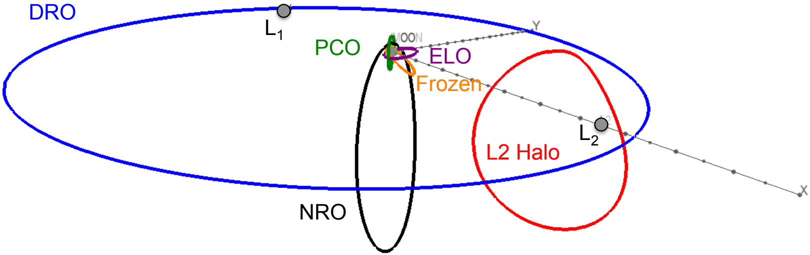
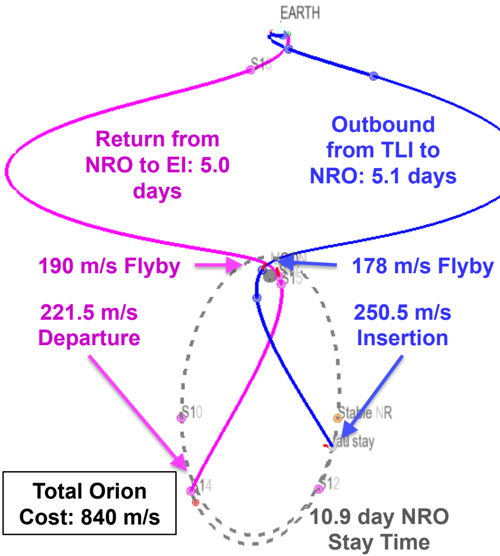


In total, 7 types of orbits were considered, relying on both previous studies from literature and new analysis, primarily for the NRO. While the analysis presented is not comprehensive for all orbits, trends and characteristics are computed to permit generalized conclusions.

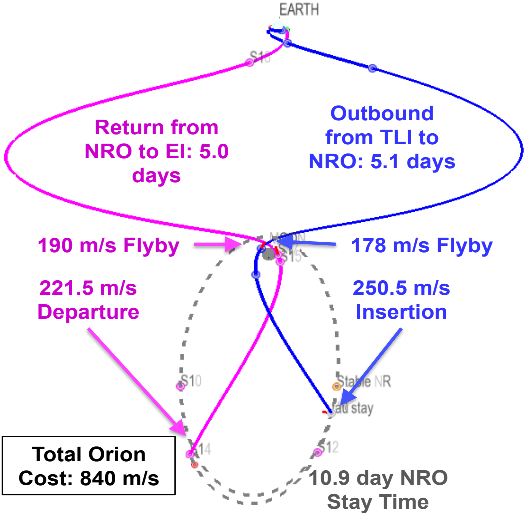
Orion Transfers from Earth to NRO and Back



21 Day Mission

Transfers to and from NRO are 5 days each way with total DV cost of 840 m/s

Orion Transfers from Earth to NRO and Back



21 Day Mission

Transfers to and from NRO are 5 days each way with total DV cost of 840 m/s

Transfer Costs from Earth TLI Condition

- An important metric for orbit viability is accessibility from Earth using existing or planned transportation elements.
- The combined performance of NASA's SLS and Orion vehicles were evaluated:
  - **[SLS]** SLS completes ascent to Low Earth Orbit and than the SLS Exploration Upper Stage places Orion on trans-lunar trajectory
  - **[Orion]** The MPCV is ~25 t, with ~8 t of usable propellant, leaving a ΔV budget of around 1250 m/s with a total lifetime constraint of 21 days for 4 crew members
- Smaller Cislunar Orbits

Orbit	Total ΔV	C_3 (Moon)
LLO	1800+ m/s	-2.67 km^2/s^2
PCO	Unknown	-.85 km^2/s^2
Frozen	Unknown	-.75 km^2/s^2
ELO	940 to 1270 m/s [a]	-.72 km^2/s^2

[a] Optimal values from 20 year epoch scan.

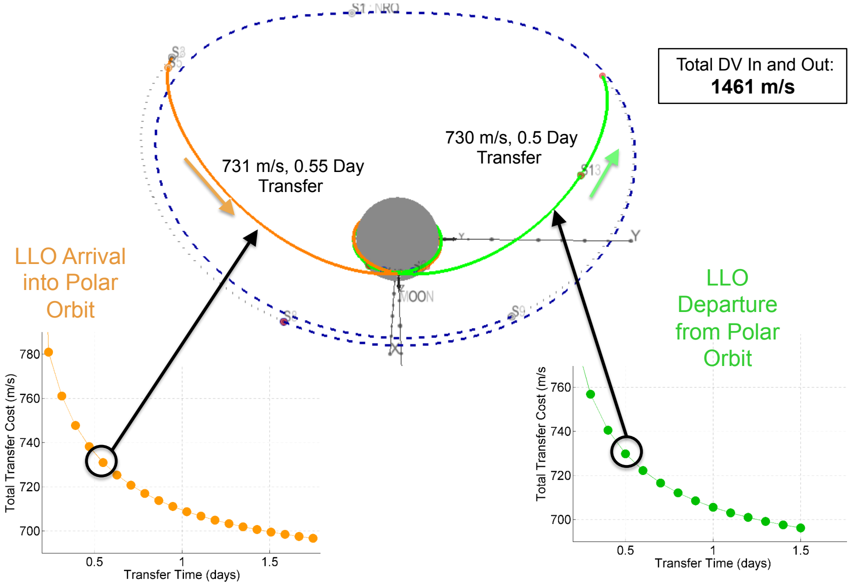
- Larger Cislunar Orbits

Orbit	Total ΔV	Stay Time	Total ΔV	Stay Time
	21 Day Mission		60 Day Mission	
NRO	840 m/s	10.9 d	751 m/s	37.6 d
	18 Day Mission		31 Day Mission	
L2 Halo[b]	811 m/s	5 d	637 m/s	10 d
	21 Day Mission		26 Day Mission	
DRO[c]	957 m/s	6 d	841 m/s	6 d

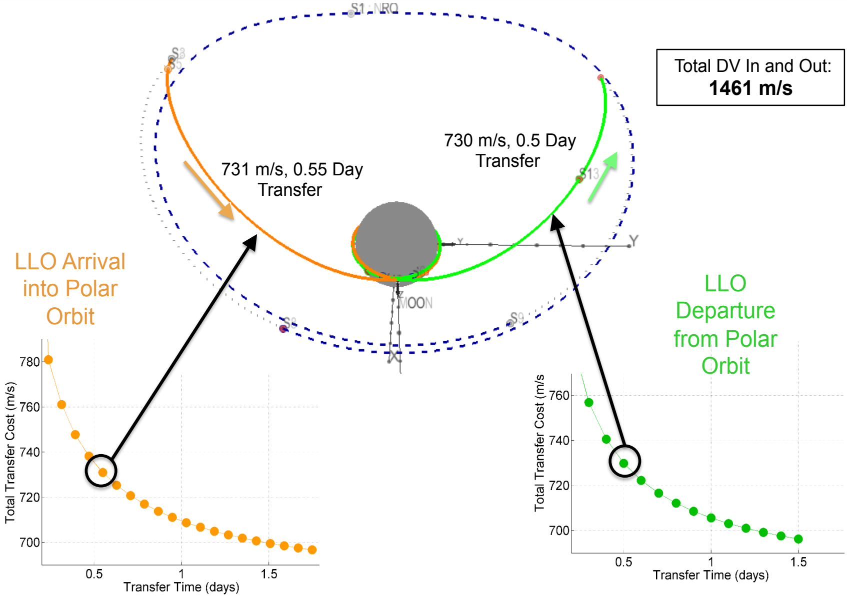
[b] From AIAA 2013-5478   [c] From AIAA 2014-1696

Orion	Feasible	Marginal	Infeasible

Accessing the Lunar POLES from NRO

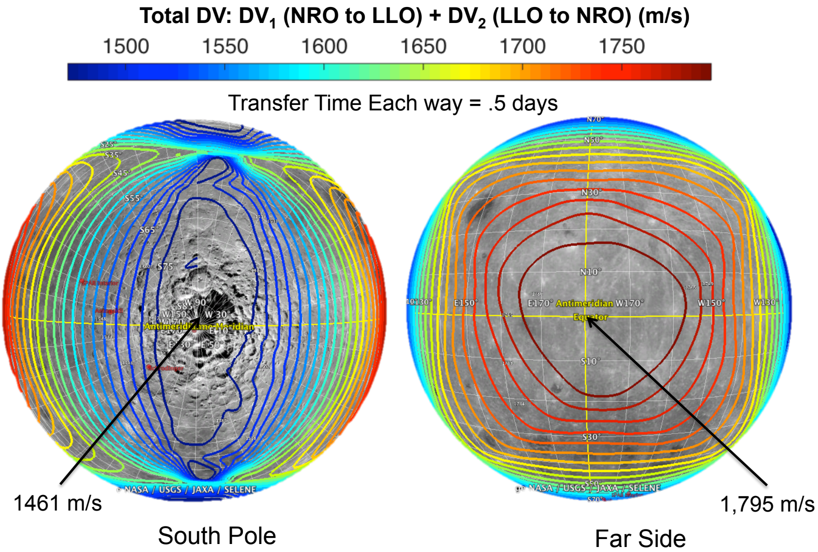


Accessing the Lunar POLES from NRO



Total DV In and Out:
1461 m/s

GLOBAL Lunar Surface Access from NRO



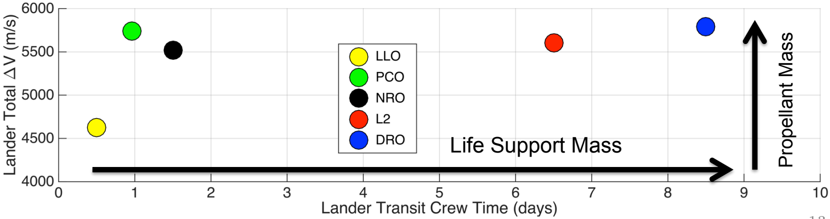
All Orbits: Lunar Surface Access

Orbit	To or From LLO ΔV	To or From LLO ΔT	Plane Change ΔV	Total ΔV
LLO (0° PC)	0 m/s	< 1hr	0 m/s [b]	0 m/s
LLO (30° PC)	0 m/s	< 1hr	846 m/s [b]	846 m/s
PCO (Pol.)	700 m/s	5 hrs	–	700 m/s
Frozen (Pol.)	556 m/s [a]	6 hrs	252 m/s [b]	808 m/s
Frozen (Eq.)	556 m/s [a]	6 hrs	408 m/s [b]	964 m/s
ELO (0° PC)	515 m/s [a]	7 hrs	0 m/s [b]	515 m/s
ELO (90° PC)	515 m/s [a]	7 hrs	478 m/s [b]	993 m/s
NRO (Pol.)	730 m/s	0.5 days	–	730 m/s
NRO (Eq..)	898 m/s	0.5 days	–	898 m/s
EM-L2 (Pol.)	800 m/s	3 days	–	800 m/s
EM-L2 (Eq.)	750 m/s	3 days	–	750 m/s
DRO (Pol.)	830 m/s	4 days	–	830 m/s

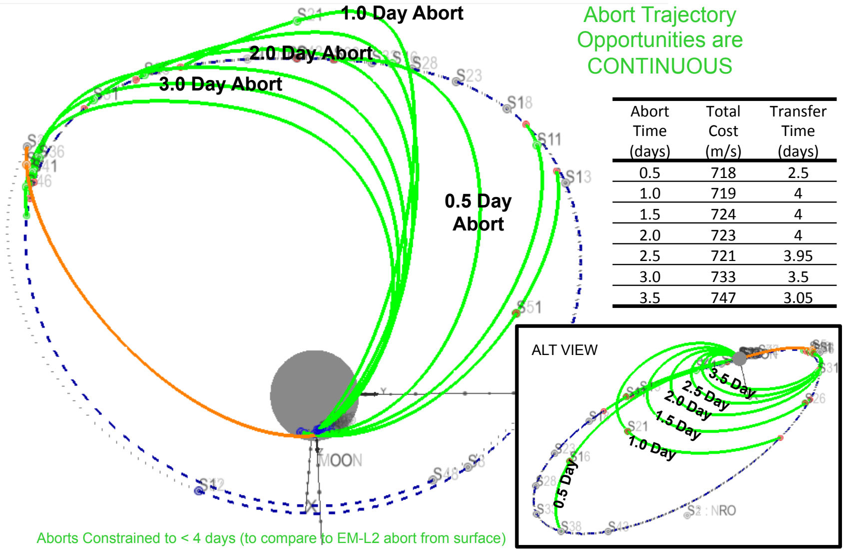
[a] Calculations assume implusive hohmann transfer

[b] Eqn: $\Delta V_{pc} = 2vsin\left[\frac{\Delta i}{2}\right]$

Legend
Favorable
Marginal
Unfavorable



Aborts to NRO

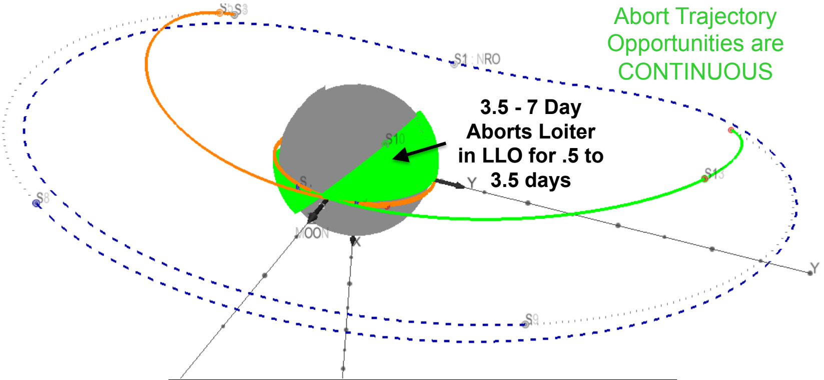


Aborts Constrained to < 4 days (to compare to EM-L2 abort from surface)

Abort Trajectory Opportunities are CONTINUOUS

Abort Time (days)	Total Cost (m/s)	Transfer Time (days)
0.5	718	2.5
1.0	719	4
1.5	724	4
2.0	723	4
2.5	721	3.95
3.0	733	3.5
3.5	747	3.05

Aborts to NRO



Abort Trajectory Opportunities are CONTINUOUS

Abort Time	Total Cost	LLO Loiter Time	Transfer Time
3.5 days	730 m/s	3.5 days	0.5 days
4.0 days	730 m/s	3.0 days	0.5 days
4.5 days	730 m/s	2.5 days	0.5 days
5.0 days	730 m/s	2.0 days	0.5 days
5.5 days	730 m/s	1.5 days	0.5 days
6.0 days	730 m/s	1.0 days	0.5 days
6.5 days	730 m/s	.5 days	0.5 days

Anytime Surface to Cislunar Orbit Abort Assessment

- For the smaller orbits, orbit precession around the moon is key.
  - Analysis performed in the mid 2000's for Constellation suggest that some amount of plane change may be required to get back to an orbiting asset.
  - If Orion is in a polar orbit and landing site is also polar that plane change cost should be minimal. The plane change cost increases as the landing site moves away from the poles.
  - If the staging orbit is in a fixed plane, such as the Frozen orbit, the PCO, or the ELO selected for analysis, the plane change cost could be substantial.
- For the larger orbits, the plane change required can be conducted at lower orbital velocities and is less impactful to total cost
  - The result of the continuous abort assessment puts the total DV at around 750 m/s for anytime aborts from the polar regions, but increases to 900 m/s from equatorial sites

Orbit	Anytime Abort Requirement			
	From Pole		From Equator	
	ΔV	ΔT	ΔV	ΔT
NRO	750 m/s	3.5 d	900 m/s	2.5 d
L2 Halo[a]	900 m/s	3.5 d	850 m/s	2.5 d
L2 Lissajous[a]	850 m/s	3.5 d	800 m/s	2.5 d

[a] See "Mission Analysis for Exploration Missions Utilizing Near-Earth Libration Points." Ph.D. Thesis by Florian Renk for detailed analysis.

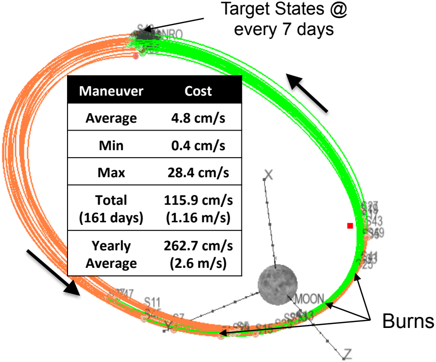
  - As the table demonstrates, for the larger orbits, NRO is substantially more favorable for polar landing sites, while the L2 Halo and Lissajous orbits are more favorable for equatorial landing sites with Lissajous generally out performing the L2 Halo.

Stationkeeping Costs

All Orbits Stationkeeping

Orbit Type	Stationkeeping
LLO	50 m/s + per year
PCO	0 m/s for 3 years
Frozen	0 m/s
ELO	>300 m/s per year
NRO	<10 m/s per year
EM L2H	<10 m/s per year
DRO	0 m/s

NRO Stationkeeping



Maneuver	Cost
Average	4.8 cm/s
Min	0.4 cm/s
Max	28.4 cm/s
Total (161 days)	115.9 cm/s (1.16 m/s)
Yearly Average	262.7 cm/s (2.6 m/s)

Legend	Favorable	Marginal	Unfavorable

For the NRO, small corrections each orbit can maintain stability at an average cost of 2.6 m/s per year (0.22 m/s per month). Two of NASA's ARTEMIS spacecraft successfully flew a similar Earth-Moon L_1 and L_2 Halo libration orbit stationkeeping strategy at 0.31 and 0.41 m/s per month cost.

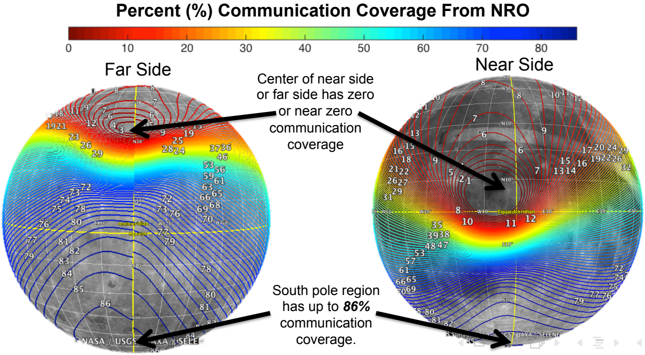
Communication (Line of sight to Earth and Moon)

All Orbits Line of Sight Communications to Earth

Orbit Type	Communication
LLO	50% Occulted
Frozen	Frequent Occultation
ELO	Frequent Occultation
NRO	No Occultation
EM L2H	No Occultation
DRO	Infrequent Occultation

Legend
Favorable
Marginal
Unfavorable

NRO Line of Sight Communications to Lunar Surface



Thermal Comparison

Heat Flux & Radiator Sizing Comparison

Orbit / Location	Maximum Heat Flux (W/m^2) Radiative	Reflective	Total	Radiator Sizing [a,b]
LLO	1545	231	1776	N/A
NRO	54	8	62	21.4 m^2
DRO	–	–	0.6	18.0 m^2
Deep Space	–	–	0.0	17.9 m^2

[a] Radiator Sizing Based on 5000 W Q_{craft}

[b] $Eqn : Q_{net} = Q_r - \alpha(Q_s + Q_a) - \epsilon Q_{IR}, \alpha = .2, \epsilon = .8, T_{rad} = 280K$

All Orbits Thermal

Orbit Type	Thermal
LLO	Radiators Insufficient
NRO	Radiators Sufficient
EM L2H	Radiators Sufficient
DRO	Radiators Sufficient

Legend
Favorable
Marginal
Unfavorable

For LLO, the radiator sizing is undefined; a radiator cannot be sized large enough to handle the flux in LLO. No increase in radiator sizing is necessary for the vehicle in NRO, E-M L2 or DRO orbits as the radiator has margin already as designed to the benign deep space environment.

Staging Orbit Summary Comparison

Orbit Type	Earth Access (Orion)	Lunar Access (to Polar LLO)	Crewed Spacecraft SK	Crewed Spacecraft Communication	Crewed Spacecraft Thermal
Low Lunar Orbit (LLO)	Infeasible	$\Delta V = 0$ m/s $\Delta T = 0$	50 m/s + per year	50% Occulted	Radiators Insufficient
Prograde Circular Orbit (PCO)	Marginally Feasible	$\Delta V <$ 700 m/s ΔT <1 day	0 m/s for 3 years	Unknown	Unknown
Frozen Lunar Orbit	Marginally Feasible	$\Delta V =$ 808 m/s ΔT <1 day	0 m/s	Frequent Occultation	Unknown
Elliptical Lunar Orbit (ELO)	Marginally Feasible	$\Delta V =$ 953 m/s ΔT <1 day	>300 m/s per year	Frequent Occultation	Unknown
Near Rectilinear Orbit (NRO)	Feasible	$\Delta V =$ 730 m/s $\Delta T =$ .5 day	<10 m/s per year	No Occultation	Radiators Sufficient
Earth-Moon L2 Halo	Feasible	$\Delta V =$ 800 m/s $\Delta T =$ 3 days	<10 m/s per year	No Occultation	Radiators Sufficient
Distant Retrograde Orbit (DRO)	Feasible	$\Delta V =$ 830 m/s $\Delta T =$ 4 days	0 m/s	Infrequent Occultation	Radiators Sufficient

Legend	Favorable	Marginal	Unfavorable

Establishing a viable staging orbit in cislunar space is a key step in the human exploration journey. Maximizing flexibility in terms of access from Earth, access to other destinations, and spacecraft design impacts are all important. From the cislunar orbits studied, **the Near Rectilinear Orbit (NRO) appears to be the most favorable orbit** to meet multiple constraints and requirements.