Options for Staging Orbits in Cis-Lunar Space

Ryan Whitley
NASA Johnson Space Center
2101 NASA Parkway
Houston, TX 77058
281-483-9577
ryan.j.whitley@nasa.gov

Roland Martinez
NASA Johnson Space Center
2101 NASA Parkway
Houston, TX 77058
281-483-3497
roland.m.martinez@nasa.gov

Abstract—NASA has been studying options to conduct missions beyond Low Earth Orbit, but within the Earth-Moon system, in preparation for deep space exploration including human missions to Mars. Referred to as the Proving Ground, this arena of exploration activities will enable the development of human spaceflight systems and operations to satisfy future exploration objectives beyond the cis-lunar environment. One option being considered includes the deployment of a habitable element or elements, which could be used as a central location for aggregation of supplies and resources for human missions in cis-lunar space and beyond. Characterizing candidate orbit locations for this asset and the impacts on system design and mission operations is important in the overall assessment of the options being considered. The orbits described in this paper were initially selected by taking advantage of previous studies conducted by NASA and the work of other authors.

In this paper orbits are assessed for their relative attractiveness based on various factors. First, a set of constraints related to the capability of the combined Orion and SLS system to deliver humans and cargo to and from the orbit are evaluated. Second, the ability to support potential lunar surface activities is considered. Finally, deployed assets intended to spend multiple years in the Proving Ground would ideally require minimal station keeping costs to reduce the mass budget allocated to this function. Additional mission design drivers include potential for uninterrupted communication with deployed assets, thermal, communications, and other operational implications. The results of the characterization and evaluation of the selected orbits indicate a Near Rectilinear Orbit (NRO) is an attractive candidate as an aggregation point or staging location for operations. In this paper, the NRO is further described in terms which balance a number of key attributes that favor a variety of mission classes to meet multiple, sometimes competing, constraints.

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1. INTRODUCTION

The next phase of human exploration is upon us. To enable this phase NASA is developing the Space Launch System (SLS) and Orion Multipurpose Crew Vehicle (MPCV). Initially, with these systems, NASA will advance capabilities and learn to conduct complex operations in cis-lunar space

on the journey to Mars [1].

To that end, a common aggregation point or staging orbit in cis-lunar space is an attractive option as it offers opportunities for multiple missions to be accomplished and objectives to be met while reusing valuable assets deployed over may years. In addition to NASA's recognition of this idea, the concept has also been accepted and described by the international space community [2]. Ideally, spacecraft would use the staging orbit to conduct in-space missions, while providing accessible transfer options to support lunar surface activities and as an intermediate step to Mars transfer orbits.

The International Space Station (ISS) has been a valuable asset for testing needed exploration needed technologies for more remote mission scenarios. However, the ISS requires constant resupply and maintenance and is designed to operate exclusively in the Low Earth Orbit (LEO) environment. For the next phase of human space flight, therefore, exploration capability beyond that of ISS is required [3]. A number of studies have been commissioned by NASA this millennium to identify potential next steps including the Trans Hab and several iterations of the Gateway concept, developed by the Decade Planning Team [4] and its successor the NASA Exploration Team (NExT) [5]. As the architectures have been considered, additional studies have assessed potential locations [6] [7] and potential functional requirements [8] for assets deployed beyond LEO.

Currently the international space community, represented by space agencies participating in the International Space Exploration Coordination Group (ISECG), is committed to "fostering broad international cooperation to further advance the exploration and utilisation of space." [9] In this context, the location of a common staging location to support multiple activities presents an interesting challenge. In support of advancing these broad discussions, NASA is investigating this topic to evaluate and compare the attractiveness of previously studied orbits, as well as to determine if other cis-lunar orbits should be considered.

2. CIS-LUNAR ORBIT TYPES CONSIDERED

In order to find an attractive orbit, a number of competing objectives need to be met. These include characteristics favorable for Earth, Moon and deep space access as well as properties favorable for crewed spacecraft. With cis-lunar being the primary driver and Moon access a constraint, all orbits considered were therefore required to be within the Earth-Moon vicinity but also be far enough away from Earth to purport a deep space equivalent environment. In the end, 7 types of orbits were considered, relying on both previous studies from literature and new analysis to conduct a comparative assessment. The orbit types are presented in increasing orbit period size starting with Low Lunar Orbit (LLO) and ending

Table 1. Orbit Characteristics Table

Orbit Type	Orbit Period	Lunar (or L-point) 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
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

with the Distant Retrograde Orbit (DRO). Specific orbits in each class are selected for study, and comprehensive analysis of each orbit is not completed, but trends and characteristics are computed that allow generalized conclusions to be made. The most significant new analysis conducted is with respect to the characterization of the Near Rectilinear Orbit (NRO).

Low Lunar Orbits (LLOs) & Elliptical Lunar Orbits (ELOs)

Keplerian orbits around primary bodies have been studied for centuries since planetary motion was described by Johannes Kepler in the 16th century. During the formulation of the Apollo lunar exploration program when Lunar-orbit-rendezvous was selected, a simple specific Keplerian orbit known as Low Lunar Orbit (LLO) became the phasing orbit for surface access [10]. LLO in the context of this paper is defined as a circular orbit of an altitude around 100 km above the lunar surface. For Apollo this was an equatorial orbit in the Earth-Moon plane. In the following decades since, additional studies have concluded LLO as a good staging orbit to the surface, including a range of inclinations to access global landing sites [11]. LLO offers many benefits to the design of a lander but has impacts to other systems and must be weighed in the balance of the entire mission architecture.

Elliptical Lunar Orbits (ELOs) are also well understood Keplerian orbits. The benefit of a ELO may be in its potential lower cost access from Earth, while maintaining a low perilune over the lunar surface to maintain favorable surface access. It also closely resembles the orbit planned for Mars mission aggregation, the Mars 1-sol as described in Mars Design Reference Architecture 5 [12].

Prograde Circular Orbits (PCOs) & Frozen Lunar Orbits

Prograde Circular Orbits (PCOs) are defined in this paper as circular orbits of various sizes that rotate in the prograde

direction and are highly stable, requiring few to 0 corrections to be maintained. Frozen orbits are similar but need not be circular and have orbital parameters that oscillate around fixed values. Highly stable and/or frozen orbits have been discovered for both the Earth [13] [14] and Moon [15] [16]. Frozen orbits are generally discovered by analyzing unique aspects of the gravitational potential and finding regions of behavior that lend themselves to canceling the effects of shape irregularities. Frozen orbits exist for only certain combinations of energy, eccentricity and inclination. Due to these limits, finding frozen orbits that balance other constraints can be difficult. The frozen orbit assessed in this study comes from published literature [17].

Near-Rectilinear Orbits (NROs)

Almost rectilinear or near-rectilinear halo orbits were discovered as a kind of bridge between L1 and L2 halos in the Earth-Moon system[18]. Since then multiple papers have explored the use of near-rectilinear halo orbits (shortened to NROs here) for use in various lunar exploration concepts, including constant south pole coverage [19] [20]. The NROs are halo orbits with large amplitudes over either the north or south pole with shorter periods that pass closely to the opposite pole. While they appear to look like large elliptical orbits, they are CRTBP orbits that remain relatively fixed in the Earth-Moon plane, rotating at the same rate as the Moon around the Earth and the Moon around its own axis.

Earth-Moon Libration Point Halo Orbits

Halo orbits located around the collinear libration points in the CRTBP have been well established in literature [21] [22]. Periodic orbit motion around the collinear libration points exists in the plane of the relative motion of the secondary body around the primary. Many orbit families exist, including a subset of orbits termed as halo orbits when, if the size of
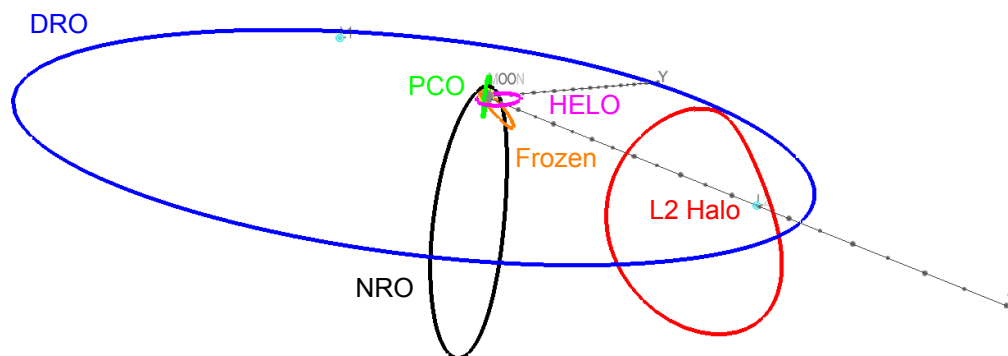
Figure 1. **Potential Staging Orbits**

the orbit is comparable to distance of L2 from the secondary body, a purely periodic three-dimensional motion is possible [22]. While purely periodic and stable in the CRTBP, in the full ephemeris model they are slightly unstable and not fully repeatable. Nevertheless, these orbits have many favorable properties, including continuous Earth visibility, relatively easy access from Earth, and predictable behavior. Missions to these orbits have occurred (e.g. Artemis) or are planned to occur (e.g. James Webb Space Telescope) [23] [24] [25]. In addition, multiple studies have concluded the favorability of these orbits for future human missions [6] [7].

Distant Retrograde Orbit (DRO)

The Distant Retrograde Orbit's (DRO's) are orbits that exist in the Circular Restricted Three Body Problem (CRTBP) that appear to orbit the secondary body in a retrograde, and relatively periodic, motion [26]. For the Earth-Moon system, DRO's appear to orbit the moon when in fact they are orbits around the Earth. They were first proposed for observational purposes in the Sun-Earth system due to their favorable deep space environment and periodic, predictable behavior. Multiple methods for accessing these orbits have been found [26] [27] [28]. For the Earth-Moon system, the DRO has been proposed for the Asteroid Redirect Mission (ARM) as the location to place a captured boulder from an asteroid [29]. For this mission, it was deemed feasible for Orion to reach the orbit and also maintain an acceptable abort strategy [30] [31].

3. Earth Access Assessment

An important metric for determining the viability of a given orbit is the accessibility of that orbit using existing or planned transportation elements. For the purpose of this study, the the combined performance of NASA's SLS and Orion vehicles were evaluated. SLS completes the ascent to Low Earth Orbit and then the SLS Exploration upper stage places Orion on a trans-lunar trajectory. From this point on in the mission, Orion is the only means by which orbital maneuvers can be conducted in and out of the target orbit. As currently designed and built, the Orion vehicle is around 25 t, with around 8 t of usable propellant. This leaves a total ΔV budget of around 1250 m/s with a total lifetime of 21 days for 4 crew members. Thus any orbit designed needs to cost less than 1250 m/s to enter and leave the orbit, or additional, currently unplanned, transportation elements will be required.

Orion's propellant load limitation makes it difficult to access smaller, low energy, lunar orbits. Starting with the smallest lunar orbit candidate, LLO, it is immediately evident that this orbit is inaccessible without additional propellant stages. In the scenarios with minimum plane change with a 3-5 day transfer from Earth, the ΔV is at minimum around 900 m/s. Orion could successfully complete the insertion burn but not the return trip which also costs around 900 m/s.

The next smallest orbits are the program circular orbit (3,000 to 5,000 km altitude), Elliptical orbit (100 x 10,000 km altitude) and frozen orbit (800 x 8,800 km altitude) respectively. All of these orbits are round trip accessible by Orion for specific epochs. However, the performance margins are small and the total costs are irregular, varying significantly with epoch. For example, the total optimal transfer costs in and out of an equatorial ELO ranges from around 940 to 1270 m/s over a 20 year epoch scan. For the frozen and prograde circular orbits, more analysis would be needed to determine regular orbit accessibility, but it likely mirrors the
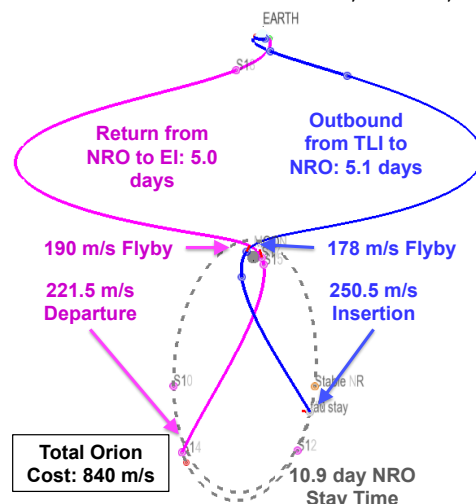

Figure 2. **Earth to NRO Transfer Cost**

ELO results. In addition, if more payload were added to Orion, these orbits may become completely infeasible or have an even more limited temporal access. Thus, for continuous access all three smaller orbits are potentially problematic.

The next set of orbit sizes are the NROs, larger E-M L2 Halos, and DROs. The larger L2 Halos and DROs have been considered for human missions and fit within Orion's capability with some margin. For the L2 Halo, the cost varies depending on the size of the halo and it's location, but the optimal cost can be as low as 637 m/s for a 31 day mission or around 811 m/s for an 18 day mission [7]. For the DRO the cost can also vary; for a 70,000 km DRO the ΔV cost can be as low as 840 m/s for a 26 day mission [30].

New results regarding the feasibility of NROs for human missions are presented in this paper. Figure 2 shows a sample transfer trajectory from Earth to NRO that meets the 21 day lifetime requirement for a crew of 4 for Orion. For a 7 day NRO, the total cost for an opportunity in February 2021 was found to be 840 m/s. Additionally, a 60 day mission was found with a stay time of 37.6 days (with 21 day total transfer time) can be completed within 751 m/s.

A comparison of feasible missions to all three orbits can be found in Table 2. While more detailed epoch scans are forward work, a first pass suggests that access to the larger L2 Halo is easiest followed by NRO and finally DRO. This result agrees with what would be expected as the relative energies of the orbit decrease correlatively with the relative ease of access.

Table 2. Round Trip Sample Missions

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[a]	811 m/s	5 d	637 m/s	10 d
	21 Day Mission		26 Day Mission	
DRO[b]	957 m/s	6 d	841 m/s	6 d

[a,b] See references [7] and [30] for detailed analysis.

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4. LUNAR SURFACE ACCESS ASSESSMENT

In addition to being Earth accessible, an important constraint for a staging orbit its capability to facilitate access to the lunar surface. Missions to the lunar surface may feature humans to the surface or robotic lunar sample return. For the former, characterizing specific landing sites of interest and abort capability from these landing sites is important. For the latter, understanding global surface access is important.

The descent and ascent $\Delta V s$ from LLO are fixed for this analysis. It is assumed that the transfer cost to and from the surface to a point in LLO that passes over the site without plane change is relatively constant (around 4000 m/s or 2000 m/s each way). The actual ΔV numbers may vary based on a multitude of vehicle assumptions such as T/W or descent to touchdown trajectory shaping for hazard avoidance, but for the purposes of characterizing staging orbits these assumptions are irrelevant. Thus all transfers are assumed to an LLO of interest that passes over a given landing site.

Global Surface Access

Transfers to a particular LLO require both ΔV and time. For robotic missions, ΔV is the primary (if not sole) driver, while for human missions both ΔV and time are critical. For the smaller orbits, the time is not much of a factor as the transfer time is measured in hours, not days. Instead ΔV and the quantity of the plane change maneuver drives the total cost. For example, if the LLO of interest is a polar orbit, due to the natural precession of the orbit, any location on the surface is accessible without additional plane change maneuvers if the mission is willing to wait for the right opportunity. Otherwise, a significant maneuver may be required. This maneuver is directly related to orbital velocity and the degree of inclination change required.

Table 3 shows the total transfer costs for optimal trajectories from the candidate staging orbits to either a polar or equatorial LLO. The base ΔV costs suggest a smaller orbit is desirable, but not if a significant plane change is required. For a plane change from one LLO to another for inclination changes from 0 to 90 degrees this cost could respectively range from 0 m/s to over 1,000 m/s. For eccentric orbits this plane change is cheaper at the highest altitude but not 0. In contrast for larger orbits, this plane change is less of an issue as the relative orbital velocity is lower. However, the nominal energy change to reach LLO is much higher, plus the transfer
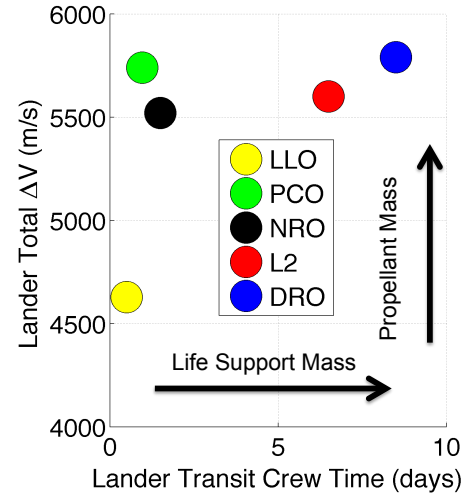

Figure 3. Lander Design Impacts

time requiring additional life support and consumables for the crew is much higher on the order of days.

In Table 3, only transfer costs from the staging orbit to the surface are considered. However, landing elements must first enter into that staging orbit. Assuming the crew arrives in Orion and transfers to the lander at the staging orbit, the landing elements have more time to transfer and insert into the lunar orbits and can thus take advantage of low-energy transfers. However, for LLO it takes at least 628 m/s orbit insertion maneuver even with a transfer time of several months [32]. For the larger, higher energy orbits, the ΔV costs to the surface may be higher, but the orbits are more easily accessible from Earth. In fact, the Earth-Moon libration point halos and NRO orbits require very small $\Delta V s$ in the 10's of m/s easily less than 100 m/s total if transfer time is free to be several months.

Balancing ΔV and transfer time with crew on-board a landing element would still prefer to rendezvous in an LLO with minimal plane change. But considering the Earth accessibility limitations, as well as large potential plane change maneuvers, the next best orbit appears to be an NRO, especially for the polar region. More detailed analysis was completed with the NRO to examine the transfer costs to any location on the surface, assuming the transfer time was limited to a half day each way. Figure 4 displays the nominal transfer geometry to a polar LLO and Figure 5 demonstrates global access when the transfer time is constrained to be a half day each way.
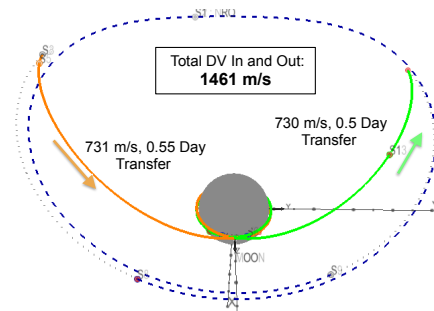
Table 3. Surface Access Costs from Various Orbits (m/s)

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

^{a} Calculations assume implusive hohmann transfer

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

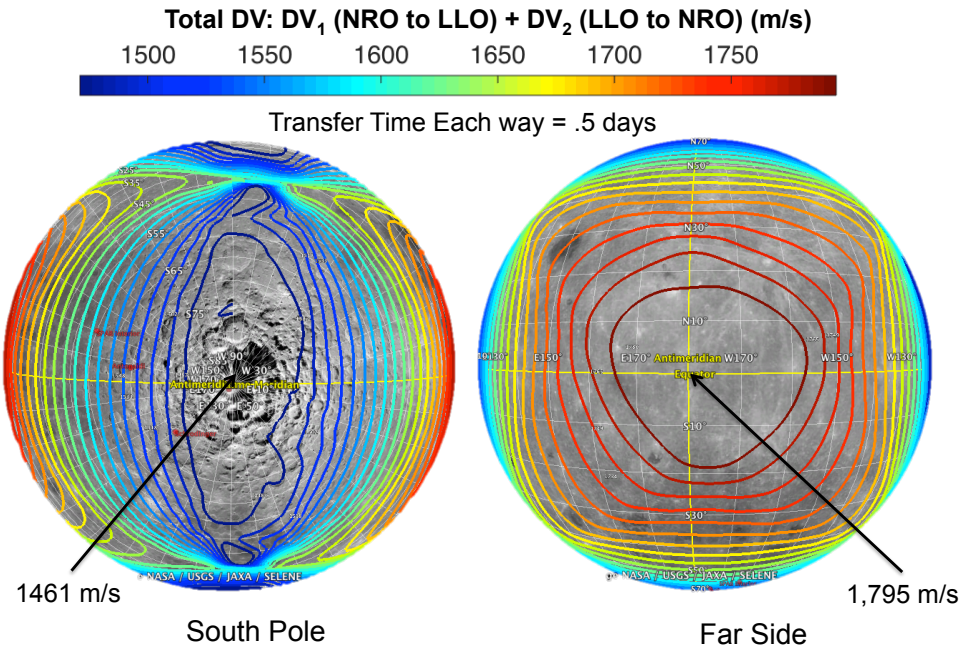**Figure 4. NRO to LLO Nominal Transfer Trajectories**

Figure 5. **NRO Global Surface Access**

Aborts from Surface

In characterizing nominal mission sequences to the lunar surface and back, it is also important to understand the potential abort scenarios. Depending on surface mission duration, the spacecraft still in the staging orbit that aligned the lunar lander for descent may not be perfectly aligned when it returns for ascent, especially if an abort is triggered.

For the smaller orbits, the orbit precession around the moon is key. Some analysis in the past has suggested that plane change either by Orion or the lunar lander would be required for smaller orbits such as LLO [33]. For this study, it is generally assumed the orbiting spacecraft is stationary and the other elements maneuver as needed. Thus, it is important to find an orbit that can be reached at any time relatively quickly.

Table 4 compares anytime access for a handful of the larger orbits, namely two E-M L2 orbits and the NRO orbit as related to two fixed surface locations: (1) the North Pole (90°, 0°) and (2) the Equator (0°, 0°). If transfer time is fixed and aborts are required anytime during the orbit, the worst abort

Table 4. Anytime Aborts

| 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 reference [34] for detailed analysis.

case during the orbit period drives the total required abort propellant load. For NRO, Figure 6 displays the two types of aborts assessed to determine the total propellant required. On the left, aborts that occur from the surface during the first half of the 7 day NRO period leave immediately from a favorable transfer LLO. For the latter half, depending on the transfer time requirement, aborts from the surface can target and loiter in an LLO until the spacecraft does its closest lunar approach and then a half day nominal transfer can be applied. For the L2 orbits, [34] provides more detail on the transfer trajectories.
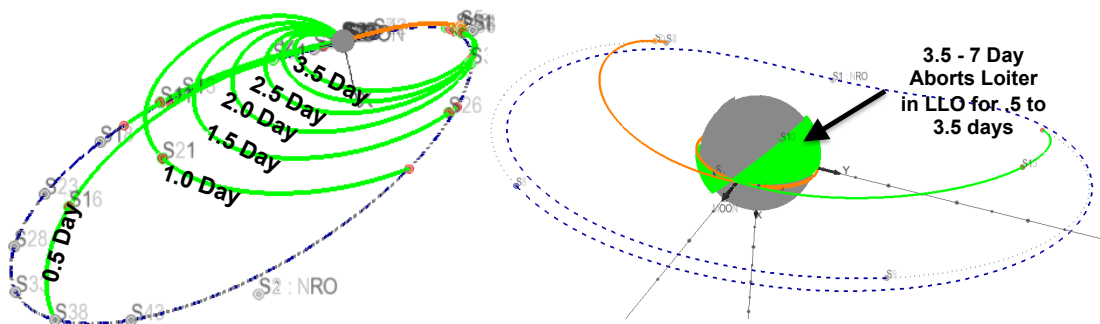

Figure 6. **Lunar Surface Aborts to NRO**

5. Long Term Spacecraft Impacts & Comparison

A favorable staging orbit must have characteristics that enable long term operations for several years. While no fixed requirement for total duration has been specified, minimizing logistics flights to assets in the orbit may be critical, permitting as much autonomy as possible for a minimally crew tended element. Thus, stationkeeping requirements, earth visibility of asset for communications and thermal environment impacts are vital factors in the orbit assessment.

Stationkeeping Requirements

Perhaps the most important factor in assessing the viability of a orbit over a long period of time is the amount of propellant required to maintain that orbit; in other words, an assessment of orbit stability. Stability in the context of orbital operations simply means that over time the trajectory will repeat in a predictable (not necessarily exact) pattern without requiring significant correction maneuvers or diminishing Earth or lunar accessibility properties. In particular, the trajectory must not result in the element easily departing the lunar vicinity or intersecting the lunar surface. The most favorable orbits in this context will necessarily have minimal to zero ongoing maneuvers.

Three of the orbits considered meet the maximum constraint already. The Frozen orbit, the PCOs and the DROs all exhibit multi-year stability, requiring 0 corrective maneuvers. The Frozen orbit will vary slightly in eccentricity from 0.6 to 0.7, but the rest of the orbital parameters are fixed. The PCOs and DROs may not be frozen, but exhibit predictable repeatable behavior without impacting accessibility.

The remaining four orbits need to be assessed. Previous work has established some reference data to examine. At this point, only gravitational forces are considered for nominal corrections in order to assess natural orbit instability. For LLO, a stationkeeping strategy to maintain a minimum altitude above the surface has been employed at a sweep of inclinations. The total stationkeeping cost with corrections only applied when the orbit altitude is less than 50 km results in a ΔV requirement between 50 and 100 m/s per year depending in orbit initial inclination [35].

For the ELO, a few cases were run that demonstrated excessive ΔV costs. While the results are preliminary, the total cost was around 300 m/s per year. The excessive costs are due to the unfavorable elliptical nature of the orbit. With a large apolune that is perturbed by Earth and Sun gravitational forces, it is easy for the trajectory to be perturbed to a close (and often impacting) approach at perilune. Maintaining a minimum altitude requires maneuver every other rev of at least 1 m/s and with half day orbit periods, the cost adds up quickly.

For E-M L2 halos, the Artemis mission has demonstrated successful stationkeeping for a quasi-halo orbit at the rate of less than 5 m/s [25]. Further studies on libration point station keeping suggest that libration point orbits in general may require from 5 to 50 m/s depending on the size of the halo [19].

NROs are a subset of L2 halos and are predicted to be have higher stability than the larger halos with total cost around 5 m/s for a year. To verify these costs, a stationkeeping simulation was run with a targeted reference and maneuvers once a revolution occurring roughly every 7 days. The results
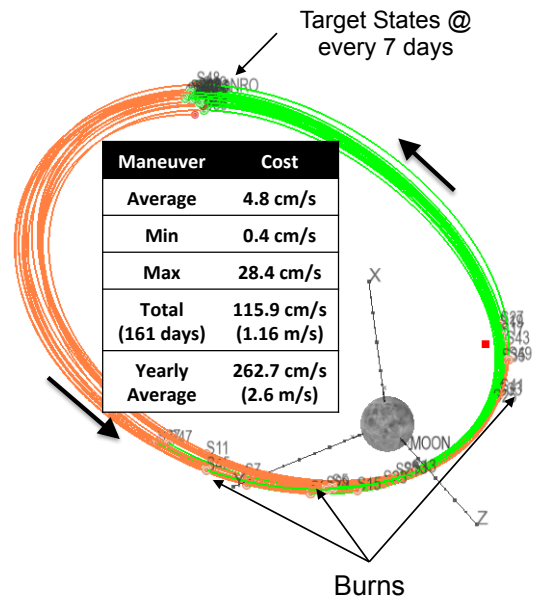

Figure 8. NRO Stationkeeping Costs

are shown in Figure 8.

Communication Assessment

Another important consideration for missions to cis-lunar space is communication. A direct line of sight with Earth may be critical during operations to mitigate unforeseen risks. For cis-lunar orbits, the moon is the most significant obstruction that must be accounted for. In addition, with missions conducted to the surface it is desirable to maintain communication with surface assets.

To Earth—Due to the nature of small periodic orbits about the moon, continuous communication is impossible for the smaller LLO, PCO, ELO and Frozen orbits. With periods ranging from 2 hrs to little more than half a day, no matter the orientation or inclination selected, the orbit will precess and be occulted from the Earth about half of the time. This fact does not make these orbits infeasible, just undesirable due to the regular blackouts that would occur lasting between one to several hours each. These blackouts could be mitigated with a relay satellite in orbit around L2, for example, but that is an additional mission with additional cost that would also need to be reliably maintained.

The larger CRTBP orbits have little to no occultation at all. In fact, both the E-M L2 and NRO orbits maintain continuous line of sight coverage with Earth due to the natural motion of the orbits around L2. The orbit is always perpendicular to the Earth-Moon plane with amplitudes larger than the radius of the moon. Some L2 orbits exist in the Earth-Moon plane with zero amplitudes and those would be more frequently occulted. Likewise, the currently designed 70,000 km DRO orbit also has a zero out of plane amplitude and thus experiences blackouts lasting several hours once every period (about every 14 days). These occultations could be minimized if some inclination was given to the DRO orbit, although the stability and Earth access properties would need to be reassessed.

To Lunar Surface—Communication with surface assets may be mission critical. Without a lunar space network, surface

assets will be site specific and thus for any orbit have limited coverage. A trade then exits to identify sites of interest and coverage of each orbit on that site. The smaller orbits are potentially problematic as the close proximity to the surface with rapid revolutions will likely give sites either very short coverage or no coverage. The larger orbits provide better coverage, but are still site specific. As the DRO orbit is in the Earth-moon plane, sites on the poles will have minimal to no coverage and other sites closer to the lunar equator will have periodic coverage.

The NRO and L2 halo orbits provide the best coverage as they are generally inclined with respect to the ecliptic. Still, they will favor one pole or another and one side of the moon or the other. Figure 7 shows one such case. Featured is the NRO studied in this paper, an L2 south family halo. As a result it favors the south pole and the far side with up to 86% coverage of the south pole and more of the equatorial region on the far side including the South Pole Aitken Basin (SPAB). If the north pole is favored, a north family halo could be selected, and if more near side coverage is desired an L1 orbit could be considered. In short, the CRTBP libration point orbits provide flexibility if certain sites have particular interest. But no orbit provides the best coverage for all global sites simultaneously.

Thermal Environment

For crewed spacecraft, another important consideration is the thermal environment. The baseline scenario is deep space in which only solar flux must be mitigated. The additional thermal challenges are then related to radiated and reflected heat flux from a planet or moon. To measure the relative difference of each orbit option, an assumption is made that the spacecraft has body-fixed radiators covering the surface of the element. As the radiators are fixed to the element, they are not able to track the sun, so the worst case scenario assumes only half of the radiator area is available for heat dissipation while the remainder is experience full sun illumination.

Each orbit therefore needs to be assessed for the additional heat flux that must be dissipated in addition to the radiators own minimum radiative capability. Three of the orbits were run in a thermal modeling simulation to determine the maximum heat flux experienced. These values can be found

Table 5. Heat Flux & Radiator Sizing Comparison

Orbit / Location	Maximum Heat Flux (W/m^2)			Radiator Sizing [a,b]
	Radiative	Reflective	Total	
LLO	1545	231	1775	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]$Eqn : Q_{net} = Q_r - \alpha Q_s + Q_a - \epsilon Q_{IR}, \alpha = .2, \epsilon = .8, T_{rad} = 280K$

in Table 5. The LLO radiator sizing is not defined, as a radiator can not be sized large enough to handle the flux in LLO. In other words, the radiative maximum is so large, essentially equivalent to the solar flux, that other thermal systems would be required. In contrast the NRO orbit has some heat flux to dissipate, but even at 62 W/m^2 total at the peak, the relative area increase is only 19%. Of course, this is accounting for the worst case heat flux which is experienced in a short amount of time. A better indication would probably be average heat flux, which is likely less than 5 W/m^2. In addition, no increase in radiator sizing may be necessary for the vehicle if the radiator has some margin already, which is likely due to the benign deep space environment and the size of the habitat on which radiators will be applied. In short, the NRO orbit, along with the E-M L2 and DRO orbits have favorable thermal environments with little to no thermal sizing impact.

Other Considerations

There are several other factors that impact habitat design for a cis-lunar environment such as attitude control requirements and eclipse durations. A full analysis comparing these qualities has not yet been conducted. Qualitatively speaking, the larger orbits will have both fewer attitude correction maneuver requirements and less frequent eclipses. In fact, for the Earth-Moon L2 halo and the NRO no lunar eclipses occur and very infrequent Earth shadowing is present.
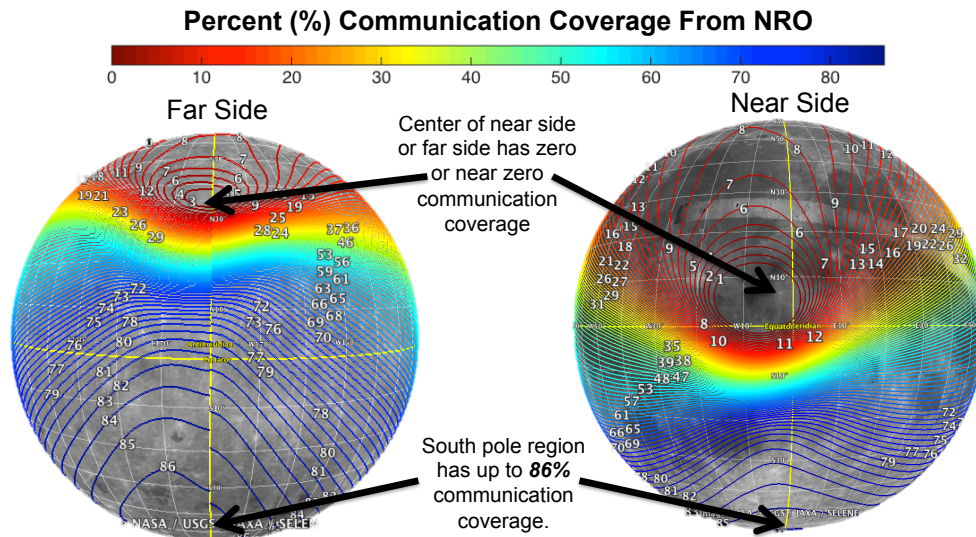

Figure 7. NRO Communication to Surface Coverage

Table 6. Staging Orbit Summary Comparison

Orbit Type	Earth Access (Orion)	Lunar Access (to Polar LLO)	Crewed Spacecraft		
			Stationkeeping	Communication	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, $\Delta T <1$ day	0 m/s for 3 years	Unknown	Unknown
Frozen Lunar Orbit	Marginally Feasible	$\Delta V = 808$ m/s, $\Delta T <1$ day	0 m/s	Frequent Occulation	Unknown
Elliptical Lunar Orbit (ELO)	Marginally Feasible	$\Delta V = 953$ m/s, $\Delta T <1$ day	>300 m/s	Frequent Occulation	Unknown
Near Rectilinear Orbit (NRO)	Feasible	$\Delta V = 730$ m/s, $\Delta T = .5$ day	<10 m/s per year	No Occulation	Radiators Sufficient
Earth-Moon L2 Halo	Feasible	$\Delta V = 800$ m/s, $\Delta T = 3$ days	<10 m/s per year	No Occulation	Radiators Sufficient
Distant Retrograde Orbit (DRO)	Feasible	$\Delta V = 830$ m/s, $\Delta T = 4$ days	0 m/s	Infrequent Occulation	Radiators Sufficient

Legend	Favorable	Marginal	Unfavorable

6. SUMMARY

Establishing a viable staging orbit in cis-lunar space is a key step in the human exploration journey beyond Low Earth Orbit. Maximizing flexibility both in terms of access from Earth, access to other destinations, and spacecraft design impacts are all important. The ability for the 7 types of staging orbits to meet these objectives is given in Table 6. While more work will be conducted to better understand the properties of cis-lunar orbits, the Near Rectilinear Orbit (NRO) appears to be the most favorable orbit to meet multiple, sometimes competing, constraints and requirements.

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BIOGRAPHY

Ryan Whitley *is currently the Deputy Systems Integration Manager in the Exploration Mission Planning Office at NASA Johnson Space Center. His current responsibilities include constructing future human exploration scenarios for Orion, SLS and other elements needed to send humans beyond Low Earth Orbit. He received his B.S. degree in Aerospace Engineering from Purdue University in 2004 and his M.S. in Aerospace Engineering from University of Texas at Austin in 2008.*

Roland Martinez *is the Systems Integration Manager in the Exploration Mission Planning Office at NASA JSC in Houston, TX. In this role he supports various NASA HQ Human Exploration and Operations Mission Directorate sponsored activities related to strategic analysis and development of future human spaceflight capabilities and missions. Current duties include: 1). Leading the Orion and SLS cross-program team for integrated end-to-end mission performance analysis in support of HQ's Exploration Systems Development Office and 2). Chairing the International Architecture Working Group (IAWG) for the International Space Exploration Coordination Group (ISECG), a multi-agency group responsible for the development of the Global Exploration Roadmap. He holds a B.S. in Aerospace Engineering from the University of Texas at Austin and a M.S. in Space Systems Engineering from Stevens Institute of Technology.*