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ASSESSMENT OF CISLUNAR STAGING ORBITS TO SUPPORT THE ARTEMIS III LUNAR SURFACE MISSION

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Since NASA's selection of an L2 9:2 lunar synodic resonant Near Rectilinear Halo Orbit (NRHO) as the baseline for the Gateway Program, the agency has worked to mature its understanding of this orbit and its use for the Artemis III, IV, and V missions. In parallel with these efforts, NASA has investigated alternative staging orbits to perform the Artemis III lunar surface landing mission and compared those options to the baseline NRHO. This paper evaluates a number of alternative orbits on their feasibility and favorability and compares them to the agency baseline NRHO.

INTRODUCTION

Through NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Agency Announcement (BAA) Appendix E and Appendix H, NASA has sought to accelerate the agency's return to the Moon.[1,2] Appendix E utilized a six-month period where 11 companies performed design analysis, technology maturation, and development of various Human Landing System (HLS) elements. Through these efforts, NASA determined that the most schedule effective

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approach was to award the integrated lander to a single vendor. In the fall of 2019, NASA released Appendix H, which was for HLS development and its first crewed lunar landing.[3] As NASA has progressed through these contracts, there has been ongoing discussing about developing a mission to the lunar surface leveraging an alternative orbit to NASA's current baseline of a southern 9:2 lunar synodic resonant L2 Near Rectilinear Halo Orbit (NRHO). This particular NRHO serves as the current baseline orbit for the Gateway Program and will serve as the location for the delivery, build up, and operation of Gateway. Through Gateway, NASA plans to conduct lunar surface missions, perform scientific research, and ultimately prepare for a crewed journey to Mars. This NRHO was selected because it possesses characteristics to effectively balance the agency's objectives.

In an effort to understand the trade space for lunar surface missions, NASA recently concluded a study to assess the viability of an alternative orbit to support lunar missions in 2024 and beyond. This study expanded beyond earlier assessments on cis-lunar orbits and their viability in support of lunar missions.[4] The current baseline NRHO is slightly different than the baseline NRHO used in the earlier assessment, yet is comparable, as it is in the same family and is similar in size. Additional information on the current baseline NRHO is summarized in a NASA white paper on the 15-year NRHO reference trajectory used for the Gateway Program.[5] This paper was also released with Appendix H as one of the white papers contained within the Attachment A reference library.

Within this study, roughly a dozen feasible alternative options were studied. Prior to the selection of Artemis III being a direct mission between Orion and HLS, Gateway was a part of the trade space. However, for all of the orbits analyzed in this paper, an Orion to HLS direct mission to the lunar surface was assumed. A detailed assessment was performed on the most favorable orbit, the Elliptical Polar Orbit with Coplanar Line of Apsides (EPO/CoLA) which was initially proposed by Min Qu out of NASA Langley Research Center's System Analysis and Concept Directorate. For all of the orbits assessed, the potential benefits and impacts were studied for both Orion and HLS.

Given the ongoing procurement of the HLS Option A contract as part of Appendix H, a government reference three-stage architecture was used for HLS in this study. The results of this study are presented and discussed within this paper.

MISSION PLANNING CONTEXT

While this investigation initially steps through the data generated in piece parts, it is critical to remember that NASA considers the mission holistically when assessing the integrated potential for a successful mission. It is often easy to focus on one component of the mission and potentially optimize to a particular parameter (often propellant). However, as the entire mission planning process comes together, all components of both the nominal mission and the numerous contingency scenarios need to be well understood and feasible to the extent possible. Throughout the mission maturation process, the decision often comes down to a trade between vehicle performance and mission risks. As a result, the intention of this paper is to show some piece parts of our evaluation up front with the final section focusing on the integration of an array of performance and mission risk components. As mentioned in the introduction, this assessment was performed with a focus on the execution of the Artemis III mission. While the driving parameters were tailored to the Artemis III mission, there was consideration to the direct applicability of all the work and understanding towards future Artemis missions.

PRELIMINARY ORBIT STUDY

The first part of the study focused on discovering alternative cis-lunar orbits beyond those investigated in the initial selection of Gateway's baseline NRHO. The cis-lunar orbit trade space was explored for orbits that fell within the Space Launch System (SLS) and Orion vehicle constraints. Through this effort, a number of potential orbits were assessed and broken into two categories: circular and elliptical orbits. For both the circular and elliptical orbits, Orion utilized a three-burn insertion and departure sequence.[6,7] This allows for the plane change burn to occur further away from the body, thereby decreasing the ΔV impact. A simplified modeled showcasing the benefits of a three-burn sequence can be seen in Figure 1.

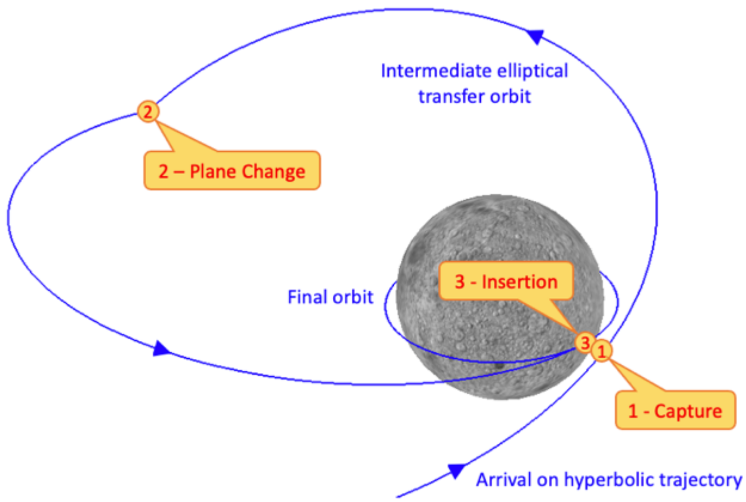

Figure 1: Simplified model showing a sample three-burn sequence.

The three-burn approach allowed for Orion to get lower into the Moon's gravity well and significantly improved mission flexibility, ultimately allowing for a much broader range of launch and arrival times as well as return opportunities. However, the three-burn sequence came at the cost of reducing the amount of time in the parking orbit to support rendezvousing with HLS and performing a surface mission.

Orbital characteristics and the mission duration breakdowns for the circular and elliptical orbits are summarized in Tables 1 and 2, respectively. Each table provides the orbital altitude, the orbit period, the length of the stay in the parking orbit, the total mission duration, and the relative cost in accessing the surface compared to the baseline NRHO. The fourth and sixth columns of the table are color coded to highlight the comparison with NRHO and the meaning of the fill color is different for each of the colored columns. The coloring of items in the parking orbit stay column represents the relative ability for that orbit to support a lunar surface mission. Orange represents likely not having enough time to perform the necessary preparation and get to the lunar surface within the allotted time in orbit. Purple represents a surface stay of a few days and blue represents a potentially longer surface stay than NRHO. The relative cost to access polar landing site represents the relative cost of accessing a polar landing site on the lunar surface compared to NRHO. For each of these, orange represents more performance compared to NRHO is required, red represents that it is likely infeasible given the significant plan change without major design changes, while blue represents more favorable.

Table 1: Circular orbits accessible within the SLS and Orion vehicle constraints.

Orbit	Orbit Altitude (km)	Orbit Period (hrs)	Parking Orbit Stay (days)	Total Mission Duration (days)	Relative Cost to Access Polar Landing Site
Circular Coplanar Posigrade	5000	13.78	**10.60**	**30.82**	**Substantial**
Circular Optimized Inclination Posigrade	4000	10.83	**8.81**	**32.86**	**Lower**
	5000	13.78	**8.34**	**32.86**	**Lower**
Circular Optimized Inclination Retrograde	8000	23.95	**2.26**	**20.47**	**Higher**
Circular Polar	5000	13.78	**8.34**	**32.87**	**Lower**
Baseline NRHO	~71000x~1500	~6.5 days	**~6.5 per rev**	~25-34	**--**

While the orbits are feasible within the vehicle performance capabilities, the mission durations and HLS performance costs in accessing the lunar south pole are comparable to the baseline NRHO. The coplanar orbit does not enable easier access to the lunar south pole and was not investigated further. For the two optimized inclination orbits, the inclination was optimized to minimize the Orion performance cost. The inclinations range from ~84-90 degrees for the posigrade orbits and approximately -102 degrees for the retrograde orbit. Given these inclinations, these orbits are highly sensitive to the Orion Lunar Orbit Insertion (LOI) and Trans-Earth Insertion (TEI) location given the precession of the orbit's Right Assentation of the Ascending Node (RAAN) at roughly 13 degrees per day. Given the precession, the added plane change cost quickly exceeds Orion's performance capability when departing on an off-nominal day.

Expanding on the circular orbits listed in Table 1, the elliptical orbits investigated provided more favorable characteristics. A breakdown of the viable elliptical orbits and their associated characteristics can be seen in Table 2. Like Table 1 above, the colored columns are the parking orbit column and the relative cost to access polar landing site column. The color coding for these indicates the relative value of the table cell to support a surface mission and a comparison to the NRHO accessibility cost respectively.

Table 2: Elliptical orbits accessible within the SLS and Orion vehicle constraints.

Orbit	Orbit Altitude (km)	Orbit Period (hrs)	Parking Orbit Stay (days)	Total Mission Duration (days)	Relative Cost to Access Polar Landing Site
Equatorial Coplanar Posigrade	4500x100	6.39	**7.00**	17.40	**Substantial**
	5500x100	7.62	**7.00**	17.40	**Substantial**
Equatorial Coplanar Retrograde	3500x100	5.24	**17.89**	30.84	**Substantial**
	9000x100	12.43	**9.85**	23.57	**Substantial**
Equatorial Fast Coplanar Retrograde	10000x100	13.94	**3.48**	9.25	**Substantial**
Inclined Fast Frozen Retrograde	10000x200	14.09	**3.47**	10.26	**Higher**
Polar with Perpendicular Line of Apsides	6500x100	8.91	**24.98**	37.13	**Lower**
	7500x100	10.27	**25.01**	37.13	**Lower**
Polar with Coplanar Line of Apsides	6500x100	8.91	**~5-14**	~18.5-27.5	**Lowest**
Baseline NRHO	~71000x~1500	~6.5 days	**~6.5 per rev**	~25-34	**--**

Similar to the circular orbits, the polar elliptical orbits introduce challenges that restrict insertion and departure opportunities due to precession of the orbit RAAN. While some of the coplanar orbits provide the ability to support a sufficient surface stay and overall mission duration, they significantly increase the propellant cost required to access a polar landing site. Similar to the polar and optimized inclination orbits, the equatorial orbits were not investigated further given the impacts to HLS performance.

In accessing all the circular and elliptical orbits listed in Table 1 and 2, the polar orbit with a Coplanar Line of Apsides was found to be the most promising of those discovered. Operating in this orbit offers the ability to design the mission to fall within the Orion 4-crew, 21-day vehicle lifetime, to account for unsuccessful docking, and to extend to the nominal mission once the two vehicles have successfully docked in the orbit. This orbit offers protection for a failed HLS and Orion docking, allowing Orion to return to Earth within the vehicle lifetime. After Orion docks with HLS, HLS provides consumables to extend Orion's lifetime, enabling missions beyond the 21-day limit. This feature is important, as Artemis III is planned to be the first docking mission for both Orion and HLS. The baseline NRHO also offers a similar protection in that there is an early NRHO departure opportunity a few days after Orion NRHO insertion in the event of a failed docking. In addition to these design features, this staging orbit retains access to polar landing sites, decreases the duration in getting between the lunar surface and Orion (for nominal and contingency scenarios), and typically offers departure opportunities throughout the parking orbit stay. Given these characteristics, the remainder of the paper focuses on the deeper dive study that was performed. Also, from this point forward, this alternative orbit is referred to as the EPO/CoLA.

ELLIPTICAL POLAR ORBIT WITH COPLANAR LINE OF APSIDES (EPO/COLA)

In further assessment of the EPO/CoLA, an effort was made to plan a mission around this staging orbit. This section summarizes the preliminary orbit maintenance scheme, which was developed to allow for multiple months of accessibility. This accessibility window is intended to cover the launch and aggregation of HLS, as well as up to three separate launch opportunities for Orion. After settling on the orbit maintenance scheme, long-term trajectory kernels were produced to assess SLS/Orion's ability to launch and Orion to rendezvous with HLS for a mission. Lastly, eclipses were investigated to identify any potential challenges or vehicle constraint violations with flying these missions.

Orbit Description

The EPO/CoLA classifies a particular orbit whose line of apsides is near-coplanar to, or lies near, the Earth-Moon orbital plane. Additionally, the orbit plane is perpendicular to the Earth-Moon orbital plane, giving it an inclination of near 90 degrees to preserve a ground track over the lunar South Pole region. As listed in Table 2, the EPO/CoLA has an apolune altitude of 6,500 km and a perilune altitude of 100 km, and the orbit is rendered in Figure 2. Depending on the landing site, the HLS can perform a single burn at perilune to transfer to a lower orbit or a two-burn sequence to target a slightly different inclined orbit. Comparisons of the orbit period, the respective time in the staging orbit, and the total mission duration for the EPO/CoLA and NASA's baseline NRHO are listed in Table 3.

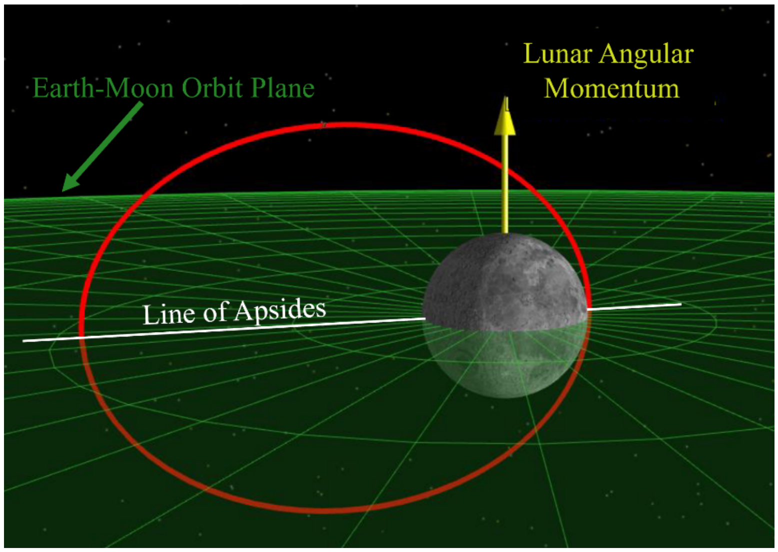

Figure 2: 6500 x 100 km EPO/CoLA reference orbit in the Moon-centered, inertial frame.

Table 3: Comparison of NASA's baseline NRHO orbit parameters to EPO/CoLA's parameters.

	Orbit Period	Time in Orbit	MET
Baseline NRHO	~6.5 days	~12-18 days	~25-34 days
Elliptical Polar Orbit (EPO) with CoLA (6500 x 100 km)	~9 hours	~7-10 days	~18.5-27.5 days

After discovering the orbit, a quick assessment was performed on the orbit's stability utilizing a 75x75 GRAIL model to represent the Moon's gravity field, along with point masses for the Earth and Sun. Without any maneuvers, the orbit lifetime prior to impacting the lunar surface is a tightly coupled with the initial argument of perilune (AoP) at insertion. In Figure 3, the orbit lifetime is plotted as a function of the initial AoP. Note that the color of the dots indicates how far the orbit was propagated backwards before impacting the lunar surface. Blue dots represent a reverse propagation time greater than 60 days, while red indicates that a reverse propagation results in the orbit impacting the Moon within 60 days. This behavior was leveraged to develop the orbit maintenance scheme to support a mission.

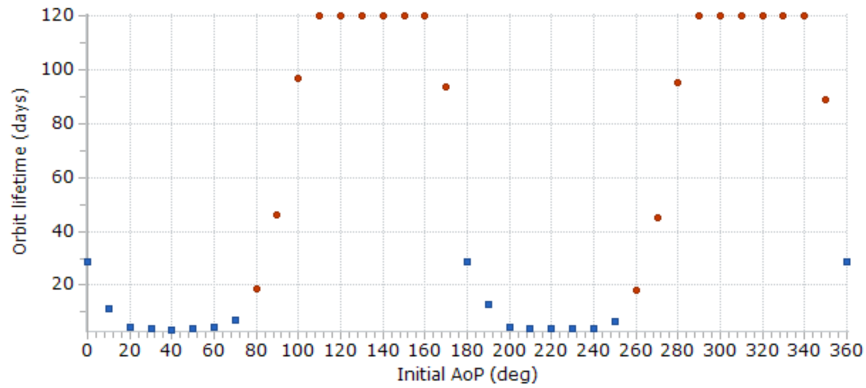

Figure 3: EPO/CoLA orbit lifetime as a function of the argument of perilune at insertion

Orbit Maintenance

Uncontrolled, the perilune altitude of the EPO/CoLA as a function of time follows an inverse parabola pattern. At the peak of the parabola, the line of apsides is parallel with the lunar orbit plane. In order to ensure flexibility for multiple surface mission opportunities and retain the ability for Orion to insert into and return from the EPO/CoLA, several orbit maintenance strategies were investigated. Most of the control strategies investigated involved perilune altitude control, apolune altitude control, argument of perilune control, or various combination of these three. Maneuvers in each of the orbit maintenance schemes were triggered after a predetermined elapsed duration or passing outside of acceptable limits for the altitude or the argument of perilune. Out of all the strategies investigated, a unique strategy that corrected all three of the above parameters over roughly three lunar sidereal periods was selected. This strategy leverages a pair of maneuvers to adjust the perilune altitude, apolune altitude, and argument of perilune to reset the inverse parabolic drift of the perilune altitude. The perilune altitude is plotted as a function of time in Figure 3. Note that after the maneuver pair is performed and resets the inverse parabolic cycle of perilune altitude.

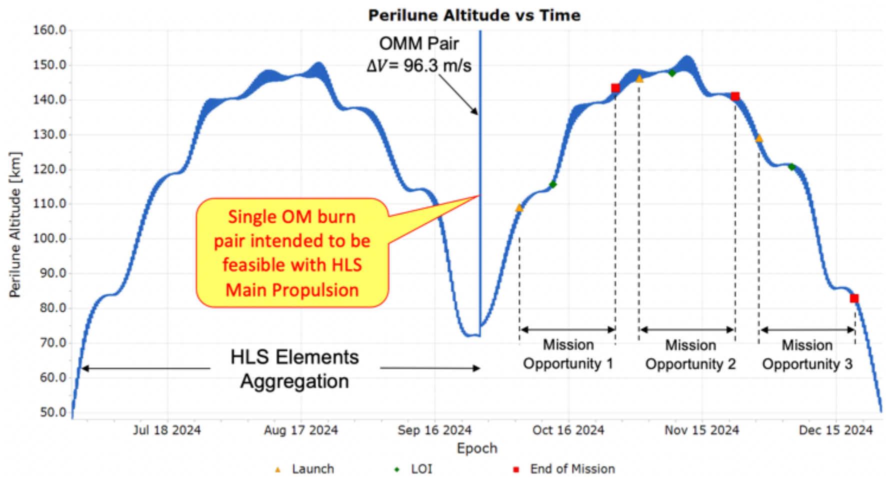

Figure 4. EPO/CoLA orbit maintenance strategy.

This solution was designed to offer roughly 6 months in lunar orbit: roughly 3 months for the aggregation of HLS and roughly 3 months for multiple SLS/Orion launch opportunities. The only pair of maneuvers occurs ~81.9 days after the insertion of the first piece of HLS. After this maneuver set, designed to return the orbital parameters to their initial state (primarily by resetting the argument of periapsis measured with respect to the Earth-Moon plane), the orbit will remain in a favorable orientation for Orion for another ~81.9 days. Note that this is intended to provide three Orion launch periods to rendezvous with HLS after the correction maneuvers are performed. Figure 4 shows the propagation of perilune altitude over time.

The single pair of orbital corrections, a total ΔV of ~100 m/s, was selected with the intent that they could be performed with the HLS main propulsion system. Utilizing this strategy minimizes the number of main engine startups and prevents growth of the RCS system in order to maintain a lower lunar orbit. Note that the protection for HLS aggregation was incorporated given the ongoing Option A selection process at the time.

Long-term Trajectory Kernels

With the selection of a particular orbital maintenance strategy, ephemeris files were developed that centered the second ~81.9 days around a trio of Orion mission opportunities. Two separate kernels were developed that spanned from June 27, 2024 to December 25, 2024 and September 11, 2024 and March 17, 2025. The first file was built around lunar surface mission opportunities in October, November, and December, while the second file was designed for opportunities in January, February, and March. Specifically, the RAAN of the EPO/CoLA orbit measured in the Earth-Moon plane was selected to support these specific mission opportunities. Throughout the remainder of the paper, these two kernels are referred to Kernel B and Kernel C, respectively.

Each of these files were used to perform scans to determine the number of viable launch opportunities for SLS/Orion and assess eclipsing while in the orbit. The relative launch periods and the time of year they correlate to can be seen in Table 4. These six periods were intentionally aligned with known NRHO launch periods in order to provide a fair comparison on the overall accessibility to each of the orbits. These labels will be used in place of the explicit launch periods throughout the remainder of the paper.

Table 4: Launch period labels and the corresponding launch periods within each of the two kernels.

Period Label	Launch Period	Kernel
Period 1 (P1)	October 2024	B
Period 2 (P2)	Early November 2024	B
Period 3 (P3)	Late November / Early December 2024	B
Period 4 (P4)	Late December 2024	C
Period 5 (P5)	January 2025	C
Period 6 (P6)	February 2025	C

Eclipsing in Orbit

Understanding the location, timing, and duration of eclipses is necessary in planning a mission through any orbit. Both the Orion and HLS vehicles are currently only capable of tolerating up to a specified eclipse duration determined by the spacecraft’s thermal and power capabilities. For the EPO/CoLA, an in-house toolset was utilized to find the number and duration of eclipses by both the Earth and the Moon for each of the kernels. The results of the eclipsing analysis are listed in Table 5.

Table 5. Lunar and Earth eclipses for the long-term trajectory kernels: Kernel B and Kernel C.

	Kernel B	**Kernel C**
Lunar Eclipses Near Apolune		
Dates:	9/11/24 to 10/4/24	9/17/24 to 10/13/24
Min:	12 min	14 min
Mean:	101 min	103 min
Max:	124 min	129 min
Lunar Eclipses Near Perilune		
Dates:	N/A	1/12/25 to 3/17/25
Min:	N/A	3 min
Mean:	N/A	24 min
Max:	N/A	31 min
Earth Eclipses		
Date:	9/18/24	3/14/25
Duration:	~2 hr 51 min (~1 hr 20 min of totality)	~4 hr 41 min (~2 hr 22 min of totality)

Kernel B encounters one Earth eclipse lasting ~2 hours and 51 minutes (~1 hour and 20 minutes of totality) on September 18, 2024. Additionally, from September 11 to October 4, 2024, the spacecraft trajectory encounters a lunar eclipse once per orbital revolution. These eclipses occur near the apolune of the orbit, resulting in durations that range from ~12 minutes to ~2 hours and 4 minutes. The trajectory from Kernel C encounters one Earth eclipse lasting ~4 hours and 41 minutes (~2 hours and 22 minutes of totality) on March 14, 2024. With regards to lunar eclipses, the trajectory generated for Kernel C encounters two sets of lunar eclipses. The first occurs from September 17 to October 13, 2024, with durations ranging from ~14 minutes to ~2 hours and 9 minutes. The second set occurs from January 12 to March 17, 2025, where the spacecraft experiences an eclipse once per revolution near perilune. These eclipses are typically shorter, ranging from ~3 to ~31 minutes, due to the relative speed near perilune.

MISSION ASSESSMENT

After developing a clearer understanding of the EPO/CoLA and building out the two separate roughly six-month kernels, trajectory scans were performed to access Orion's capability to get into and out of the selected EPO/CoLA over the second half of the kernel. In this effort, all of the nominal baseline trajectories that ultimately feed the scans were built in NASA's Copernicus

Spacecraft Trajectory Design and Optimization Tool and run through the Python extension interface built into it. As discussed above, for the nominal mission profile, Orion utilizes a three-burn sequence for both insertion into and departure from the lunar orbit. As mentioned in the Preliminary Orbit Study section, this allows Orion to maneuver low enough into the gravity well and significantly improve mission flexibility, while staying within the performance limitations.

The trajectories being designed to a destination EPO/CoLA kernel decouple the Orion outbound and return trajectory design process to assess Orion's ability to support an early departure or abort. In this way, ΔV totals for different combinations of outbound and return trajectories are compared against Orion's performance capabilities. While not a perfect representation – HLS and Orion dispersions and perturbations would need to be accounted for – this analysis provides a relatively accurate assessment of the ability of the vehicle's capability to support this mission. To examine the transfer trajectory trade space, potential orbit arrival and departure opportunities were considered at every revolution of the orbit near perilune. Each of these trajectories were also examined within the context of Orion's ability to abort to Earth in a contingency situation and what the relative return durations are for these abort scenarios.

In addition to Orion trajectories, analysis was also run to assess the difference between HLS leveraging the EPO/CoLA as compared to the baseline NRHO. Given the requirements of the NextSTEP BAA Appendix H requirements, HLS was sized to support operations in the NRHO. Thus, the propellant savings of using the EPO/CoLA were seen as potential offloads that could be recognized at launch for HLS. Additionally, HLS abort trajectories were investigated to assess the duration to return to Orion in the EPO/CoLA scenario as compared to the duration of HLS aborts to the NRHO scenario.

Performance Comparison

With Orion and HLS trajectories for missions through the NRHO and the EPO/CoLA, Table 7 summarizes a comparison between the two orbits from a variety of performance driving standpoints. The contents of Table 7 provide a comparison on the number of launch opportunities, the relative HLS performance impacts, the lunar surface stay duration, the cost of orbit maintenance, eclipse durations, and the relative Orion thermal concerns or impacts. For each of the comparisons, the cells in Table 7 in the EPO/CoLA row are color coated based on if the value is more or less favorable than the comparative value for the baseline NRHO. Blue filled cells correlate to better performance than the NRHO, while orange filled cells correlate to scoring worse than NRHO. All of the respective values for the NRHO have been pulled from NASA's internal Exploration Mission Analysis Cycle (EMAC) 3.0 in developing and maturing the Artemis III mission.

Table 6: Performance comparison between NASA's baseline NRHO and the EPO/CoLA.

	Launch Opportunities		HLS Performance Impacts	Surface Stay	Orbit Maintenance	Eclipses	Orion Thermal Impacts
Baseline NRHO	25 total opps		N/A	~5.6 days	< 5 m/s per year	Designed to avoid Earth eclipses – Moon eclipses always < 80 min	Lower concern due to perilune altitude and orientation
	P1 - 0	P2 - 1					
	P3 - 4	P4 - 8					
	P5 - 7	P6 - 5					
EPO / CoLA	20 total opps		~3-6% mass reduction (~1.3-2.5 t total)	~1.6-5 days	~96 m/s per ~180 days	Two Earth eclipses and seasonal Moon eclipses (see Table 3)	Potential to eliminated multiple launch periods
	P1 - 3	P2 - 2					
	P3 - 3	P4 - 4					
	P5 - 4	P6 - 4					

For launch opportunities (see Table 4 for period definitions), missions through the baseline NRHO and the EPO/CoLA provide a relatively comparable number of opportunities over the roughly six-month span. However, the distribution over those six launch periods is more consistent for the EPO/CoLA, around 3-4 opportunities per period. Given the larger variability in launch opportunities for the NRHO (ranging from 0-8 per period), some cells score as more favorable than the NRHO and others worse. Looking at the performance deltas for HLS showed mass savings of approximately 3-6% of the stack, equivalent to roughly 1.3-2.5 metric tons of propellant. All the performance savings occur for propellant slated for the main propulsion system as the vehicle still needs to be capable for comparable amounts of RCS throughout the mission. While the EPO/CoLA was designed to be perpendicular to the Earth-Moon orbital plane, the tilt of the Moon's axis with respect to the Earth-Moon plane also impacts HLS propellant savings. As the orbital plane aligns with the Moon's axis, these savings near the high end of the range seen in Table 7. As the alignment shifts away from the Moon's axis, the savings drop towards 3% due to the added cost associated with the plane change in getting to the South Pole. While the performance costs are lower for HLS getting between the lunar surface and orbit, there are increased costs associated with orbit maintenance. Implementing the scheme laid out earlier with a single pair of burns, HLS has to account for an additional ΔV of ~96 m/s.

In accessing the potential duration in the EPO/CoLA, preliminary timelines were generated to determine the HLS departure and return times in order to support the surface mission. These timelines accounted for the initial and return Orion and HLS Rendezvous, Proximity Operations, and Docking (RPOD), activities required to prepare for the lunar surface mission (vehicle checkouts, logistics transfers, suit checkouts, etc.), preparation in preparing for the return to Earth, as well as the transfers between the EPO/CoLA and the lunar surface. The same assumptions in preparation times when the vehicles are docked were used for both the NRHO and the EPO/CoLA. With these assumptions, the NRHO scenario surface durations are relatively consistent with an average duration around ~5.6 days. This consistency is driven by the departure and return locations to and from the lunar surface being relatively fixed. By comparison, the EPO/CoLA yields a shorter surface stay. Given the variability in the overall time spent in the EPO/CoLA, as seen in Table 3, the surface time can be maximized for the particular surface mission opportunity lunar orbit stay time. Utilizing this approach, the EPO/CoLA surface durations range from ~1.6-5 days. The lower end of this range presents some challenges in performing and completing more than one EVA and brings into question the value of surface durations that low.

Additionally, the EPO/CoLA faces potential eclipses that exceed current 90-minute capabilities. As discussed in the Eclipsing in Orbit section above, the orbit experiences seasonal variation, with the fall eclipses lasting up to ~2 hours in length. Also, the EPO/CoLA encounters periodic Earth eclipses which are longer in duration compared to the lunar eclipses. However, given that they occur more sparsely, a mission could potentially be designed within a timeframe to avoid them. The NRHO was tailored such that the synodic period of the orbit avoided any eclipses from Earth. While NRHO experiences periodic eclipses from the Moon, they always possess durations less than ~80 minutes and occur on approaching or departing perilune (driven by the particular NRHO rev). Additionally, the NRHO yields a thermal environment that typically resembles deep space for most of the orbit. As Orion approaches perilune, it will face an increased thermal load from lunar irradiance, but only remains at lower altitudes for a few hours. The EPO/CoLA presents a more difficult thermal environment than the NRHO, with much lower perilune altitudes and some perilune passages oriented towards the Sun direction. Preliminary Orion thermal analyses indicate performance challenges. While higher-fidelity analysis is required if an orbit like the EPO/CoLA was pursued, there is a real likelihood that there would be mission availability impacts with the elimination of multiple launch periods.

Mission Risk Comparison

In addition to the performance comparison above, the level of mission risk is directly compared. Of the concerns related to the NRHO, the duration of the crew return is longer than the return durations seen by the Apollo crew. To better understand the risk posed to the crew, the abort durations (to the staging orbit and Earth) were investigated. Additionally, the impact of a missed trans-Earth injection opportunity, the number of mandatory burns, and anticipated communications outages were compared to provide a broader assessment of the two orbits. Each of the values for these metrics are listed in Table 8.

Table 7: Comparison of the mission risk between NASA's baseline NRHO and the EPO/CoLA

	Abort Time (Surface to Orion w/o RPOD)	Abort Time (Orion to Earth)	Total Abort Time	Delay for Missed Earth Return Window	Mandatory Burns (# of HLS Burns Consistent)	Communication Outage to Orbit
Baseline NRHO	~0.5-2.5 days	~5-8 days ~1-2 day window per 6.5 day NRHO rev	~7-15 days	~4.5 days (Logistics enabled option)	OPF, NRI, RPODUs NRD, RPF (critical)	N/A
EPO / CoLA	~11-13 hours	~5-12 days Opps most revs (~9 hours) and potential blackouts up to ~2 days	~4-12 days	~14-18 days (Logistics enabled option?)	3 burn LOI and TEI Sequence (TEI-3 critical) RPODUs	Kernel comm cutous: Min: <1 min Mean ~34 min Max: ~2 hr 11 min

In assessing abort durations, only the region between the Orion staging orbit insertion and departure was examined. The return was broken into two parts: the surface to the staging orbit and the staging orbit to Earth. For the aborts back to the staging orbit, the durations were measured from ascent ignition through completion of the insertion into the staging orbit. Note that these values do not include RPOD and that they would need to be added in. For the NRHO, the abort durations range anywhere from ~0.5-2.5 days. The explicit value is determined by where Orion is in the NRHO at the time of the abort declaration as HLS needs to chase and catch up to Orion. For the EPO/CoLA, these values are more consistent at ~11-13 hours. Given the smaller orbit size, there are more favorable conditions to get back to Orion every ~9 hours. In aborting back to Earth, both the NRHO and EPO/CoLA offer comparable return durations with ranges of ~5-8 days and ~5-12 days, respectively. However, the NRHO only has departure opportunities within a ~1-2 day window around the optimal NRHO departure location (only one window per rev). Combining the abort duration from the surface, the corresponding orbit stay time, and the duration to abort to Earth yields total abort durations of ~7-15 days. A similar comparison for the EPO/CoLA yields total abort durations of ~4-12 days. While there is overlap in the durations, the EPO/CoLA does offer the opportunity to reduce the total abort duration to Earth. Note that missions through both orbits can be designed to allow for potential contingency returns within Orion's 21-day, 4-crew lifetime to protect for a failed docking scenario.

Should the crew miss the nominal departure opportunity to Earth, a situation could arise where Orion no longer has the performance to return to Earth and must loiter until the next departure opportunity. For the NRHO, the next departure window opens roughly 4.5 days later. This duration could be covered with additional logistics. However, for the EPO/CoLA, these durations range from ~14-18 days. The increased duration is driven by the fact that, for the EPO/CoLA orbit, the Moon must travel around its orbit until it returns to a location where alignment for Orion departure is satisfactory. For the number of mandatory burns, the three-burn sequence used to arrive at and depart from the EPO/CoLA added two additional maneuvers compared to a mission through the NRHO. Additionally, a mission through the EPO/CoLA results in periodic communication outages with Earth when Orion is behind the Moon. Depending on the time of year, these outages could last a little over two hours. In comparison, the NRHO was designed such that communication with Earth is constant. Thus, the NRHO proves slightly more favorable for all three of these categories.

CONCLUSION

While the NRHO remains NASA's baseline for the Artemis III mission and beyond, there are periodic questions around potential alternate staging orbits for the initial lunar surface mission. Building off previous analyses, this study explored the cis-lunar trade space further in an effort to uncover alternate potential orbits accessible by SLS/Orion that still enable performing a lunar surface mission. In this study, HLS was assumed to be the three-stage government reference architecture. The announcement of SpaceX and Starship winning the Option A contract in NASA's NextSTEP Appendix H did not occur until after the completion of this study.

In the preliminary phase of this study, a multitude of potential circular and elliptical orbits were discovered. Each of the discovered orbits were assessed on their ability to support a lunar surface mission, the overall mission duration compared to Orion's vehicle lifetime, and the relative cost compared to the NRHO in accessing a polar landing site. The EPO/CoLA proved to be the most promising out of those discovered and spurred a deeper dive assessment on the potential feasibility of flying the Artemis III mission through this orbit. Orbital maintenance schemes and long-term trajectory kernels were developed to access the launch availability over a six-month period and comparison various mission performance and risk components between the NRHO and the EPO/CoLA. Examining all of the factors for a viable Artemis III mission, the NRHO offers advantages in some areas, while the EPO/CoLA offers some in others. The NRHO offers slightly more launch availability, but the distribution across months fluctuates more than for the EPO/CoLA. Additionally, the NRHO enables longer surface stays, avoids concerning eclipses and communication outages, and provides a less challenging thermal environment for Orion. Comparatively, Orion's thermal challenges in the EPO/CoLA have the potential to further eliminate multiple launch periods. On the other hand, the EPO/CoLA's advantage lies in the reduced durations between the staging orbit and the lunar surface. This typically allows for lower return times to Earth in a contingency scenario. While there is some overlap in the distribution of total aborts times, the average is lower for the EPO/CoLA.

Combing these factors highlights the trade that often arises between vehicle performance and mission risks. While there are some favorable factors for the EPO/CoLA, wholistically examining the mission and the direct applicability to future missions reaffirms the selection of NASA's baseline NRHO. NASA continues to investigate and understand all the risks associated with flying a mission through the NRHO and works to address and mitigate them.

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