National Aeronautics and
Space Administration

White Paper

ARCHITECTURE CONCEPT REVIEW 2022

WHY NRHO: THE ARTEMIS ORBIT

INTRODUCTION

The programs and systems that today comprise Artemis have evolved from a series of agency initiatives. These systems, along with the Moon to Mars and Artemis drivers, have been determined through feasibility analyses and assessments of mission design and architecture conducted over many years. One of the key architectural features is the staging orbit from which Artemis and the programs, including Orion, Gateway, and the Human Landing System (HLS), will operate.

The key relevant drivers influencing the selection of the orbit can be summarized in three distinct areas:

- Cislunar Needs: Accessible and repeatable support for Lunar South Pole surface operations and exploration, and orbital capabilities to demonstrate Mars forward integrated missions and operations. These two fundamentals form the "where" and "why" drivers of the orbit selection in the architecture that are expanded on later in this paper.
- Vehicle Performance and Access: Capability and performance needs to access the cislunar orbit and return to Earth along with the transit to and from the lunar orbit to the South Pole to support the base Artemis goals.
- Environment and Operations: Integrated vehicle performance of both transportation and orbiting platform vehicles in the designated orbit environment when considering orbit maintenance, power, thermal, communications, and vehicle design for sustained operations in a relevant deep-space environment.

ORBIT ARCHITECTURE COMPARISON

In assessing Artemis architectures, multiple orbits have been considered and evaluated against the architectural goals and the performance needs. The following discussion provides a comparison for a selection of broad categories of orbits representative of the trade space. Actual orbits and variations assessed in studies number in the tens of orbits and alternatives. The significant orbits shown in this comparison include Low Lunar Orbit (LLO), an Elliptical Polar Orbit (EPO), Near-Rectilinear Halo Orbit (NRHO), an Earth-Moon L2 Halo, and Distant Retrograde Orbit (DRO). A diagram of the orbits is shown in Figure 1 to illustrate the relative size and orientation of each.

The relevant characteristics of each orbit are summarized at a high level as follows:

- LLO: approximately 100 km circular orbit with an inclination at or near 90 deg, orbit period of roughly 90 min
- EPO: polar oriented elliptical orbit with a Coplanar Line of Apsides, roughly 9 hr orbit period
- NRHO: an L2 halo orbit oriented approximately 90 deg out of the Earth-Moon

plane and perilune near the Lunar North Pole, roughly 6.5 day orbit period

- L2 Halo: the class of L2 halo orbits ranging from 0 to 60,000 km from L2 with orbit periods of 8- 14 days
- DRO: Earth-Moon coplanar with extremely high stability, roughly 12 day orbit period

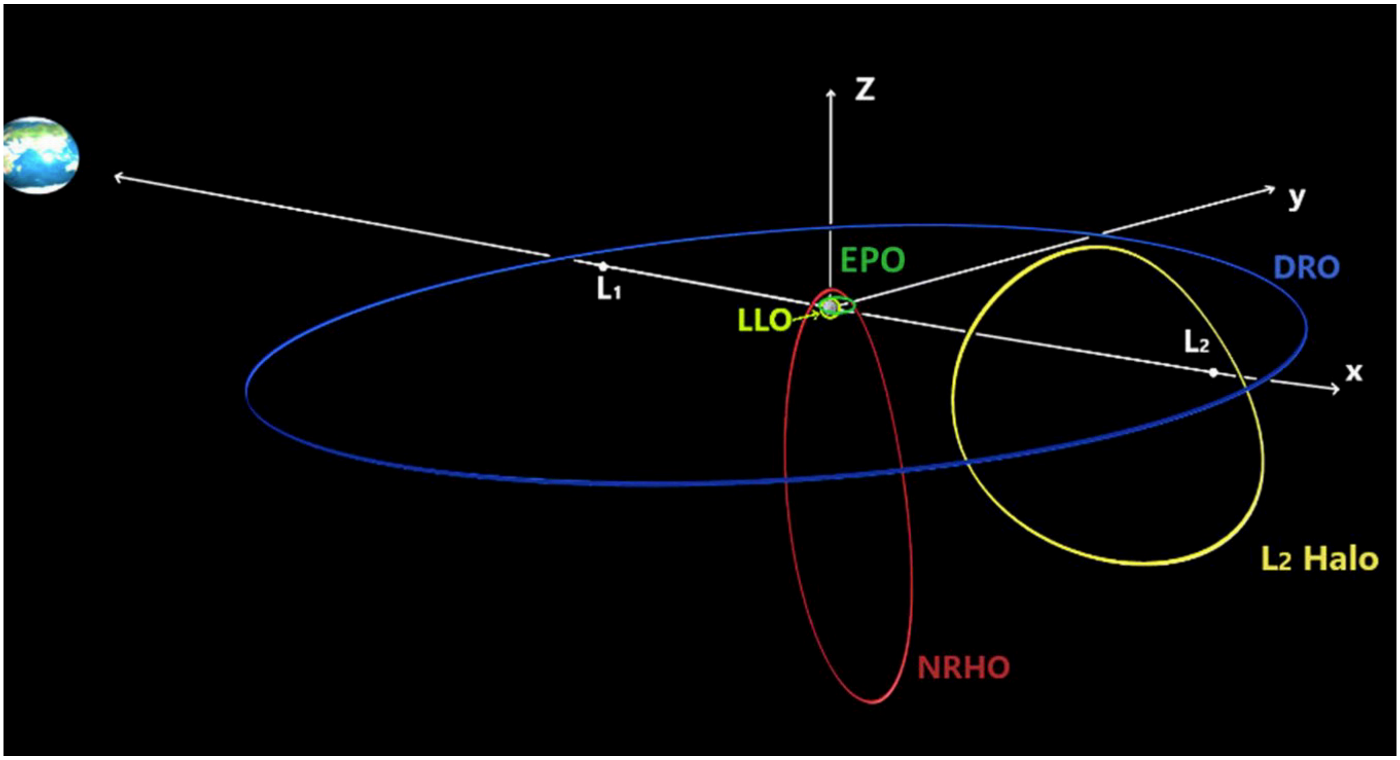


Figure 1. Alternative orbit architecture examples.

While the results of the analytical studies are not discussed in detail, an overall comparison of these orbits to the selected NRHO is provided at the end of the paper

ARCHITECTURE SELECTION: NEAR RECTILINEAR HALO ORBIT

One of the defining characteristics for the selection of the Artemis architectural orbit is the sustaining operation and extensibility to future missions. This need tends to motivate solutions that utilize halo orbits for the advantages of low-cost maintenance and stability over years of operation. Halo orbits generically are deviations about stable LaGrange points utilizing both Earth and Lunar gravity to maintain that stability. They can be thought of as resulting from an interaction between the gravitational pull of the two planetary bodies (Earth and Moon) and the Coriolis and motion of a spacecraft. These halo orbits exist in any 3-body system, e.g., an Earth-Moon-orbiting satellite system. Continuous "families" of both northern and southern halo orbits exist at each Lagrange point. The selected Artemis NRHO orbit is from one of the southern families of the L2 halo orbits and has a synodic resonance (revs to months) of 9:2. It is the lowest altitude NRHO with useful resonance and has an orbital period of 6.5 days (see Figure 2).

NRHO ASSESSMENT AND CHARACTERISTICS

For selection of this particular NRHO, several characteristics were examined. A brief discussion of the characteristics and how they manifest in the NRHO are provided.

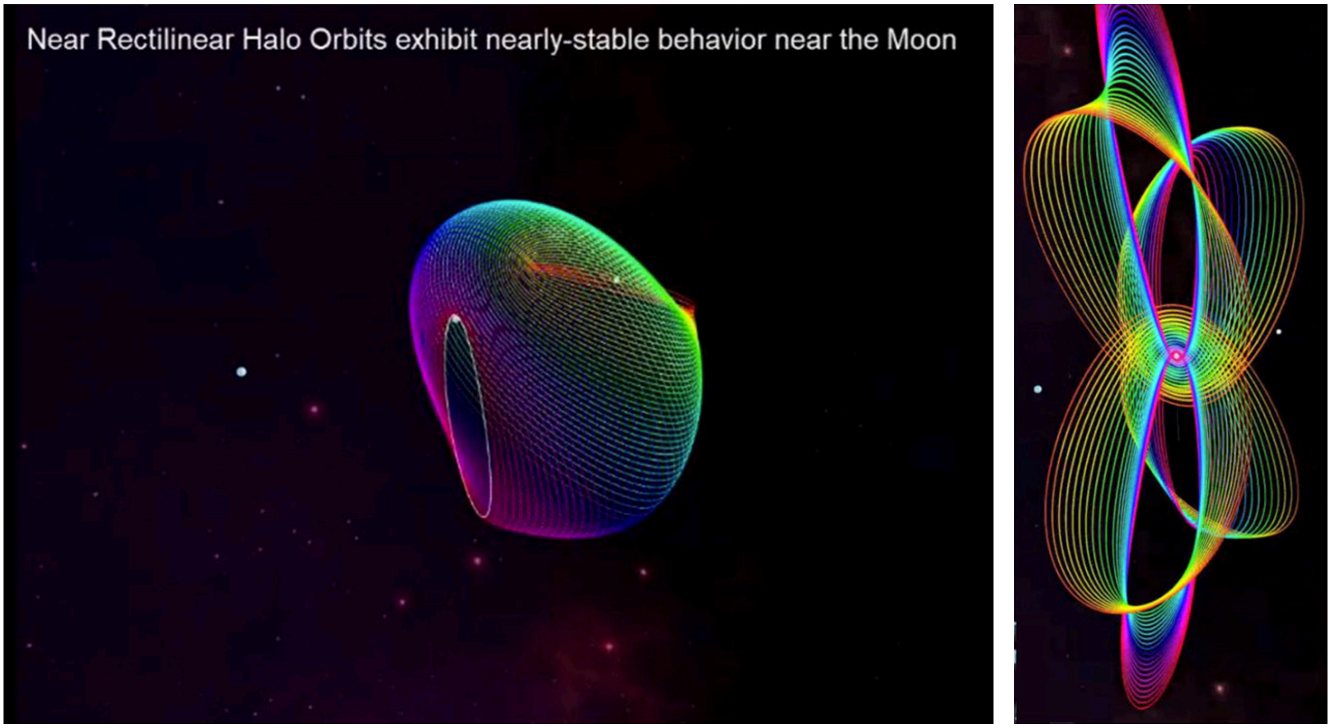
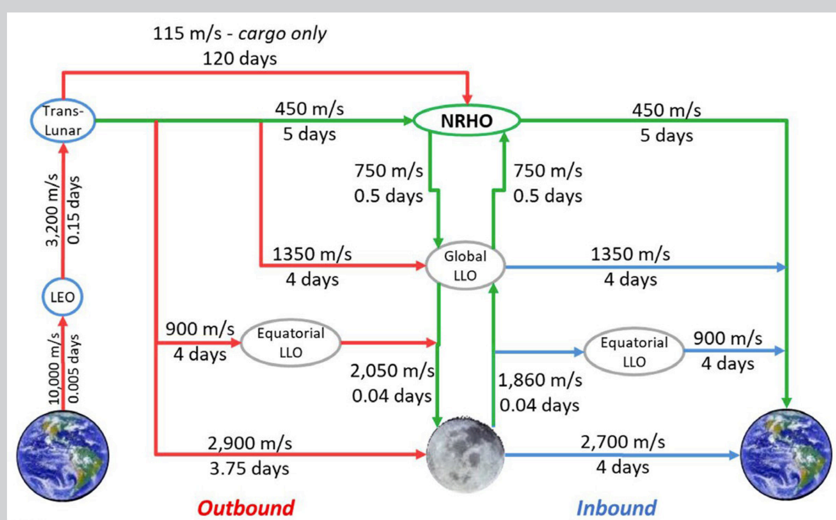


Figure 2. Illustration of the family of NRHOs; the Artemis – Gateway selected NRHO is highlighted in white on the left image.

Vehicle Access and Performance

The first rendezvous orbit characteristic assessed is the accessibility of both Earth transiting vehicles (Orion) and the lunar access (HLS) and performance costs of both for staging through that orbit. A simplified diagram of approximate performance cost and transit time to support Orion access while performing both Lunar Orbit Insertion (LOI) and Trans-Earth Injection (TEI) operations is shown in Figure 3. The access to the lunar South Pole is a significant driver in landing system designs. The ability to support sustained long-duration surface exploration must consider the performance costs of aborts and contingency operations. For the NRHO, the weekly repeatability and relative predictability of operations can be considered a significant advantage. As shown in the diagram, delta-velocity costs for NRHO and the Global LLO, which would be required to sustain extended operations and support contingency aborts, result in similar overall performance. Not shown in this diagram are orbit access costs for L2 Halo or DRO, which result in even higher orbit to surface costs that would be incurred on any associated lunar landing system with minimal benefit of reduced TLI to orbit cost.

Figure 3. This diagram illustrates the approximate performance costs and transit times of various access options for lunar and surface operations. Lunar South Pole access is a driver in the overall architectural selection. The chart can be read by following a 'path' outbound in red to selected orbits, following the lunar surface and return paths in blue, and adding delta-velocity costs for each segment to estimate the total architectural needs. The Artemis Architecture utilizes the green paths for crewed missions.



ORBIT MAINTENANCE AND SUPPORT FOR SOLAR ELECTRIC PROPULSION

Consideration of the long-term sustainability of the orbit results in the need to identify an orbit with limited orbit maintenance costs. This minimizes the demand for resupply of propellant and intensive maintenance operations. On-going cost of maintenance in the NRHO is on the order of 10 m/s per year, which is significantly less than lower lunar orbits given the instabilities caused by the Moon gravitational instabilities. Further, placement at higher gravity well staging supports the demonstration of large scale Solar Electric Propulsion (SEP) capabilities, which is a key objective for Mars forward technology developments. NRHO insertion is both achievable for unassisted SEP and supports future relocation and Mars forward demonstration missions. Shown in Figure 4 is a diagram of the relative orbit position of the NRHO and comparatively the LLO with respect to the gravity well around the moon and the strength of the local gravity environment. This illustrates the relative access and maintenance costs with respect to orbit locations.

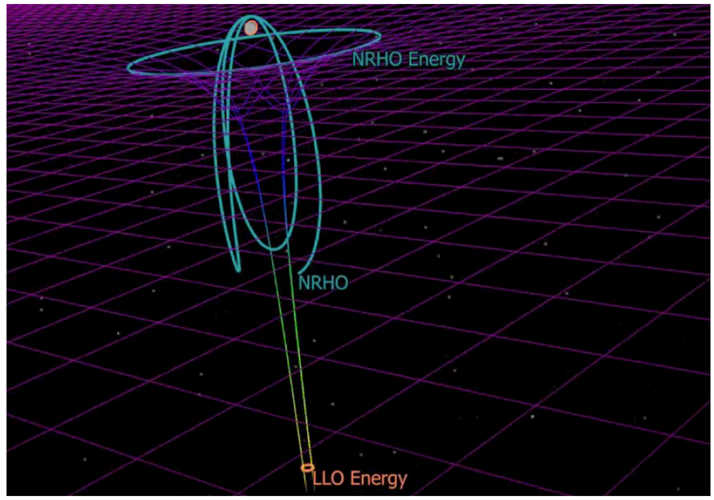
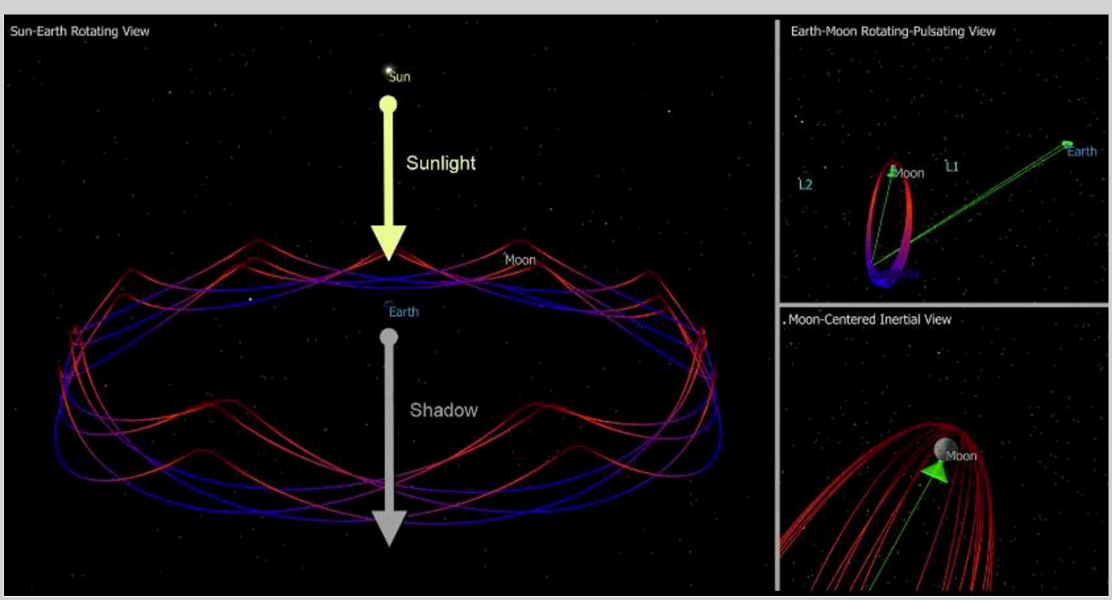


Figure 4. Illustration of the relative gravity around the Moon and the location of both NRHO and Low Lunar Orbits to the gravity well.

ENVIRONMENTAL PERFORMANCE CHARACTERISTICS

Sustainability and the achievability of a vehicle design that could support the long-term operations in the Artemis architecture also guided the exact phasing of the NRHO. At these distances, the shadow cast by the Earth can lead to multiple hour occlusions. The ability to support vehicle systems for power and survive the thermal environments posed by these durations were a primary consideration in the selection of the 9:2 resonance. This alignment of the orbit ensures a repeatable inertial orientation such that the vehicles will travel through apolune and below the Earth's shadow, avoiding long eclipses entirely as shown in Figure 5. This allows for vehicle friendly thermal environments and reduces the quantity or mass of power storage systems required. Additionally, an advantage of the NRHO is the continuous Earth facing orientation that allows for uninterrupted communication as necessary for mission operations. As a staging orbit, this provides any NRHO-based vehicles a significant line of sight and coverage of the lunar South Pole to support telerobotic operations, communication relay, science observation, and other activities for the majority of the orbit.

Figure 5. Three panel views for various reference frames and orientations of NRHO to the Earth and Moon such as Sun-Earth Rotating, Earth-Moon Rotating Pulsating, and Moon-Centered Inertial.



ARCHITECTURAL COMPARISON

A summary of the relative comparison of the key characteristics analyzed across the various orbit is in Table 1. These characteristics are normalized to NRHO to indicate the relative value as better or worse than NRHO. When taken as a whole, the NRHO was selected as the optimal Artemis architectural orbit to support the overall goals for sustained exploration, lunar South pole exploration, and achievable systems design. In particular, the NRHO provides the closest orbit to the Moon that balances both the long-duration orbital platform needs with the accessibility of the lunar South Pole.

CISLUNAR ORBITS		Crew Vehicle Access ΔV to/from Earth	Lunar Access (ΔV to/from Surface)	GATEWAY ORBIT FEATURES					
				Gateway Access ΔV	Orbit Maintenance	RPOD	Comm Cutouts	Power/ Thermal	Mars Forward
Low Lunar Orbit (LLO)	Equatorial	High	Infeasible/Short	High	Low/ Moderate	Circular Orbit	Moderate	Most Challenging	Minimal
	Polar	Highest Shorter Earth Return	Low/Short Duration	Moderate/ High					
Elliptical Polar Orbit with Coplanar Line of Apsides (CoLA)		Moderate/High	Moderate Short Duration	Moderate/ High	Moderate	Challenging	Moderate	Challenging	Minimal
Near Rectilinear Halo Orbit (NRHO)		Moderate	Moderate Medium Duration	Moderate	Minimal	Near Linear Dynamics	None	Deep Space Equivalent	Extensible
Earth-Moon L2 Halo		Low/Moderate Longer Earth Return	Moderate Long duration	Low/ Moderate	Minimal	Near Linear Dynamics	None	Deep Space Equivalent	Partial Extensibility
Distant Retrograde Orbit (DRO)		Low/Moderate Longer Earth Return	High Long duration	Low/ Moderate	N/A	Near Linear Dynamics	Infrequent	Deep Space Equivalent	Minimal

Table 1. Artemis Architectural Orbit Comparison

Table normalized for comparison:

Better		NRHO		Worse

SUMMARY AND CONCLUSION

A broad suite of assessments was conducted to determine the Artemis architectural orbit strategy. In particular, the driving considerations were identified through key exploration regions (lunar South Pole), leading to a sustainable and extensible architecture. These factors influenced the orbit selection to address how to support both long-term cislunar orbital platform capabilities and the accessibility between Earth, the staging orbit, and the Moon.

Analysis concluded that the NRHO was the optimal orbit to support the various and diverse goals of the Artemis campaign to support Moon to Mars development and operations needs. This orbit provides low-cost long-term stability, an environment achievable for vehicle designs, and the accessibility for transportation elements.

REFERENCES AND ADDITIONAL BACKGROUND

- R. Whitley and R. Martinez, "Options for Staging Orbits in Cislunar Space," IEEE Aerospace Conference 2015, Mar. 2015.
- D. C. Davis, et. al., "Orbit Maintenance and Navigation of Human Spacecraft at Cislunar Near Rectilinear Halo Orbits," 27th AAS/AIAA Space Flight Mechanics Meeting, Feb. 2017.
- N. Merancy, et. al., "Artemis Lunar Mission Availability & Design," 73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.

KEY TAKE-AWAYS

- NASA has studied numerous architectural options for staging orbits to support Artemis and future missions beyond the Moon; the Near-Rectilinear Halo Orbit provides a balanced approach to support the multiple objectives and goals of the architecture.
- NRHO is a highly stable orbit that offers repeatably and frequent access both to and from the Earth and Moon with ideal environmental characteristics to support vehicle power, thermal, and communications capabilities.

This white paper was developed as part of NASA's 2022 strategic analysis cycle to address topics of frequent discussion. For the latest white papers or other architectural documents related to human missions to the Moon and Mars, please visit: **www.nasa.gov/MoonToMarsArchitecture**.