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Analytical Techniques for Assessing Gateway and Other Spacecraft Antenna Line-of-Sight

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Abstract

NASA's Artemis program is committed to landing the next man and the first woman on the Moon by 2024. A critical piece of infrastructure for the mission, the Gateway will inaugurate a sustainable crewed presence beyond low-Earth orbit in cis-lunar space and serve as a staging point for a lunar landing system. The Near Rectilinear Halo Orbit of the Gateway offers numerous operational benefits in terms of its Earth access via the Orion Multipurpose Crew Vehicle, the degree of lunar visibility and surface access it provides, and favorable conditions for station-keeping. To minimize burns during station-keeping and conserve propellant, the Gateway will continually align itself to a solar pressure equilibrium attitude with the Sun; this is convenient for solar array orientation and power generation, but causes difficulties in terms of communication line-of-sight with the Earth, Moon, and visiting vehicles, which appear to be continually rotating about the Gateway's local frame. A fixed antenna on the Gateway is continually subject to a moving target and can find itself obstructed by the Gateway's own geometry frequently if not placed carefully. To understand the performance of either Earth-pointing or Moon-pointing antenna placements for a given Gateway geometry, a transient solar system simulation of the Gateway is used to step through orbital ephemeris data and determine the periods in which line-of-sight to a chosen target is achieved and lost. Antenna placements can be tested in the simulation and optimized to increase the average line-of-sight exposure to the target, while also minimizing the maximum duration cut-out in line-of-sight communication experienced; long durations without a successful communication link could pose threats to operations, safety, and mission success. It may be necessary to deviate from the Gateway's solar pressure equilibrium attitude for short periods of time in order to continue a successful line-of-sight link to a chosen target. Communication coverage spheres can offer insight into what these necessary attitude adjustments may be and are generated by using a 3D mesh of the Gateway and an implementation of the Möller-Trumbore intersection algorithm. This paper outlines the analytical techniques used to perform such antenna placements on the Gateway, offering examples of how line-of-sight strength can be enhanced with an understanding of the Gateway geometry and attitude constraints. These techniques have had direct impact on the writing of communication requirements for NASA and international partner-owned Gateway elements.

Keywords: Artemis, Gateway, Communication, NRHO, Möller-Trumbore

Acronyms/Abbreviations

CR3BP	Circular Restricted 3-Body Problem
DRO	Distant Retrograde Orbit
HALO	Habitation and Logistics Outpost
HGA	High-Gain Antenna
HLS	Human Landing System
LEO	Low-Earth Orbit
LLO	Low-Lunar Orbit
MPCV	Multi-Purpose Crew Vehicle
NRHO	Near Rectilinear Halo Orbit
PPE	Power and Propulsion Element
SLS	Space Launch System
SPEA	Solar Pressure Equilibrium Attitude
SRP	Solar Radiation Pressure
STK	Systems Tool Kit

1. Introduction

NASA's Artemis lunar exploration program is committed to landing the first woman and the next man on the Moon by 2024. Named after the goddess of the Moon in Greek mythology and the twin sister of Apollo, Artemis now personifies NASA's exploration campaign of returning to the Moon and demonstrating reusable engineering infrastructure that will allow NASA, alongside both its international and commercial partners, to sustain increasingly longer expeditions that become more Earth-independent with time. Cis-lunar space and the lunar surface will serve as NASA's next arena for proving the technologies needed to sustain ambitious expeditions to Mars and those further into deep space [1].

The Artemis program oversees the convergence of several major NASA projects, all of which play a key part in making Artemis lunar surface missions possible. The Space Launch System (SLS) will serve as the heavy-lift launch capability for the Orion Multi-Purpose Crew Vehicle (MPCV). Artemis I will be the first un-crewed test flight of these two systems, followed by Artemis II, which will take a crew of four astronauts into a lunar flyby with a free return trajectory back to Earth. Artemis III, planned for 2024, will use Orion to transport a crew of four to the Gateway – an orbital station to be assembled in a Near Rectilinear Halo Orbit (NRHO) around the Moon that will serve as a short-term habitation outpost for staging missions to the lunar surface, as well as a platform for conducting scientific research in cis-lunar space. A proposed, yet currently undeveloped, Human Landing System (HLS), rendered in Figure 1, would then transport crew members from the Gateway to the lunar surface; upon completion of the surface mission, the crew would return to the Gateway in the Ascent Element of the HLS before returning to Earth via Orion [2]. Gateway serves as the staging point for aggregating the necessary elements of the HLS architecture in order to perpetuate ongoing Artemis mission cycles to the lunar surface, and unlike ISS which is constantly manned, Gateway will only host crew approximately 30 days out of the year, pending the cadence of SLS and Orion launches [3].

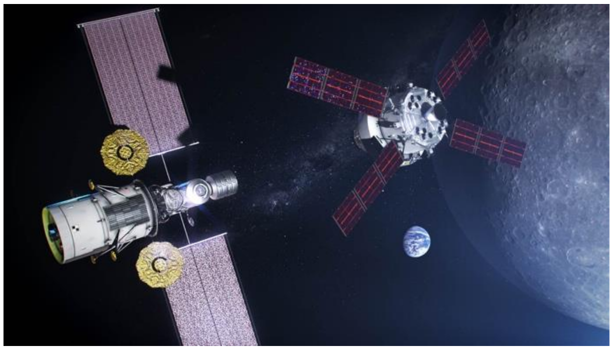

Fig. 1. Artist's rendition of Orion rendezvous with Gateway and HLS [1]

In the realm of maintaining communication with assets in space, systems in cis-lunar space pose a new level of complexity in a unique environment when compared to systems that have supported manned spaceflight for the past several decades in low-Earth orbit (LEO). With the Moon as the destination and ground operations and support still on Earth, these missions that concern multiple central-bodies pose additional complexities for maintaining a continuous communication line-of-sight from an asset like the Gateway to both Earth and assets on the lunar surface. As an integrated system of numerous elements and visiting vehicles, the Gateway will have to support many, sometimes competing, system requirements, whether they be in the realm of communication, attitude, thermal, or power among others. If not placed carefully, antennas on the Gateway run the risk of being frequently occulated by the Gateway's own geometry, limiting the long-term operational behavior of how Artemis missions are executed. An orbital simulation using a reference Gateway geometry and attitude constraints can be used to test for the line-of-sight capability of a chosen antenna location on Gateway. This paper then discusses the generation and use of communication coverage spheres by employing the computationally efficient Möller-Trumbore intersection algorithm to determine if attitude adjustments from a nominal flight attitude can rectify line-of-sight outages while still satisfying other system requirements on Gateway.

2. Gateway Communication in NRHO

The NRHO has served as the baseline orbit for Gateway mission design, driving many decisions in the concept of operations for the orbital outpost and staging point. While a very non-traditional orbit, its unique characteristics that complement Orion and Gateway demands, including communication line-of-sight to Earth and the poles of the Moon, made it the front-running contender for where NASA would insert its next crewed piece of orbital infrastructure [4]. Halo orbits are not defined by orbital elements or conic sections – their three-dimensional behavior is made possible by orbiting one of the L_1, L_2, or L_3 Lagrange points in the three-body problem in orbital mechanics. Continuous families of halo orbits exist beyond those immediately surrounding L_1 and L_2; NRHOs are halo orbits with bounded stability properties in that they have large amplitudes over either the north or south pole, exhibiting a nearly polar behavior [5].

2.1 Rationale for NRHO

After SLS inserts Orion into LEO, the second stage commits Orion to a trans-lunar injection burn to depart from Earth orbit and head for the Moon. From there, Orion's onboard propellant must perform all necessary orbital maneuvers for the mission; a fixed ΔV budget must allow for Orion to enter and leave the target orbit while performing all necessary corrections burns. Orion does not have sufficient ΔV to arrive at orbits that are continually very close to the lunar surface, such as Low-Lunar Orbits (LLOs) – only orbits such as NRHOs, halo orbits, and Distant Retrograde Orbits (DROs) are feasible from a propellant budget standpoint. Access to the lunar surface from an NRHO via HLS is also feasible in that it keeps the ΔV necessary to transit from NRHO to LLO affordable while keeping transit time to approximately half a day [6].

A southern NRHO also exhibits attractive characteristics for station-keeping and communication line-of-sight to Earth and the poles of the Moon. When simulated in a high-fidelity force model, all NRHOs are slightly unstable, but the orbit can be maintained by performing orbit maintenance maneuvers that cost mm/s of ΔV per revolution [5]. Because the NRHO is Earth-centric in that it is based on the family of L_2 halo orbits, the NRHO appears to rotate about the Moon at the same rate the Moon rotates about the Earth in an inertial frame. With an NRHO whose perilune distance is greater than the radius of the Moon itself, the entire NRHO will always be visible from Earth's vantage point. Halo orbits very close to L_2 would not exhibit the high orbital amplitudes of the NRHO and would be subject to occulations by the Moon.

2.2 Gateway Baseline NRHO

Gateway is intended to reside in a southern L_2 NRHO with a 9:2 synodic-resonance, meaning that Gateway completes roughly nine revolutions about the Moon for every 2 revolutions of the Moon about the Earth. The baseline orbit has a period of approximately 6.5 days with a perilune radius of about 3,200 km and apolune radius of about 70,000 km. A southern L_2 NRHO has the orbit's apolune location below the south pole of the Moon [4]. In order to conserve specific orbital energy, as Gateway tends towards the higher parts of its orbit, its velocity will decrease. This implies that the Gateway will spend a majority of its time with a view of the lunar south pole – the landing site of the Artemis III mission [2]. This chosen NRHO is far enough from the L_2 halo orbits such that the Moon poses no threat to blocking communication line-of-sight.

2.3 Attitude Constraints

In operating in cis-lunar space, while the impact of the residual atmosphere on a spacecraft's orbit may not be much of a concern like it is in LEO, there are other perturbations to consider that do have noticeable effects on the orbit stability in NRHO, such as solar radiation pressure (SRP) forces. SRP can be attributed to the exchange of momentum from electromagnetic radiation and a spacecraft's surface area, in this case, the Gateway's exposed surface area to the Sun. In order to avoid putting more load than necessary on the momentum management system of the Gateway, and thus conserving propellant, the Gateway is held in a Solar Pressure Equilibrium Attitude (SPEA) that attempts to keep an even distribution of SRP forces on the vehicle [4].

Orion has a tail-to-sun requirement stating that the direction out of the aft end of the vehicle needs to be aligned to the sun-pointing vector ±20° with only short allowable deviations if necessary; this is much of the reason why Orion docks axially to Gateway rather than radially so that as much geometric symmetry can be maintained in order to generate SPEA angles that are not far from the Gateway's direction of stack build-up [4,5]. In its reference attitude, the axis along Gateway's primary solar arrays hosted on the Power and Propulsion Element (PPE), are continually kept normal to the ecliptic plane, allowing the PPE arrays to orient towards the Sun with no cosine loss in exposure. Incorporating these attitude constraints on the Gateway begins to limit the line-of-sight capability of a chosen antenna position on the vehicle due to the fact that continually maintaining SPEA has the Earth constantly moving with respect to a fixed Gateway coordinate frame, now confronted with the possibility that line-of-sight may be obstructed by the Gateway geometry itself.

2.4 NRHO Ephemeris Model

The propagation of the orbit is governed by the Circular Restricted 3-Body Problem (CR3BP), generating a quasi-periodic ephemeris dataset in a high-fidelity force model. The reference ephemeris data has mm/s per revolution of station-keeping burns incorporated in order to maintain the periodicity of the NRHO [7]. Systems Tool Kit (STK) is used as the main simulation package for propagating the orbit and assessing antenna line-of-sight to different targets. The NASA ephemeris data for the NRHO can be translated to an Earth-Moon rotating frame and charted across several revolutions to visualize the orbit, as shown in Figure 2.

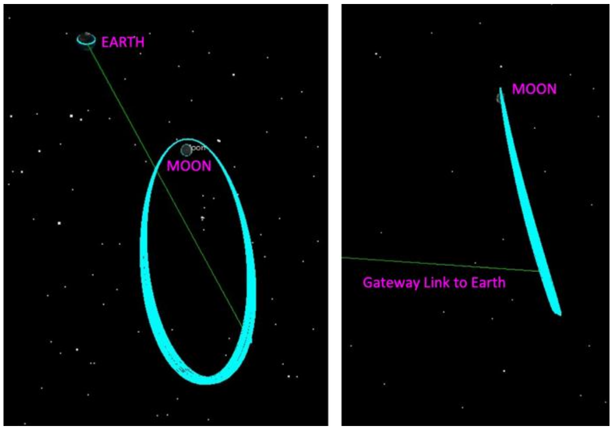

Fig. 2. NASA reference NRHO ephemeris orbit track visualized in Earth-Moon rotating frame

3. Transient Line-of-Sight Analysis Methodology

While the NRHO may appear quasi-periodic and close to fixed in the Earth-Moon rotating frame, the Sun appears to be continually circling the Earth-Moon system. Thus, in order to maintain SPEA and have one direction of the Gateway stack always sun-pointing, the Gateway appears to continually rotate about an axis normal to the ecliptic plane as it translates throughout NRHO. While the entirety of the baseline NRHO has line-of-sight to Earth, and a majority of the orbit has line-of-sight to the south pole of the Moon, it cannot be presumed that a line-of-sight access actually exists; due to the fact that Gateway must continually orient itself to maintain SPEA, a gimbaling antenna in a fixed location on Gateway can, and very likely will, be obstructed by the Gateway structure that appears to revolve about the fixed antenna head.

The optimality of antenna placements are assessed with two heuristics in this study. The NRHO ephemeris data for this simulation is truncated to be exactly one year in length, yielding over 50 revolutions in NRHO to assess. One heuristic is simply the percentage of the year in which line-of-sight to the chosen target, the Earth or lunar surface, is achieved. The access percentage can give us insight to the average performance of a chosen high-gain antenna (HGA) position, but it does not take into account what type of cut-out behavior in communication is observed. For instance, even though a chosen antenna location may be able to view the Earth 75% of the year, it is important to understand how the 25% gap in coverage is patterned throughout the rest of the year; if the cut-out in coverage happens all at once, this could cause significant limitations to Gateway operations during that time period. Full transient line-of-sight access can be charted for the entire ephemeris year, providing the exact times line-of-sight is acquired and lost. To get a quick understanding of the maximum threat to communication loss for an antenna placement, the second heuristic for highlighting placement optimality is the longest-duration communication cut-out experienced during the ephemeris year. Therefore, the intent is to find an antenna placement on the Gateway that maximizes year-long access percentage while minimizing the year's longest-duration cut-out.

3.1 Gateway Configuration and CAD Model

Numerous iterations of the approach outlined in this paper have been conducted by the Gateway program to assess the evolving configuration of the integrated stack. While specifics concerning the exact geometric footprint of the Gateway are yet to be fully realized, a basic reference Gateway model is used to demonstrate the analytical techniques outlined in this paper. The 3D CAD model geometry, shown in Figure 3, represents a generic outer mold line of the Gateway architecture for the Artemis III mission. The elements include the PPE, HLS, Orion, a Logistics Module, and a habitation module coined the Habitation and Logistics Outpost (HALO), that affords the crew space for on-orbit operations and translating from Orion to HLS. The configuration shown represents a maximum obstruction case regarding line-of-sight in Artemis III simply because all visiting vehicles are present. A body-fixed reference Gateway cartesian coordinate system is also shown in Figure 3 to describe HGA placements. The origin is centered at the forward hard-capture surface of the PPE, with the +X-axis pointing towards the direction of Gateway stack build-up, while the +Z-axis points parallel to the PPE solar array away from the Moon when the Gateway is at apolune, and the +Y-axis completes the right-handed coordinate frame.

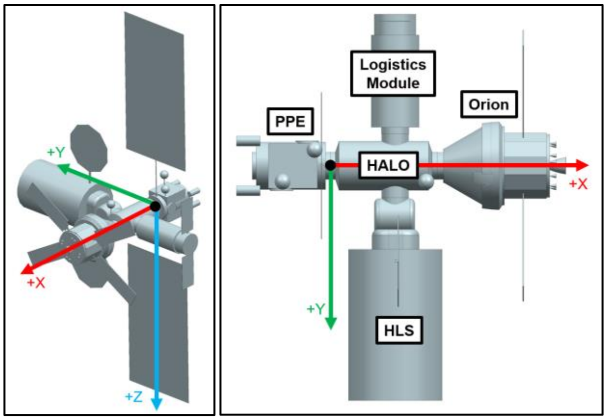

Fig. 3. Simplified Gateway reference model with body-fixed coordinate system shown

A sample set of antenna placements are shown on the PPE and HALO and are represented by 1-meter diameter spheres to protect for a 1-meter diameter dish geometry gimbaling in any orientation, as highlighted in Figure 4. As PPE will be the first element of the Gateway, it must be able to maintain communication with Earth on its own, demanding it support an Earth-pointing HGA. For the sake of this simplified analysis and demonstration of these analytical techniques, both the PPE and HALO host one lunar HGA each.

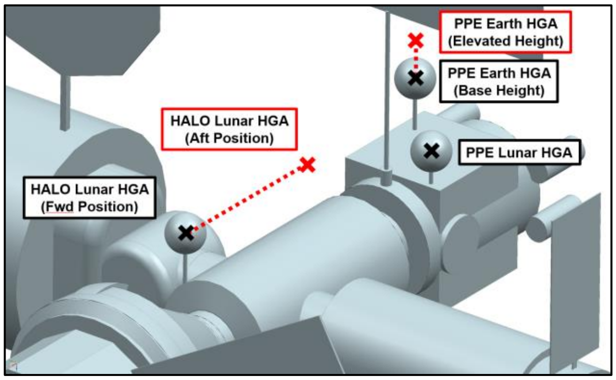

Fig. 4. Earth and lunar HGAs on PPE and HALO – locations in red mark additional test cases

3.2 Varying Antenna Positions to Understand Impact

In order to demonstrate the impacts of how placement of the antennas can significantly impact long-term communication performance on the Gateway, two different placements of the Earth HGA on PPE and the lunar HGA on HALO are show in Figure 4 and compared with corresponding cartesian positions in Table 1. In one case, the boom height of the Earth-pointing HGA on PPE is elevated off the stack by one meter in an attempt to understand how a higher vantage point off the Gateway structure can increase the percentage of the year-long line-of-sight to Earth. In the other case, the position of the lunar-pointing HGA on HALO is repositioned from the forward-end of the element to the aft-end in an attempt to mitigate the footprint of the largest obstruction for viewing the lunar surface – the PPE solar arrays.

Table 1. Antenna Positions Assessed with Respect to Body-Fixed Reference Gateway Coordinate System

	X (m)	Y (m)	Z (m)
Earth HGA Base Height	-3.0	1.0	-3.0
Earth HGA Elevated Height	-3.0	1.0	-4.0
HALO Lunar HGA (Fwd)	6.0	1.0	-2.5
HALO Lunar HGA (Aft)	2.0	1.0	-2.5
PPE Lunar HGA	-1.0	-1.0	-2.5

3.3 Combining Line-of-Sight from Multiple Antennas

With multiple antennas on Gateway that share the same intended target, such as the lunar HGA on PPE and the lunar HGA on HALO, the combined coverage of the antennas can be considered to simulate a case in which line-of-sight is lost on one antenna due to obstruction from the Gateway, which offers the alternate lunar-pointing antenna the opportunity to pick up the communication link where the previous left off. In this study, the combined coverage of the HALO lunar HGA in its aft position will be considered in tandem with the PPE lunar HGA to understand how the two coverages complement one another.

3.4 Generating Results through Propagation

The assessment of each antenna location requires a unique CAD model in that the geometry of the antenna being assessed must be removed from the model in order to prevent immediate line-of-sight blockage with the gimbaling envelope of the antenna of interest. Prior to running the simulation, mask files are generated from the vantage point of the antenna location; six perspective silhouette images are taken along all orthogonal directions of the body-fixed frame in order to provide a mask for blocking line-of-sight. Figure 5 depicts a snapshot in time of an Earth-pointing simulation scenario with the imported Gateway CAD model, and its line-of-sight access to Earth projected in green. A SPEA angle of 20° about the +Z-axis is assumed for the sake of analysis and would somewhat reflect the configuration shown due to the HLS's large geometric footprint biasing the SRP forces and pushing the SPEA angle demanded to the edge of the Orion tail-to-sun requirement. The simulation propagates by translating the Gateway to each ephemeris data point, aligning the Gateway such that it complies with the attitude constraints put forth. At each new ephemeris location and attitude, the simulation checks whether the fixed antenna on Gateway can see its intended target without being geometrically intercepted by the silhouette mask file. If the mask file intercepts the line drawn between the antenna and its target, line-of-sight is lost for that ephemeris point and the simulation propagates to the next point in time. Results are summarized in a transient fashion, parsing out periods in which line-of-sight is achieved and lost. The ephemeris data is automatically interpolated where necessary to deliver results that have precision on the order of one second.

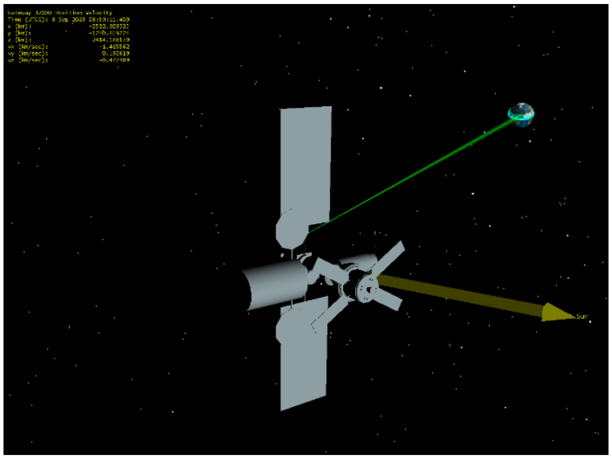

Fig. 5. Gateway model in simulation environment with link to Earth and SPEA offset

4. Communication Coverage Sphere

While it may be possible to optimize an antenna location in NRHO given a certain Gateway geometry, further attempts can be made to rectify any loss of communication experienced from an operational perspective. During more critical operations, such as crew-tended periods, in which a link to Earth or a specific lunar asset may be necessary, Gateway could adjust its attitude off SPEA to temporarily see past a line-of-sight obstruction. Orion's tail-to-sun requirement must still be considered but can be deviated from for short periods of time if necessary.

To visualize what possible pitch, roll, or yaw maneuvers may be necessary to see past the Gateway geometry in order to maintain a critical communication link, a communication coverage sphere can be generated by using the Gateway 3D CAD model and an efficient algorithm for ray tracing – the Möller-Trumbore intersection algorithm. The 3D CAD model is repackaged as a mesh, or a simplified outer mold line composed of triangles, so that the algorithm can check whether a ray intersects each triangular face of the model. The angular widths of the Gateway obstructions can then be understood from the antenna's perspective, offering insight into what type of demand on attitude adjustment may be necessary, and thus to what degree SPEA will be deviated from and propellant consumption increased.

4.1 Möller-Trumbore Intersection Algorithm

In a conventional ray-tracing process, the most intuitive way to test for ray intersection with a triangle is to compute where the ray intersects the plane in which the triangle lies on, and then determine whether that intersection point is within the edges of the triangle, defined by its three vertices. The Möller-Trumbore intersection algorithm is more efficient in that it foregoes the need to store intermediate data concerning the derivation of the plane that the triangle of concern lies on. Instead, the algorithm geometrically translates the triangle such that one of its vertices lies at the origin; the triangle is then transformed into a unit triangle that lies in one of the cartesian planes, with the transformed ray direction aligned to the orthogonal direction of the transformed triangle. After the translation and change of base of the ray origin, an easy check can be performed to determine whether the ray intersects the unit triangle. For large triangle meshes, such as those derived from high-fidelity models of the Gateway or other spacecraft, memory savings are significant, often ranging from about 25% to 50%, and computation time is reduced while providing results with no loss in precision [8]. While the demonstration 3D CAD model used for this study is very low-fidelity reference geometry, future high-fidelity models of the Gateway imply large amounts of computation for generating the communication coverage sphere. Employing the Möller-Trumbore intersection algorithm to perform the ray tracing for the coverage sphere generation helps prevent concerns over computer memory limitations.

4.2 Coverage Sphere Mesh

Relative to the simulation, the ray origin for line-of-sight would be coincident with the antenna location being assessed, and the ray direction defined in the direction of the target body. The triangles that would be transformed for checking against the ray would be the individual triangles of the mesh derived from the 3D CAD model. An example omni-directional coverage sphere is shown in Figure 6, taken about the Earth HGA position on PPE at its base height (refer to Table 1). While an omni-directional coverage shows all the possible communication cut-out geometries, it can be easier and faster to simplify the visualization and just perform the necessary ray tracing to the expected area the target is expected to be in given the Gateway's attitude constraints. Using Earth-viewing as an example, knowing the angular offsets between the Earth and Moon with respect to the ecliptic and the Moon and the Gateway at perilune and apolune in NRHO, a maximum elevation above and declination below the Gateway's fixed XY-plane can be determined, providing a window of viewing for where the Earth could possibly be seen with respect to the Gateway at any point in time; this orbital geometry for the Moon's inclination with respect to the ecliptic and the NRHO angular offsets from the Moon are depicted in Figure 7 [9]. The given orbital angles in Figure 7 imply that when flying according to assumed attitude constraints, the Gateway's view of the Earth will always be bound by approximately 16.7° above and 5.7° below the Gateway's local XY-plane.

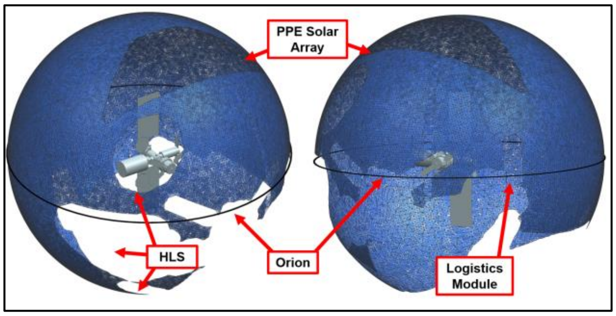

Fig. 6. Example communication coverage sphere centered at the base height Earth HGA on PPE – holes in coverage due to Gateway geometry are called out

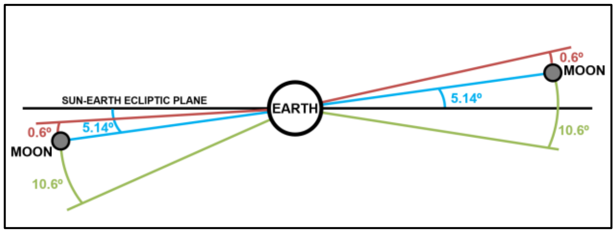

Fig. 7. Angular offsets from the ecliptic plane for the Moon and a spacecraft in NRHO perilune or apolune

5. Example Results for Analytical Techniques

5.1 Earth-Pointing Line-of-Sight

Full simulations of the ephemeris dataset incorporating the Gateway 3D CAD model were run for both Earth-pointing HGA positions given in Table 1. An example of a full year-long timeline of the line-of-sight performance for the Earth HGA at base height is shown in Figure 8. This behavior of line-of-sight cut-outs clumped together in a nearly monthly periodic fashion makes sense because the Earth HGA position being assessed lies on the aft-end of the Gateway, only being obstructed by possible geometry when the Earth is in the direction of the forward-end of the vehicle. Since the NRHO is Earth-centric in the Earth-Moon rotating frame, the Sun appears to rotate about the two-body system in accordance with the Moon's period about the Earth, which is roughly one month. Figure 9 depicts a truncated view of the timeline from Figure 8, pointing out the geometry obstructions that compose the line-of-sight cut-outs. The order of the geometry interference relates to how the Earth HGA continually needs to rotate counter-clockwise atop the Gateway in order to see the Earth while SPEA is maintained.

Concerning the two heuristics of interest, the annual access percentage and the maximum cut-out duration, Table 2 outlines the overall metrics derived from the PPE Earth HGA at its base position and its elevated height one meter higher. Simply raising the Earth HGA a meter higher off the PPE surface yields an almost 3% annual

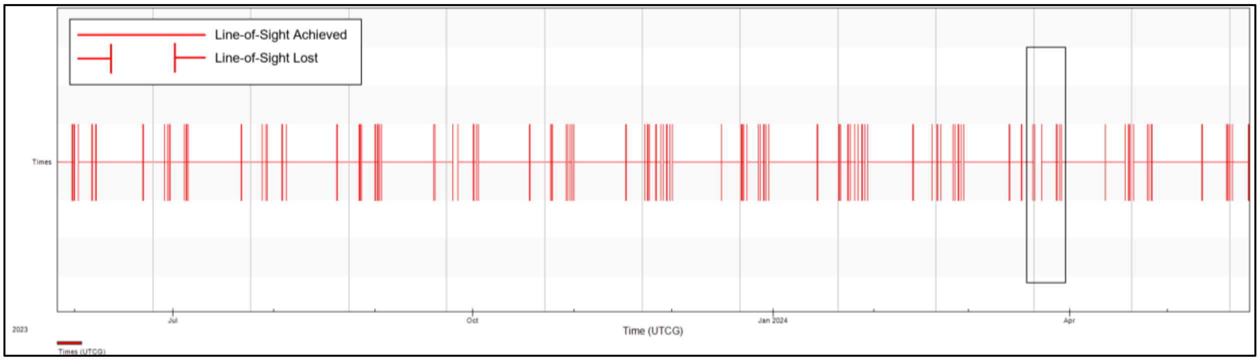

Fig. 8. Transient Earth-pointing line-of-sight communication results through one year of ephemeris data

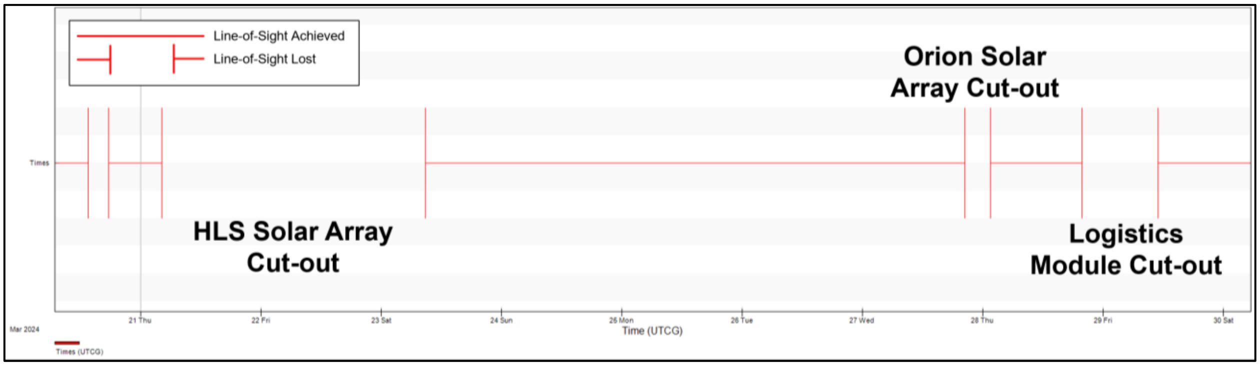

Fig. 9. Enlarged portion of boxed area from Figure 8 showing structural causes of line-of-sight loss

line-of-sight access increase; an increase in annual access percentage is expected since an elevated position allows the antenna to see over the stack for more visibility of the Earth.

Table 2. Earth HGA Line-of-Sight Results

	Annual Access	Maximum Cut-out Duration
Earth HGA Base Height	90.68%	2.17 days
Earth HGA Elevated Height	93.5%	2.12 days

5.2 Lunar-Pointing Line-of-Sight

The primary geometry interference to a lunar HGA on the Gateway that prioritizes south-pole lunar coverage is the PPE -Z solar array. Table 3 summarizes the results of moving the HALO lunar HGA from forward to aft, closer to the base of the PPE solar arrays. As expected, the coverage is enhanced when the antenna is closer to the PPE array, as the obstruction now appears to take up less of the visible sky from the antenna's vantage point. Peculiarly, the maximum cut-out duration for the HALO aft position is almost two days longer than that of the forward position; this is due to a period in which the line-of-sight stalls over the PPE array due to the net-dynamic behavior of the system.

To understand the possible combined coverage of two lunar HGAs, asking the question of when at least one of the antennas can see the lunar south-pole, a tandem coverage simulation was run for the PPE lunar HGA and the HALO lunar HGA aft location together; results are also given in Table 3. Figure 10 shows the line-of-sight timeline for the combined lunar antennas. The results show an almost perfectly periodic behavior with cut-outs only occurring when the Gateway is above the Moon's northern hemisphere and physically cannot see the south-pole; no further obstructions due to the Gateway geometry is shown because whenever one lunar HGA is blocked by the PPE -Z solar array, the other's view of the south-pole is not blocked on the other side of the array.

Table 3. Lunar HGA Line-of-Sight Results

	Annual Access	Maximum Cut-out Duration
HALO Lunar HGA (Fwd)	71.39%	2.47 days
HALO Lunar HGA (Aft)	88.11%	4.32 days
Combined Lunar PPE and HALO Aft HGAs	97.10%	0.42 days

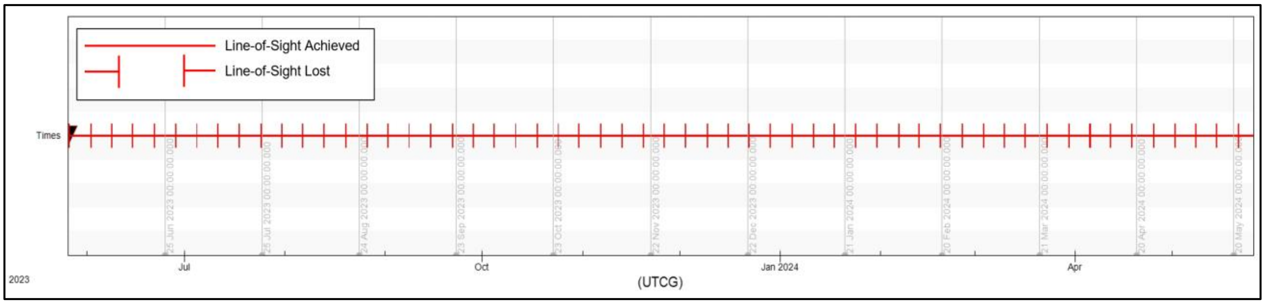

Fig. 10. Combined lunar line-of-sight for PPE and HALO (aft) HGA locations

5.3 Möller-Trumbore Communication Coverage Sphere

Figure 11 shows an example of a communication coverage sphere that only concerns Earth-pointing coverage, disregarding any areas and unnecessary computation for an Earth-pointing antenna. With an overlaid latitude and longitude sphere surrounding the coverage band, the necessary attitude adjustments to regain communication line-of-sight with the Earth during a cut-out can be quickly understood; more precise angular measurements can be taken directly off the model. A decision to deviate from SPEA incorporates numerous operational inputs, and depending on the dynamic behavior of the Gateway in a certain instance, the attitude deviation may make sense in order to maintain an ongoing communication link, as long as other system requirements, such as the Orion tail-to-sun requirement, are not violated.

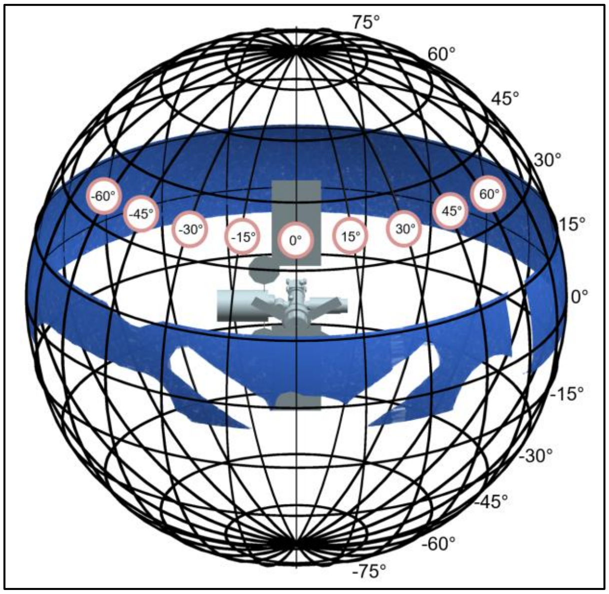

Fig. 11. Coverage Sphere just concerned with Earth

6. Possible Applications

From the standpoint of space communications, Earth-centric orbits like the NRHO are incredibly appealing in that their entire orbit track is continuously visible from the Earth's vantage point. If future infrastructure is to be developed in the vicinity of the Moon or other planets, they too will be subject to unique dynamic behaviors concerning spacecraft attitude and control so that propellant usage can be minimized while flying in a manner that still complies with other system-level requirements. Finding optimal antenna placements on these assets would be key if strong, consistent communication with dependable line-of-sight access is desired. As NASA and other space agencies pivot to focus on human presence beyond LEO, the demand for such integrated assessments are sure to be continually addressed in the future.

7. Conclusions

The cis-lunar space environment and NRHO of the Gateway poses a new set of challenges in the realm of maintaining communication with Earth and assets on the Moon. While one the greatest benefits of the NRHO is its continuous communication visibility to the Earth, maintaining SPEA for the Gateway implies antennas that need to continuously gimbal as the Gateway rotates in the Earth-Moon rotating frame. While the Gateway's own geometry will block line-of-sight to targets, steps can be taken to further optimize the placements of those antennas such that their viewing opportunities are maximized for the long-term life of the Gateway. Using communication coverage maps made possible by the Möller-Trumbore intersection algorithm, NASA can further understand the degree to which deviation from nominal flight attitude may be necessary to recover communication line-of-sight in critical operational instances.

References

[1] B. Dunbar, What is Artemis? 25 July 2019, https://www.nasa.gov/what-is-artemis, (accessed 25.09.19).
[2] NASA Moon to Mars, 19 May 2019, https://www.nasa.gov/what-is-artemis, (accessed 25.09.19).
[3] J. Crusan, Future Human Exploration Planning: Lunar Orbital Platform-Gateway and Science

Workshop Findings, 27 March 2018, https://www.nasa.gov/sites/default/files/atoms/files/20180327-crusan-nac-heoc-v8.pdf, (accessed 25.09.19).

[4] C. Newman, D. Davis, R. Whitley, J. Guinn, M. Ryne, Stationkeeping Orbit Determination and Attitude Control for Spacecraft in Near Rectilinear Halo Orbits, AAS 18-388, AAS/AIAA Astrodynamics Specialist Conference, Snowbird, Utah, 2018.

[5] S. Phillips, D. Davis, Cloud Computing Methods for Near Rectilinear Halo Orbit Trajectory Design, AAS 19-874, AAS/AIAA Astrodynamics Specialist Conference, Portland, Maine, 2019.

[6] R. Whitley, R. Martinez, Options for Staging Orbits in Cis-Lunar Space, JSC-CN-35647, IEEE Aerospace Conference, Big Sky, Montana, 2016.

[7] E. Zimovan, K. Howell, D. Davis, Near Rectilinear Halo Orbits and their Application in Cis-Lunar Space, IAA-AAS-DyCoSS3-125, 3rd IAA Conference on Dynamics and Controls of Spacecraft Systems, Rome, Italy, 2014.

[8] T. Möller, B. Trumbore, Fast Minimum Storage Ray/Triangle Intersection, Cornell University, Ithaca New York, 1996.

[9] K. Lang, The Cambridge Guide to the Solar System, second ed., Cambridge University Press, 2011.