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PRELIMINARY DESIGN OF THE LUNAR DATA NETWORK CONSTELLATION UNDER OPERATIONAL CONSIDERATIONS

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Intuitive Machines intends to launch and operate the first United States based Lunar Communication and Positioning, Navigation, and Timing constellation starting in 2026. This paper describes the design considerations for the constellation's orbits under the performance requirements for coverage and quality of service. The selected five satellite elliptical frozen lunar orbit constellation is presented together with a performance analysis. Additionally, the outbound Ballistic Lunar Transfer trajectory for the constellation's first satellite is presented together with a Delta-V budget assessment.

INTRODUCTION

Intuitive Machines (IM) intends to launch and operate the first United States based Lunar Communication and Positioning, Navigation, and Timing (PNT) constellation starting in 2026 as part of LunaNet. LunaNet is a multi-agency initiative to build an interoperable communication and PNT network capability for future users at the Moon. The LunaNet Interoperability Specification (LNIS) has been developed via coordination between NASA, ESA, and JAXA in order to enable international partners to contribute to building cooperative infrastructure to enable future human exploration of the Moon.[1,2] In September 2024 IM was awarded NASA's Near Space Network (NSN) Subcategory 2.2 "GEO to Cislunar Relay Services" contract. IM intends to fulfill the 2.2 contract with its Lunar Data Network (LDN), which, at full operational capability, will be comprised of ground segments and a lunar constellation. The LDN is planned to provide both Earth-based and in-situ communications and PNT services to users on and around the Moon and in Cislunar space.

LDN ORBITAL REQUIREMENTS

The LDN constellation is designed to meet the requirements detailed in NASA's Lunar Communications Relay and Navigation Systems (LCRNS) Lunar Relay Services Requirements Document

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Table 3-3 Minimum Constellation Sizing Requirements

	IOC-Alpha			IOC-Bravo				IOC-Charlie			EOC		
Service Type	Ka-band	S-band	AFS	Ka-band	S-band	AFS		Ka-band	S-band	AFS / LANS	Ka-band	S-band	AFS / LANS
Number of simultaneous links	1	1	1	1	1	2	3	2	2	4	2	2	5
Forward/ Return Link	R only	F+R	F only	F+R	F+R	F only	F only	F+R	F+R	F only	F+R	F+R	F only
Service Volume	SV1			SV1				SV2			SV3		SV3
Min. % Coverage of an Earth Day	70% TBR			75%	90%	70 %	40 %	75%	90%	40% (with max. spatial GDOP<6)	75%	95%	99%

Notes:
-Links from AFS need to provide geometric diversity; LANS is defined by a minimum of four links in view simultaneously from geometrically diverse relays.
-Per requirement LCRNS.3.0030, links for AFS will be ubiquitous for each relay.
-Minimum percent coverage of an Earth Day throughout an active Artemis campaign.

Figure 1: Table 3-3 from NASA's LCRNS SRD[3] with IOC-C performance highlighted

(SRD).[3] Primarily, the constellation design fulfills the Initial Operating Capability Charlie (IOC-C) which defines Service Volume II (SV2) in a region centered at the Lunar South Pole (LSP). SV2 includes the surface areas south of -75 degrees latitude and up to an altitude of 200 km. This SV is meant to support crewed and robotic landers operating in the LSP region, as well as polar low lunar orbit missions and landing missions while they descend/ascend to/from the surface (when those are in the SV). For IOC-C the SRD requires LDN to provide communications and PNT services to SV2 as described below. The assumption is that these services can only be provided by an orbiting satellite with Line-of-Sight (LOS) to assets in SV2. The communication services include S-band and Ka-band two-way relay to landers and orbiters in SV2. The PNT services include two-way ranging and Doppler radiometric tracking via communication links as well as one-way Augmented Forward Signals (AFSs) that provide pseudorange and Doppler measurements together with time transfer and other data. When provided from multiple orbiters the AFS and associated data establish the Lunar Augmented Navigation Service (LANS). LANS allows surface and orbiting users to compute their own state in-situ and in real-time, similarly to Global Navigation Satellite Systems (GNSS) users on and around Earth. While the two-way communication relay and radiometric tracking service can be provided by a single orbiting asset, the LANS service requires multiple assets to provide adequate geometry and coverage for users to derive real-time Position, Velocity and Time (PVT) estimates.

The relative geometry of the LANS orbiters is a factor in the quality of the user's state solution and can be quantified using Geometric Dilution Of Precision (GDOP). Due to user clock uncertainty the desired minimum number of AFS sources needed to provide a state solution is four, three for the 3-dimensional state and one for time knowledge. The GDOP calculation described in Langley et al. (1999)[4] accounts for a four signal sources and quantifies the geometric diversity of orbiter locations. Smaller GDOP values represent better geometry for state estimation.

Figure 1 presents NASA's LCRNS SRD[3] Table 3-3 (Minimum Constellation Sizing Requirements) with the IOC-C performance highlighted. The table details the number and type of simultaneous links needed, the required service volume (e.g. SV2 for IOC-C), and the minimum percent of an Earth day in which the service needs to be available. The communication relay and two-way radiometric tracking services required for IOC-C call for two simultaneous links, which can be provided from a single orbiting asset (with two or more antennas) or two orbiters. The Earth day percent coverage required for these services is 75% for Ka-band and 90% for S-band. For simplicity of results in this paper we will assume that the two simultaneous links will be provided from two separate orbiters. The AFS/LANS service requirement is 40% of an Earth day (or 9.6 out of 24 hours) at GDOP$<$6. The SRD's Table 3-3 also mentions that the minimum daily percent is required throughout an active Artemis campaign. This means these levels of services are required while Artemis components (crewed and robotic) are actively operating inside SV2. Table 3-3 is referenced by 17 requirements in the SRD and its primary purpose is to assist in characterizing the LDN constellation design to meet those requirements. One notable requirement is LCRNS.3.0130 which specifically calls for an orbiter geometry that provides GDOP$<$6 for the percent coverages detailed in Table 3-3.

Additionally, requirement LCRNS.3.0240 defines a duration and cadence of lunar surface Extra-Vehicular Activities (EVAs) to receive PNT services from the LDN. This requirement is not linked to Table 3-3 but calls for PNT services to allow two EVAs (per Earth day) with a maximum duration (nominal and contingency) of 5 hours. Even though the specific performance of the PNT services is not fully defined, it is the intent of the LDN constellation to provide LANS services below, or around, GDOP = 6 for these EVA windows. This level of GDOP should enable surface user state estimation position uncertainty around 10 meters.

In addition to the NASA LCRNS SRD, Intuitive Machines has imposed several design goals, such as minimizing the number of satellites while meeting LDN requirements, an orbit design that can be achieved using a lunar rideshare launch, and an orbit that allows some level of science observations of the lunar surface. Thus, the LDN constellation design core requirements can be boiled down to:

- For any point in SV2 have at least two orbiters in LOS for 90% of an Earth day (here we are taking the more stringent of the two-way communication and tracking requirements).
- For any point in SV2 have at least four orbiters in LOS and sufficient geometry to reach GDOP$<$6 for 40% of an Earth day.
- For any point on the SV2 surface have sufficient geometry to reach GDOP$\sim$6 (or below) for two continuous 5 hour windows per Earth day.
- Constellation with smallest possible number of satellites that can also provide surface observations.

It should be noted that prior to full deployment of the LDN constellation and fulfillment of the IOC-C performance requirements, the evolving LDN constellation is designed to meet the IOC-A and IOC-B requirements. However, the IOC-A and IOC-B analysis are not in this paper's scope. As described below, the evolving constellation's design consists of one and then three orbiters before the full five orbiter constellation deployment.

LDN CONSTELLATION DESIGN

Elliptical Lunar Frozen Orbits

As discussed in the previous section, the LDN constellation is required to provide services to a specific region of the Moon, the LSP region. The focus on that region calls for an orbit in which satellites spend the majority of their time with LOS to it. Recalling the desire to minimize the number of orbiters together with this temporal understanding, near polar (high inclination) elliptical orbits are obvious candidates for the LDN constellation. Specifically, Elliptical Lunar Frozen Orbits (ELFOs) answer those design needs while presenting high degree of stability over time. Folta and Quinn (2006)[5] derives the conditions to reach a frozen lunar orbit in the Earth-Moon rotating system. Specifically, for orbits with high inclinations the conditions are

$$\omega = 90^\circ, 270^\circ \qquad e = (1 - \frac{5}{3}\cos^2(i))^{1/2} \tag{1}$$

where ω is the Argument of Periapsis (AoP), e is the orbit eccentricity, and i is the orbit inclination. Note that, for this analysis these orbit elements are in the Earth-Moon rotating frame. For a southerly orientated constellation the selected AoP is $\omega = 90^\circ$, placing the perilune above the northern hemisphere and the apolune, where the satellites spend most of their time, above the southern hemisphere.

Figure 2 presents the orbit perilune and apolune magnitudes as a function of orbit inclination for ELFOs of various Semi-Major Axes (SMA, a) under the conditions in Equation 1. In addition, the perilune plot shows the corresponding orbit eccentricity for each inclination. Due to the inclination symmetry around polar orbits the range of inclinations spans the $\sim$40° lower limit defined in Folta and Quinn (2006)[5] and the polar 90° angle. Inclinations above 90° would show a mirror image of those in Figure 2. The figure also shows the Moon's radius, as well as altitudes of 500 and 20000 km which were defined as lower and higher bounds for the LDN operational regime. Although, these altitude limits were not defined as requirements, their definition stems from a desire to keep the perturbation environment somewhat consistent, reducing the affects of both the non-spherical gravity field for lower altitudes and the 3rd body perturbing forces for higher altitudes.

Observing Figure 2's perilune plot on the left shows that inclination angles above 70° result in orbits below 500 km altitude (or the lunar surface), orbits with inclinations below 50° show high perilunes that would reduce opportunities for scientific surface observations. The apolune plot shows orbits with SMAs much larger than 12000 km result in orbits above 20000 km altitude. Thus, the range or ELFOs to be examined for the LDN was defined as $i \in [50^\circ, 70^\circ]$ and $a \in [9000\ km, 13000\ km]$. Additionally, to reduce accumulated effects from the Earth's gravity, SMAs corresponding to lunar period resonances were selected for examination. This is done by using orbit periods that divide by the lunar period by an integer.

Constellation Design Process

Recalling the desire to minimize the number of satellites in the LDN constellation for IOC-C, the design process was set to start with the smallest number of satellites possible to meet the LCRNS SRD. That initial number selected was 5 satellites. If analysis showed that 5 satellites would not meet the requirements additional satellites would be considered.

With the inclination and SMA ranges defined above, a two step process was used to find and evaluate candidate constellations:

1. Short duration Keplerian propagation of candidate constellation geometries and examination of the resulting performance on a small set of surface points.

2. Use of a Particle Swarm Optimizer (PSO)[6] with a high fidelity propagator for multiple lunar periods to refine initial conditions for a stable constellation.

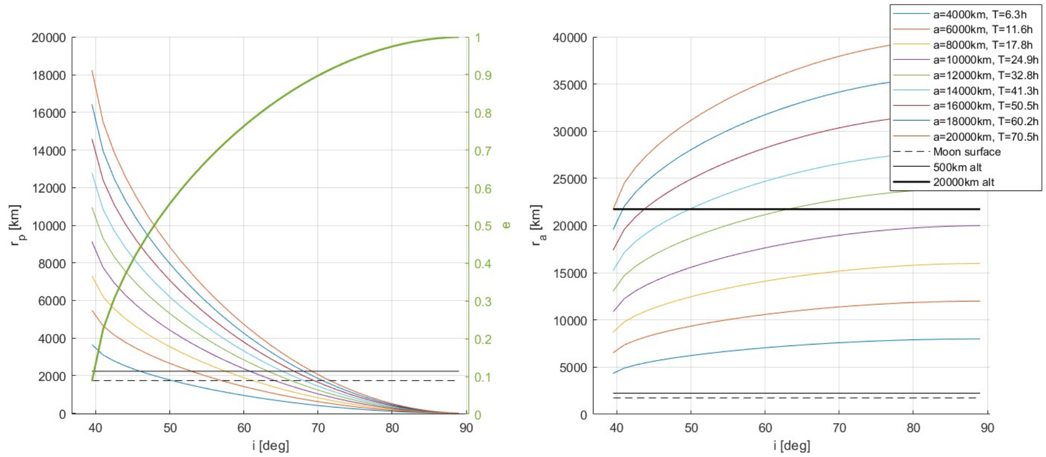

Figure 2: Perilune and apolune magnitudes vs inclination for ELFOs of various semi-major axes

Keplerian candidate search

By definition, this Keplerian search ignores all perturbing forces, including the Earth's gravity which enables the ELFO characteristics. The Moon's GM[7] for this segment was set to $\mu = 4.9 \times 10^3\ km^3/s^2$. Because of the low fidelity of this model a short duration propagation of 5 days is used to provide a necessary but not sufficient test for examined geometries. Additionally, the LSP is selected as a single point for examination of the constellation performance instead of multiple point throughout SV2, again, providing a necessary but not sufficient test. Even though the Earth's effects are ignored, when transferring the orbit element states to the PSO step, those are transferred in the Earth-Moon rotating frame. This step of the search examines the number of orbit planes as well as a range of SMAs, inclinations (and correlating eccentricities), and satellite orbit phasings.

Given that the AoP is predefined for a southerly ELFO, the only control for orbit plane orientation is the Right Ascension of the Ascending Node (RAAN, Ω), and thus a number of RAAN sets are used to define the number of planes examined. The RAAN angles are spaced at 180°, 120°, and 72° for two planes, three planes, and five planes, respectively. An anchor RAAN value is selected arbitrarily given that they will precess multiple revolutions throughout the constellation's lifetime due to the Earth's gravity.

As mentioned, the SMA values examined are set to span lunar period resonant orbits between 9000 and 13000 km, or 18:1 to 30:1 resonances. Inclinations are checked at 0.5° increments between 50° and 70°. And orbit phasings set various satellite spacing values between 45° and 72° in Mean Anomaly (MA, M) with an initial satellite anchor at $M = 0°$.

Table 1 presents a small subset of Keplerian search test cases. In addition to the inputs described above, the table shows the minimum percent of an Earth day (out of the 5 days propagated) in which the constellation geometry provides GDOP<6. This result correlates with requirement LCRNS.3.0130 described above. Additionally, the table shows the duration of the minimum 2nd longest continuous (Earth) daily window in which the constellation provides GDOP<6 (again, out of the 5 days propagated). This result is meant to show the constellation performance in relation requirement LCRNS.3.0240 described above. The reason to only look at the 2nd longest continuous window is because, by definition, the 1st longest window would be equal or exceed the 2nd in duration. Thus, examining the 2nd is sufficient to show adherence with the requirement.

The results presented in Table 1 show examples of constellations that both meet and fail the

	N_{Planes}	a $[km]$	res	i [°]	e	ΔM [°]	min % coverage	min 2^{nd} window [h]
i	3	12002.5	20:1	56.5	0.701	60	53.7	6.00
ii	3	10934.7	23:1	56.5	0.701	60	53.9	5.11
iii	2	12002.5	20:1	55.0	0.672	60	51.8	5.39
iv	3	10628.8	24:1	58.5	0.738	50	42.3	2.77
v	5	10934.7	23:1	54.5	0.661	60	32.4	1.89

Table 1: Select Keplerian search results

performance test. The PSO analysis presented in the next section found that even though some constellations met the Keplerian performance test, when transitioning to the high fidelity propagator their performance degraded below the LDN requirements.

It should be noted that combinations of orbit element sets, mostly different SMAs and inclinations, were checked and, of those examined, none were found to provide results sufficient to meet the requirements.

Particle swarm optimizer

Once a candidate constellation is found using the Keplerian search, its general geometry is transferred to a high fidelity propagation tool using each satellite's orbit element set. This high fidelity propagation is done using NASA's Copernicus software.[8,9] The propagation force model includes the Moon's gravity field up to degree and order 50 (using the GRAIL GRGM1200B model), the Earth's and Sun's point mass third body gravity (using the JPL-DE440 ephemeris), as well as a Solar Radiation Pressure (SRP) cannonball model. The SRP model accounts for Moon shadowing and assumes an area-to-mass ratio of 0.02 m^2/kg and reflectivity coefficient of 1.

Preliminary analysis of the constellation geometries as they are defined in the Keplerian search finds rapid degradation in performance after several days. Figure 3 presents the LSP daily percent coverage with GDOP$<$6 for constellation i in Table 1 (1-i). This degradation is primarily due to a mismatch between the osculating orbit elements and the mean orbit elements that account for all perturbing forces over an orbit period. Thus, simply using the Keplerian step elements as initial conditions leads to different mean elements. Primarily, the difference in average SMA, causes a difference in mean motion which results in the satellites phasing to change over time, degrading the geometric diversity needed for the LANS performance. Figure 4 shows the osculating and mean SMAs for constellation 1-i, a maximum difference of roughly 25 km in mean SMA can be seen. This mean SMA difference correlates to roughly a 6 minute difference in orbit period which causes the constellation to fall out of phase.

Due to the sensitivity to initial conditions, when moving to high-fidelity dynamical models, the initial conditions must be further refined to meet requirements. A PSO[6] is used to slightly perturb the orbit element states found by the Keplerian search, propagate the state for several lunar periods, and analyze the requirement performance. In addition to the high fidelity model and longer propagation the PSO's surface coverage performance test is also expanded from the Keplerian LSP-only test point to more than 400 test points distributed on the entire surface intersection of SV2. The test point placement assumes a spherical Moon with no topography, but includes a 5° elevation mask angle when accounting for satellites in view. The performance of each set of orbit elements is then graded using a cost function. Use of a PSO allows for this process to be parallelized for multiple

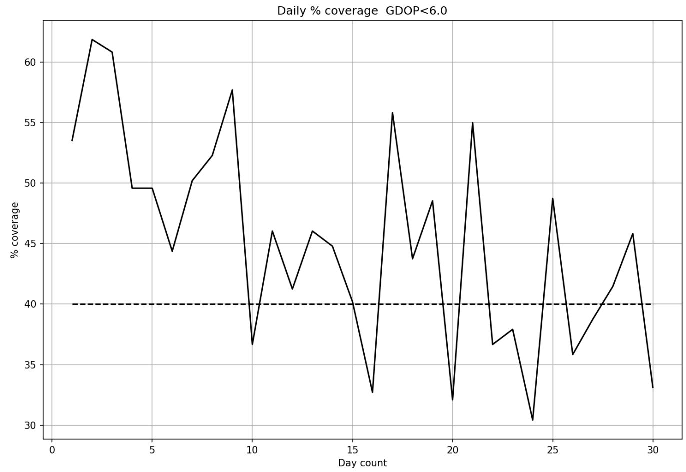

Figure 3: Percent of Earth day in which GDOP<6 for the LSP under constellation 1-i

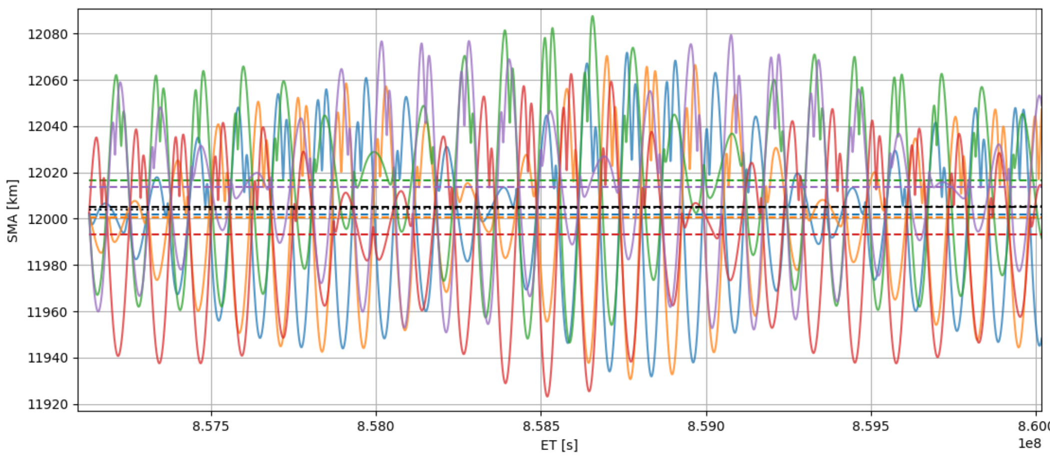

Figure 4: Osculating and mean SMAs for constellation 1-i

sets of perturbed initial conditions while benefiting from some information exchange between the various sets. To simplify the PSO cost function, only a small number of parameters are reflected in it. Those include the overall differences in mean SMA (across all satellites) and the number of days out of the propagated period in which 2nd longest EVA window is smaller than 5 hours. Minimizing the differences in mean SMA leads to longer term stability in orbit phasing. Selecting the 2nd longest window as a representative for all coverage performance is done with the understanding that two 5 hour window per day account for requirement LCRNS.3.0130 because these windows are 41.6% of an Earth day. Working to minimize instances when the 2nd window is less than 5 hours provides a cutoff line that does not try to affect window durations longer than 5 hours, thus reducing the chance of outliers skewing results. As results will show in the next segment, the two-way communication and tracking requirements are fully met under these conditions.

Various permutations of constellations 1-i, 1-ii, and 1-iii were processed through the PSO for a period of 60 days to find the best possible constellation initial conditions. The permutations primarily examined possible constellation inclination angles in granularity finer than 0.5°. The lower SMA constellation (1-ii) showed substantially reduced performance compared to the other two. Constellations 1-i and 1-iii showed similar performance with 1-i showing slightly fewer instances where the 2nd window is less than 5 hours. The next section will present the selected constellation that was found from the process described here.

Selected LDN Constellation

The selected LDN constellation initial state at epoch of March 1, 2027 00:01:09.2 UTC is presented in Tables 2 and 3 as sets of Keplerian orbit elements and Cartesian state vectors, respectively. The orbit elements presented are the full set of osculating elements together with the average SMA, inclination, and eccentricity, as well as calculated averaged altitudes of perilune and apolune (marked using upper bar). These elements are the Moon centered in the Earth-Moon rotating frame. The Cartesian states are Moon centered International Celestial Reference Frame (ICRF). This constellation average SMA is roughly 12000 km, which corresponds to a 32.8 hour orbit period and a 20:1 lunar resonance orbit. Figure 5 shows the osculating and mean SMAs for the LDN constellation. When comparing the figure to Figure 4, the clustering of mean SMA values in the LDN constellation is noticeable, with mean SMA varying up to 2 km vs the 25 km seen for the Keplerian step solution.

	$a\ [km]$	$i\ [°]$	e	$\Omega\ [°]$	$\omega\ [°]$	$M\ [°]$	$\bar{a}\ [km]$	$\bar{i}\ [°]$	$\bar{e}$	$\bar{h}_p\ [km]$	$\bar{h}_a\ [km]$
LDN-1	12002.3	56.24	0.678	40.10	90.03	0.62	12002.5	56.89	0.672	2200.8	18332.2
LDN-2	12005.1	56.14	0.706	41.18	89.64	183.51	12003.9	57.07	0.683	2069.3	18466.6
LDN-3	11988.1	56.71	0.695	161.41	90.32	60.37	12004.1	56.40	0.702	1841.2	18695.0
LDN-4	12013.8	55.84	0.683	160.82	90.69	236.41	12004.5	55.83	0.688	2009.4	18527.6
LDN-5	11997.3	57.24	0.698	279.93	89.84	114.83	12003.7	57.53	0.701	1853.1	18682.3

Table 2: LDN constellation orbit element sets, Earth-Moon rotating frame, at Epoch March 1, 2027 00:01:09.2 UTC

	$r_x\ [km]$	$r_y\ [km]$	$r_z\ [km]$	$v_x\ [km/s]$	$v_y\ [km/s]$	$v_z\ [km/s]$
LDN-1	-498.38	406.4	3574.46	-1.5057	0.0321	-0.1559
LDN-2	1399.33	-2297.64	-20301.43	0.2640	-0.0014	0.0279
LDN-3	9755.11	-11.22	-9165.94	0.2545	0.4087	-0.3031
LDN-4	6942.65	15259.40	-8474.55	-0.2483	0.0439	0.2244
LDN-5	-4569.24	15449.53	-8975.25	-0.2257	-0.0017	-0.2686

Table 3: LDN constellation Cartesian state, ICRF, at Epoch March 1, 2027 00:01:09.2 UTC

Figure 6 presents the 60 day propagation in both the rotating (left) and inertial (right) frames. Given that the constellation is symmetrical with respect to the Earth-Moon rotating system, the inertial view appears skewed with respect to the ICRF XY plane. Additionally, due to the Moon's 6.68° obliquity[7] the constellation's symmetry with respect to the rotating frame is also skewed with respect to the LSP.

Figure 7 presents the number of satellites in view and GDOP values for 3 days arbitrarily selected from the propagated period at a number of points of interest in the LSP region. These points include

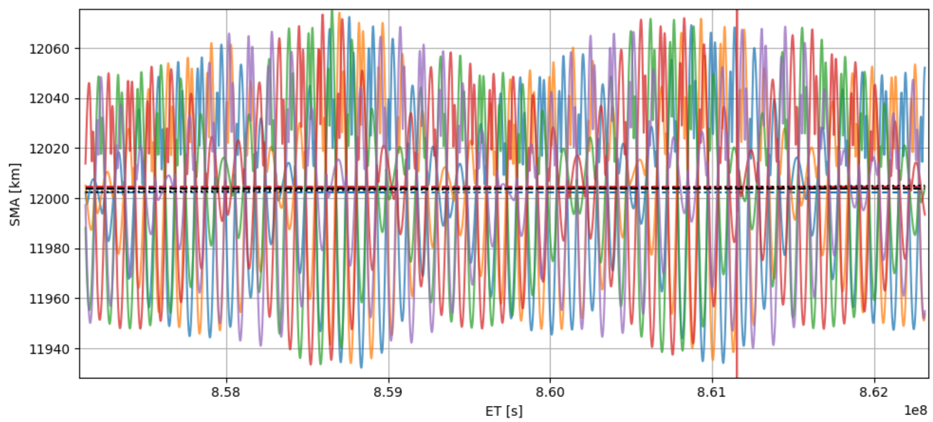

Figure 5: Osculating and mean SMAs for the LDN constellation

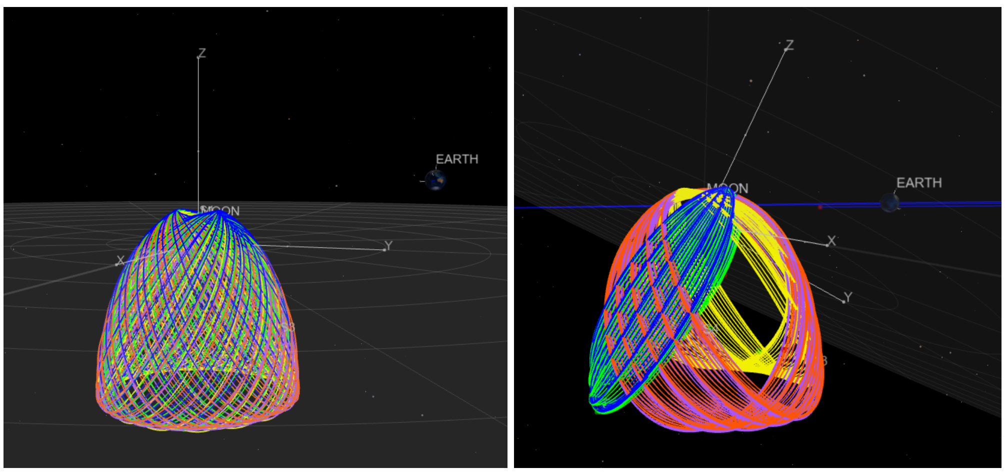

Figure 6: LDN constellation view in Earth-Moon rotating frame (left) and ICRF (right)

the LSP itself and candidate landing sites for the Artemis 3 mission.[10] The figure shows that each Earth day has two or three windows, 5-7 hours in duration, in which GDOP is less than 6. However, the figure also shows that for most of the period there are at least 4 satellite in view, allowing for GDOP values slightly above 6. Thus providing more longer periods in which a surface user can use LANS for PVT solution, even though those solutions might be degraded compared to the GDOP<6 windows.

Figures 8 to 12 present the constellation's performance with respect to the requirements described above. The performance is examined using the more than 400 SV2 surface points described above. Figure 8 shows the percent coverage on the surface of SV2. These (and all subsequent) polar plots show the LSP in the center of the plot with the radial direction representing latitudes from -90° to -75°. The angular coordinate in these plots represents the Moon's longitudes. The Artemis 3 landing sites are also presented in the polar plots. The results presented in Figure 8 show both the average daily percent coverage with GDOP<6 (left) and the minimum daily percent coverage with GDOP<6 (right) over the 60 day propagation period. The results show that, on average, every

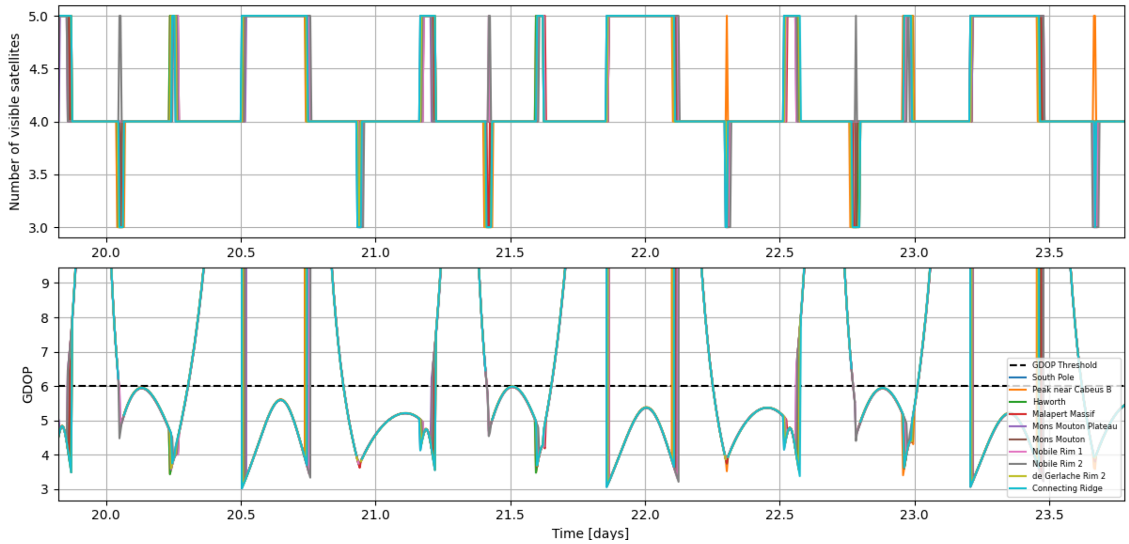

Figure 7: Number of satellites in view and GDOP levels at candidate Artemis 3 landing sites during 3 days of the propagated period

point on the surface has coverage of ∼53% or more of an Earth day. However, when looking at the minimum daily coverage values it can be seen that some regions experience coverage as low as ∼34%. It should be noted that the lower performance is primarily presented in the edge of SV2's surface where potential surface users are less likely to operate during the active Artemis campaign due to the distance from the LSP and the Artemis 3 landing sites. Additionally, a skew to one side of the Moon can be seen, which means that the constellation can be rephased to provide higher coverage to that region, if needed. The skew is attributed to the Moon's obliquity and skew with respect to the Earth-Moon rotating frame, and therefore will precess over time.

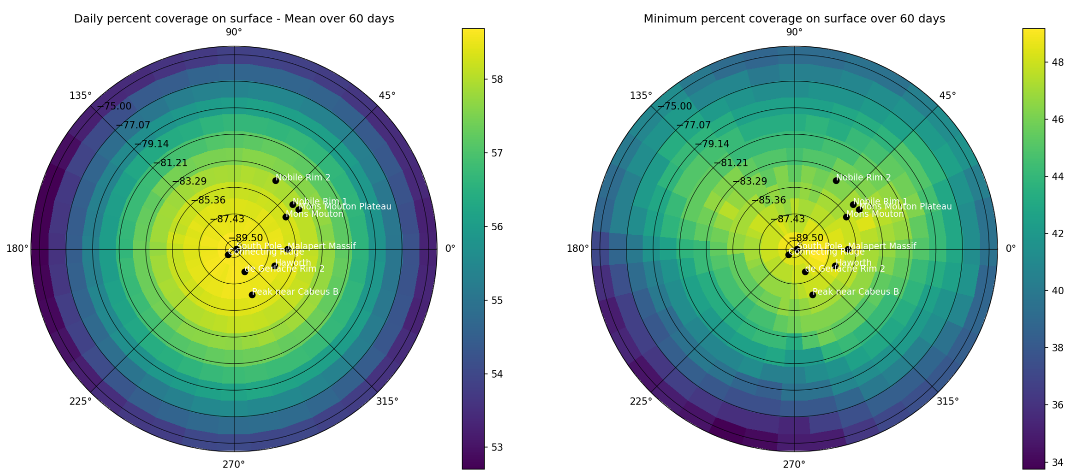

Figure 8: Surface coverage performance for 40% GDOP<6 coverage requirement. Average (left) and minimum (right) values over 60 days

Figure 9 shows a temporal presentation of the GDOP<6 percent Earth day coverage (left) and a count of the number of days in which the percent coverage falls below 40% (right). In the left subfigure percent coverage for all points is seen for each day in the propagated period. The lowest percent coverage per day (solid black line) and the 40% threshold (dashed black line) are also marked in the figure. The points of interest described above are marked as dot-dashed lines with blue shades. The right subfigure shows a polar plot of the number of days in which each surface area falls below the 40% threshold. The results show that during most of the propagated period no points fall below this threshold. However, points that fall below the threshold tend to be on the SV2 perimeter, and, at maximum, this occurs for 2 days out of the 60 day propagated period. When summing all points and days, the percentage of instances in which the 40% threshold isn't met is 0.347%, which again, can be addressed operationally. It should be noted that a small downward trend in percent coverage can be seen in the left subfigure. This trend is likely the result of the perturbations experienced by the spacecraft in the constellation. However, given that this constellation design currently does not include any orbit maintenance maneuvers it is expected that the long term trend will be addressed by active maneuvering.

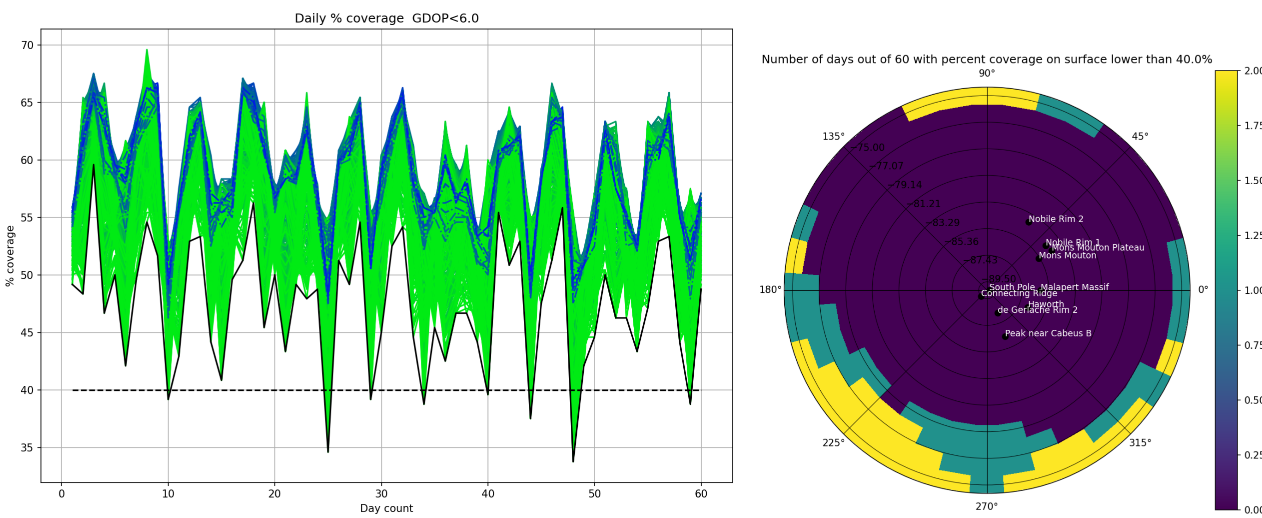

Figure 9: Percent of each Earth day in which GDOP<6 for the SV2 surface (left) and number of days per point in which the coverage falls below 40% (right)

Figure 10 presents the average (left) and minimum (right) daily 2nd longest continuous window with with GDOP<6. The figure shows that the average 2nd longest window for the area around the LSP including the Artemis 3 sites the 2nd longest window is indeed longer than 5 hours. However, points on the perimeter of the SV2 surface dip below 5 hours even for average values. Examining the minimum 2nd longest window durations shows that most points, other than the LSP immediate vicinity, experience GDOP<6 windows shorter than 5 hours. As seen in the right subfigure of Figure 11, some of the lower 2nd longest window points experience that level of performance for up 35 days out of the propagated period. However, the need for 5 hours windows with continuous coverage with GDOP<6 is defined to support EVAs and thus relevant for the Artemis 3 sites and neighboring areas. With that in mind, examining the results in Figure 11 shows that, aside from two periods during the 60 days, the Artemis 3 sites reach a 2nd longest window at or near 5 hours in duration. Overall, when summing all points and days, the percentage of instances in which the 2nd window threshold isn't met is 19.66%, but again, this is primarily exhibited in the perimeter of the

SV2 surface where no Artemis 3 sites can be found. And, as discussed earlier, those 5 hour EVA windows can achieved with constellation rephasing when the need arises.

It should also be noted that top left subfigure in Figure 11 presents the longest window with continuous GDOP<6 coverage. These results show that most points on the surface of SV2 do have at least one 5 hour window with continuous GDOP<6 coverage. These windows can often get to be as long as 9 hours depending on the location and day. As mentioned above, the constellation geometry with respect to the Moon provides an opportunity to rephase the orbiters such that specific regions receive longer continuous windows per operational needs from surface missions.

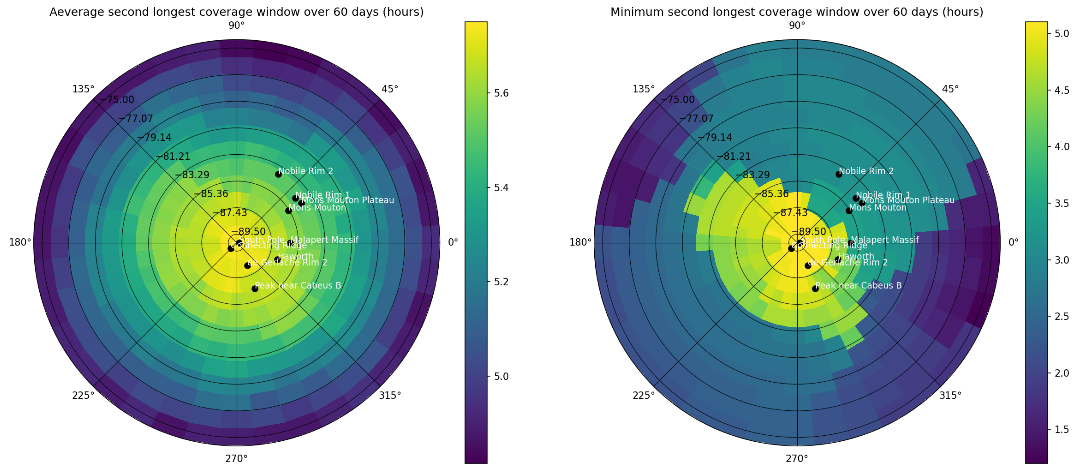

Figure 10: Daily 2nd longest continuous window with with GDOP<6. Average (left) and minimum (right) values over 60 days

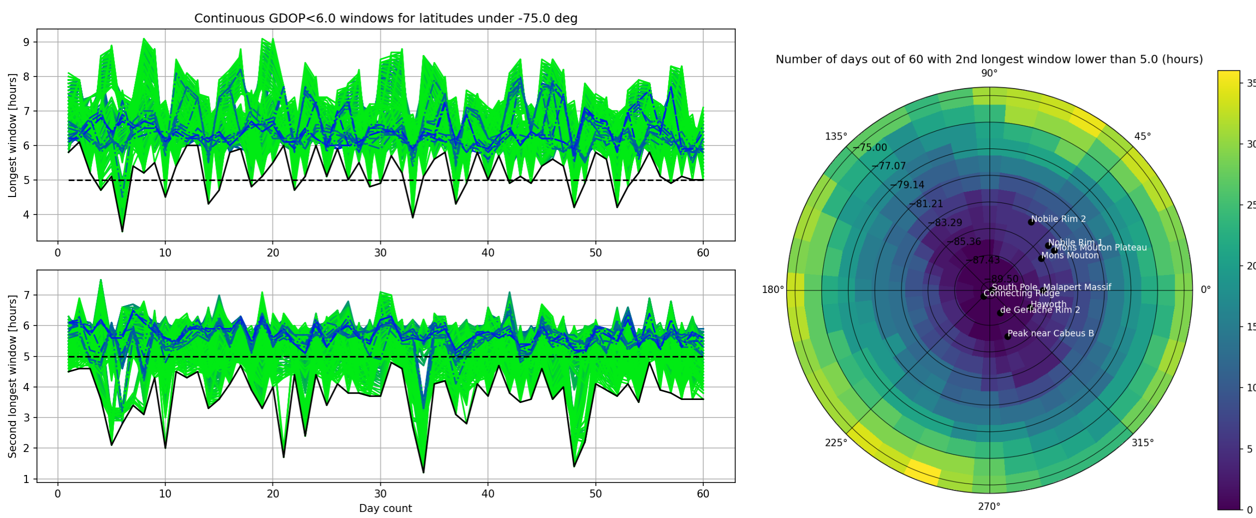

Figure 11: 1st and 2nd longest window with continuous GDOP<6 coverage (left) and number of days per point in which the 2nd longest window falls below 5 hours (right)

Figure 12 presents the percent of days in which two (left) and four (right) orbiters are in LOS with the SV2 surface region. As seen in the left subfigure, all of the SV2 surface has LOS to at least two orbiters at all time. This result meets and exceeds the IOC-C two simultaneous two-way links requirement in full. The right subfigure shows that SV2 areas have a least four orbiters in LOS for 91% to 97%, meaning that even if the GDOP<6 threshold isn't met at that time there is some capability for a degraded PVT solution for users in the SV. Again, the lower performance is seen in the SV2 perimeter, farther away from the Artemis 3 sites.

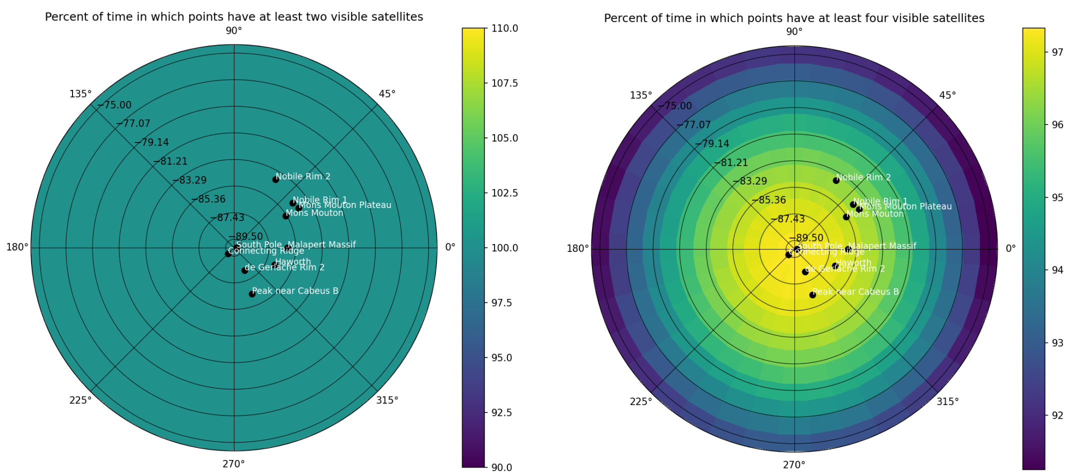

Figure 12: Percent of time during 60 propagation of the LDN constellation in which SV2 surface points have two and four orbiters in LOS

Figure 13 presents the constellation's perilune and apolune altitudes for the 60 day propagated period. The plots shows that constellation meets the bounds described above. The lowest perilune altitudes (per orbiter) range between ∼1400 km and ∼1900 km, which allows for scientific observations of the Moon's northern hemisphere.

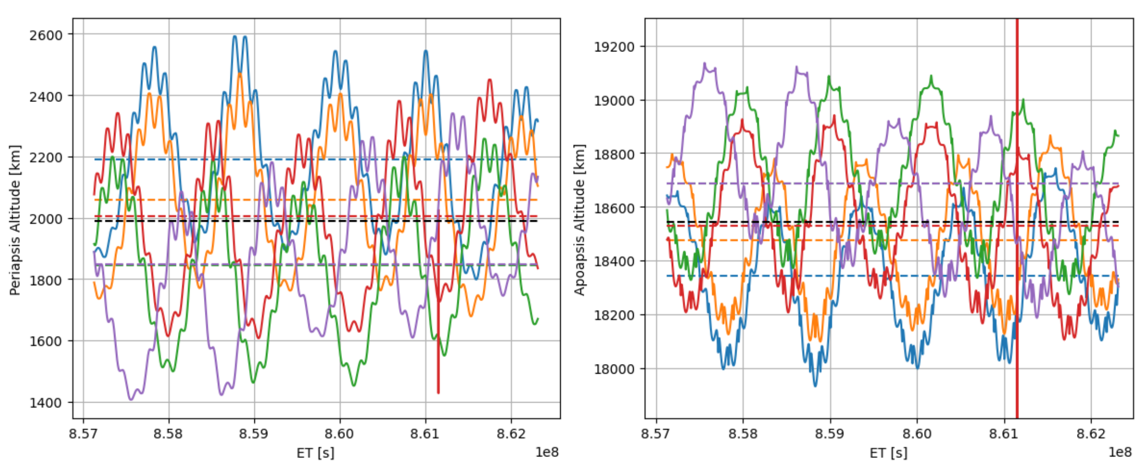

Figure 13: Perilune and apolune altitudes of the LDN constellation

LDN-1 OUTBOUND TRAJECTORY DESIGN

The LDN constellation's first satellite, LDN-1, is scheduled to launch in mid 2026 as a rideshare with IM's third lunar lander mission, IM-3. Similarly to previous IM missions,[11] the IM-3 launch is planned to be a high-energy direct lunar transfer. However, for conservation of Delta-V and relaxation of operational timelines, the LDN mission design team has selected a Ballistic Lunar Transfer (BLT) as the outbound trajectory for LDN-1. Due to the high-energy nature of the IM-3 launch and its targeting of the Moon, LDN-1 will perform a lunar flyby en-route to the BLT apogee. Figure 14 presents a preliminary representative BLT trajectory for the April 22, 2026 IM-3 launch opportunity. The trajectory was solved and optimized using Copernicus and presented in the figure in the Sun-Earth rotating frame. The LDN-1 trajectory includes a Course Maneuver (CM) shortly after launch, the lunar flyby, a Deep Space Maneuver (DSM) at an optimized location after apogee, and a Lunar Orbit Insertion (LOI) upon arrival at the Moon. Additionally, several Trajectory Correction Maneuver (TCM) opportunities are scheduled in this scenario. Table 4 summarizes the trajectory events and timeline. As seen in the table, the LDN-1 trajectory will take 110 days to reach the operational orbit at the Moon. The operational orbit for LDN-1 shares the baseline characteristics as the constellation design above. For the first LDN satellite, there are no constraints on the orbit plane (RAAN angle) or orbit phasing (time of perilune pass).

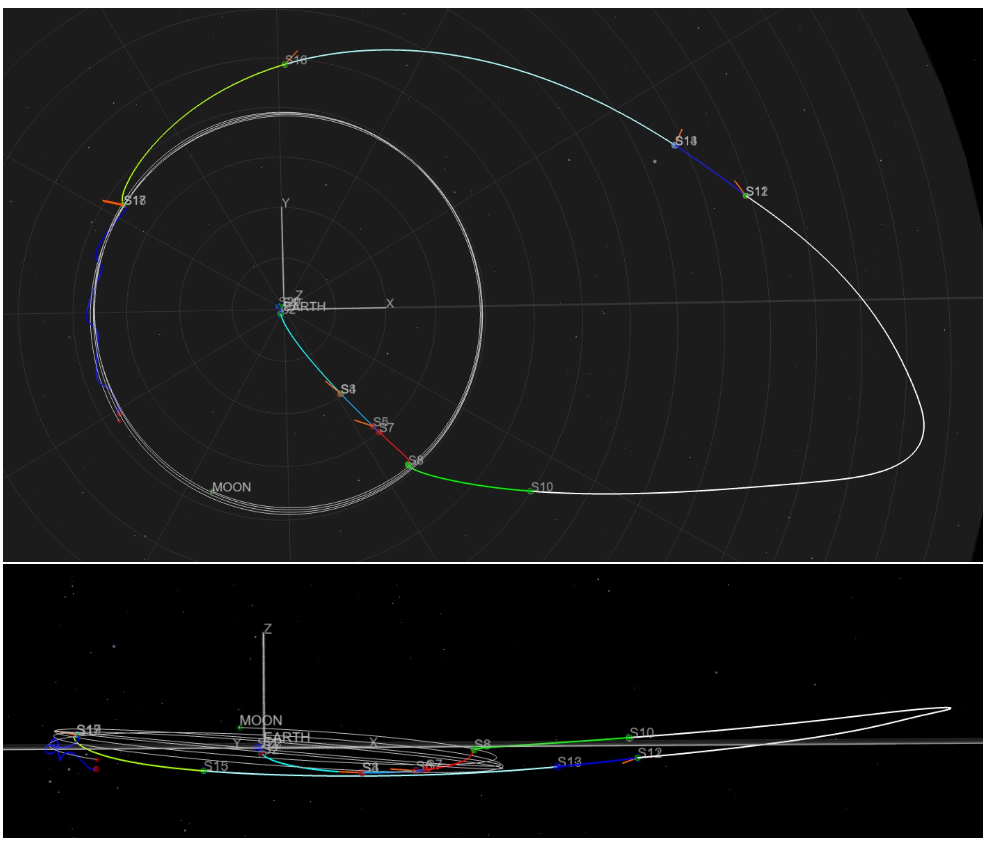

Figure 14: LDN-1 outbound trajectory in the rotating Sun-Earth frame

The following LDN satellites are planned to launch in pairs in 2027 and 2028 to complete a full five satellite constellation. In addition to similar launch constraints to LDN-1, following LDN satel-

Event	Time	Notes
Launch	L+0	
CM	L+18 hours	Δv_{CM} = 22.6 m/s
TCM-1	L+42 hours	Statistical
TCM-2	Flyby-24 hours	Statistical
Lunar flyby	L+4.8 days	flyby altitude $\sim$2500 km
TCM-3	Flyby+5 days	Statistical
Apogee	L+44 days	Earth distance $\sim 1.3 \times 10^6$ km
DSM	L+85 days	Δv_{DSM} = 73.2 m/s
TCM-4	DSM+5 days	Statistical
TCM-5	LOI-5 days	Statistical
LOI	L+110 days	Δv_{LOI} = 122.3 m/s
Total	110 days	Δv_{tot} = 218.2 m/s

Table 4: LDN-1 Outbound trajectory events

lites' outbound trajectories will need to insert into orbits adhering with the constellation design. Each subsequent satellite 'losing' some degree of freedom in orbit plane and orbit phase. As mentioned above, LDN-1 and then LDN-1 to -3 are intended to provide service to the LSP region even prior to full deployment of the constellation described in this paper.

CONCLUSIONS AND FUTURE WORK

The LDN constellation design presented here is intended to provide communication and PNT services to the LSP region. The analysis presented shows that the five satellite constellation geometry generally meets the LCRNS requirements. Assuming some operational activities could be done to address real time needs on specific regions of the surface, this solution is likely sufficient to achieve mission objectives. In addition to the LCRNS requirements, the constellation design supports the IM design goals; minimizing the number of orbiters, constructing the constellation using rideshare launches, and providing opportunities for science observations of the surface.

Future work will focus on the day-to-day operations of the constellation, such as maintenance maneuvers and rephasing strategies. Additionally, as launch opportunities approach, outbound trajectories for LDN-1 and subsequent orbiters will be further optimized and refined.

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