Cislunar Communications Path Delays:
A Comparison Between Two Idealized Relay Satellite Constellations

Savan C. Becker[1], Michael E. Johnson, PhD[2], John Carrico Jr.[3]

[1] *Department of Engineering, Capitol Technology University, Laurel, MD, USA*
[2] *Adjunct Professor, Department of Engineering, Capitol Technology University, Laurel, MD, USA*
[3] *Chief Technology Officer/Astrogator, Space Exploration Engineering (SEE), Laurel, MD, USA*

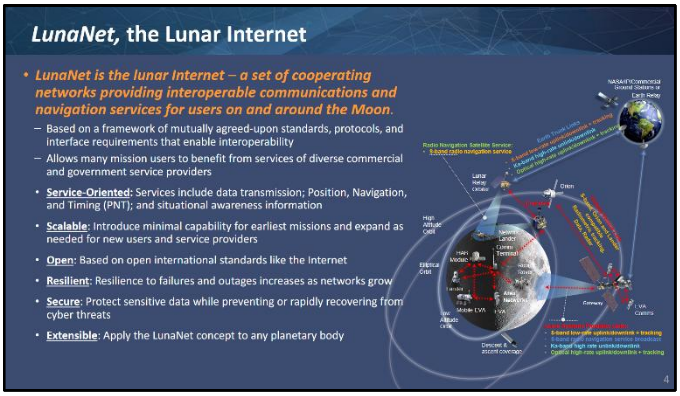
***

***Abstract** - Multiple National Aeronautics and Space Administration (NASA) sponsored and independent studies have examined and/or proposed deployment of spacecraft in key cislunar orbits as part of LunaNet, a communications relay and navigation network to support operations on and around the Moon [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Additional research promotes the possibility for immersive, collaborative, multi-user human and human-robotic exploration during future lunar and interplanetary space exploration initiatives, including Artemis [11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. Delay (i.e., latency) due to distance and frequency/duration of access intervals are significant, fundamental factors in determining the extent and quality of dynamic communications, teleoperation of robotic systems, and immersive interaction – particularly in space operations [11, 17, 18, 21, 22, 23, 24]. This article describes how we used Systems ToolKit (STK) software to investigate the access intervals and path delays (PD) in an idealized lunar relay satellite constellation modeled on a proposed LunaNet baseline [3, 8, 9, 10, 25]. We also compare these results to a hypothetical "Lagrange-Centric" (i.e., Earth-Moon L1) alternative relay constellation. While simplified, our estimates for PD and access intervals may help bound "worst-case" scenarios and expectations when considering feasibility, quality, and frequency of collaborative cislunar exploration activities.*

Key Words: Technology, NASA, Space, Spaceflight, Artemis, Gateway, Shackleton, LunaNet, Satellite, Satellites, Communications, Constellations, Spacecraft, Moon, Mars, Cislunar, Space Exploration, Telepresence, Exploration Telepresence, Astrodynamics, Orbits, Orbital Mechanics, Systems ToolKit, Satellite ToolKit, STK, Astrogator, CODE, Lagrange, Libration

1. INTRODUCTION

Research conducted by independent investigators and sponsored by the National Aeronautics and Space Administration (NASA) suggests the possibility for immersive, collaborative, multi-user human and human-robotic exploration of the Moon during the planned *Artemis* program [1, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. Communications delays in space operations impact the extent to which astronauts, researchers, and enthusiasts can dynamically participate in collaborative exploration [11, 17, 18, 21, 22, 23, 24]. When considering cislunar space, it is well known that the average *light travel time* (LTT) between the Earth and the Moon is approximately 1.3 s, with a *round-trip time* (RTT) of 2.6 s [18]. However, future lunar exploration programs will involve more than just point-to-point communication between Earth and the lunar surface. *Artemis* plans include the establishment of an orbiting space station (i.e., Gateway), a possible surface outpost near the Moon's South Pole, a constellation of relay satellites in lunar orbit (i.e., LunaNet), and the construction of additional terrestrial Lunar Exploration Ground Stations (LEGS) (see Fig – 1) [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 25].

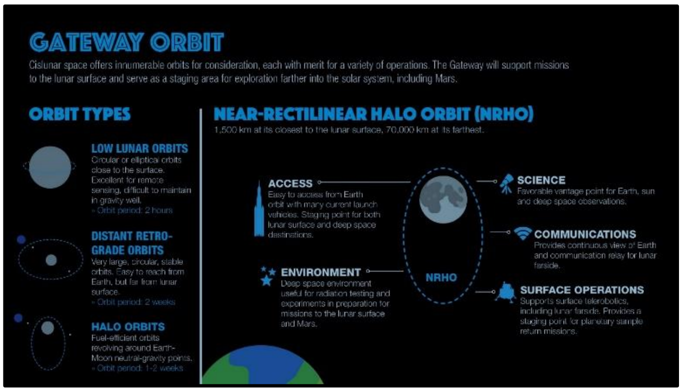


LunaNet, the Lunar Internet

- *LunaNet is the lunar Internet – a set of cooperating networks providing interoperable communications and navigation services for users on and around the Moon.*
  - Based on a framework of mutually agreed-upon standards, protocols, and interface requirements that enable interoperability
  - Allows many mission users to benefit from services of diverse commercial and government service providers
  - **Service-Oriented**: Services include data transmission; Position, Navigation, and Timing (PNT); and situational awareness information
  - **Scalable**: Introduce minimal capability for earliest missions and expand as needed for new users and service providers
  - **Open**: Based on open international standards like the Internet
  - **Resilient**: Resilience to failures and outages increases as networks grow
  - **Secure**: Protect sensitive data while preventing or rapidly recovering from cyber threats
  - **Extensible**: Apply the LunaNet concept to any planetary body

Fig – 1: LunaNet described in NASA LunaNet Overview. [8]

Consequently, when performing collaborative exploration, the aggregate delay – or latency – encountered by communicants using any elements of this network will differ based upon the specific locations involved (e.g., terrestrial ground stations, orbiting spacecraft, and lunar outposts), and whether the paths used are line-of sight (LOS) and/or via relay. In a satellite communications system, one very basic parameter factored into latency estimations is the free space *path delay* (PD; or propagation delay) between space and ground elements in the network. The PD between two locations is equivalent to the LOS signal travel time (i.e., the LTT), and the RTT represents the overall delay between initial contact and response/acknowledgement (i.e., twice the PD) [26]. Also, the *access intervals* between the various elements and users of the system are often examined when designing and operating communications satellites constellations. Access intervals represent the frequencies and durations that various elements in a satellite-based communications network can connect with each other under ideal circumstances [26]. These time periods are usually dependent upon whether spacecraft and ground stations are "in view" of one another, or if contact can be facilitated by relay – i.e., via elements that can bridge the gap between the end-point communicants.



GATEWAY ORBIT

Cislunar space offers innumerable orbits for consideration, each with merit for a variety of operations. The Gateway will support missions to the lunar surface and serve as a staging area for exploration farther into the solar system, including Mars.

ORBIT TYPES

LOW LUNAR ORBITS
Circular or elliptical orbits close to the surface. Excellent for remote sensing, difficult to maintain in gravity well.
› Orbit period: 2 hours

DISTANT RETRO-GRADE ORBITS
Very large, circular, stable orbits. Easy to reach from Earth, but far from lunar surface.
› Orbit period: 2 weeks

HALO ORBITS
Fuel-efficient orbits revolving around Earth-Moon neutral-gravity points.
› Orbit period: 1-2 weeks

NEAR-RECTILINEAR HALO ORBIT (NRHO)

1,500 km at its closest to the lunar surface, 70,000 km at its farthest.

ACCESS
Easy to access from Earth orbit with many current launch vehicles. Staging point for both lunar surface and deep space destinations.

ENVIRONMENT
Deep space environment useful for radiation testing and experiments in preparation for missions to the lunar surface and Mars.

SCIENCE
Favorable vantage point for Earth, sun and deep space observations.

COMMUNICATIONS
Provides continuous view of Earth and communication relay for lunar farside.

SURFACE OPERATIONS
Supports surface telerobotics, including lunar farside. Provides a staging point for planetary sample return missions.

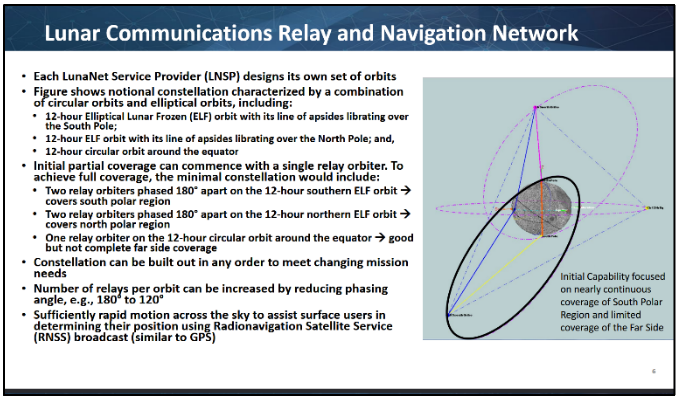
Fig – 2: Gateway NRHO – orbit selection criteria. [25]

In this article, we describe how we used System's ToolKit (STK) orbit and trajectory modeling software developed by Ansys Government Solutions (AGI) to examine basic PD and access intervals between elements of two idealized satellite-based cislunar communications architectures [26]. The first is derived from NASA's "minimal constellation" LunaNet concept, as reviewed and discussed in several NASA and academic sources, including [3], [8], [9], and [10]; we call this "LunaNet Baseline". The second imagines a "Lagrange-Centric" constellation, with three satellites deployed in phased halo variant orbits around the Earth-Moon L1 libration point.

In the spirit of multi-user collaborative exploration, we focus on a conceptual scenario in which the goal is to achieve low-latency, concurrent communication between terrestrial researchers, personnel aboard a lunar orbiting facility, and explorers on the Moon's surface [16, 17, 18, 19, 20, 21, 22, 23, 24]. Note that all computations are generalized and based on idealized LOS parameters; they do not consider factors such as terrain restrictions, antenna pointing constraints, and other environmental or operational limitations. Further, this study focuses on the satellite elements comprising the possible LunaNet constellation, and – for simplicity – does not consider alternate communications methods that could help mitigate outages (i.e., deployment of antennas across the Moon's surface) [27]. The process was solely meant to gain a baseline appreciation for "worst-case" space-associated PD/LTT values and access intervals; more detailed investigation is left to future research.

2. CISLUNAR COMMUNICATIONS ELEMENTS

NASA has indicated that the "…incremental build-up of capabilities on and around the Moon is essential to establishing long-term exploration of Earth's nearest neighbor and preparing for human exploration of Mars" [1]. Several agency-sponsored and independent studies examined and/or proposed deployment of spacecraft in key cislunar orbits to support the development of LunaNet, a lunar communications relay and navigation network, including: [2], [3], [4], [5], [7], [8], [9], and [10]. NASA is pursuing LunaNet with international partners, including the ESA via that agency's "Moonlight" initiative [28, 29]. The architecture will likely begin modestly – perhaps with a single relay satellite – but build up over time into a service-oriented, scalable, resilient network of commercial and government provided communications and PNT services [9]. NASA's proposed Gateway lunar space station – in addition to being an operations and logistics hub for crewed missions to the Moon and beyond – will also serve as a node in this evolving network, using its communications and ranging capabilities to help facilitate cislunar human and robotic activities [5, 8].



Lunar Communications Relay and Navigation Network

- Each LunaNet Service Provider (LNSP) designs its own set of orbits
- Figure shows notional constellation characterized by a combination of circular orbits and elliptical orbits, including:
  - 12-hour Elliptical Lunar Frozen (ELF) orbit with its line of apsides librating over the South Pole;
  - 12-hour ELF orbit with its line of apsides librating over the North Pole; and,
  - 12-hour circular orbit around the equator
- Initial partial coverage can commence with a single relay orbiter. To achieve full coverage, the minimal constellation would include:
  - Two relay orbiters phased 180° apart on the 12-hour southern ELF orbit → covers south polar region
  - Two relay orbiters phased 180° apart on the 12-hour northern ELF orbit → covers north polar region
  - One relay orbiter on the 12-hour circular orbit around the equator → good but not complete far side coverage
- Constellation can be built out in any order to meet changing mission needs
- Number of relays per orbit can be increased by reducing phasing angle, e.g., 180° to 120°
- Sufficiently rapid motion across the sky to assist surface users in determining their position using Radionavigation Satellite Service (RNSS) broadcast (similar to GPS)

Initial Capability focused on nearly continuous coverage of South Polar Region and limited coverage of the Far Side

6

Fig – 3: LunaNet constellation description from NASA LunaNet Overview. [8]

For this paper, an idealized simulation of the cislunar environment as it may manifest during the early *Artemis* era was constructed, to gain an appreciation for some of the fundamental communications access and latency constraints associated with cislunar communications. This basic cislunar communications relay model was primarily informed by concepts laid out in several LunaNet design papers and overview presentations, including: [3], [4], [8], [10], [30], [31], and [32]. Significant components of this overall architecture include:

- The Gateway station in a southern L2 near rectilinear halo orbit (NRHO) (see Fig – 2).
- LunaNet relay satellites in southern and northern elliptical frozen orbits (i.e., SELFO, NELFO), and lunar equatorial orbit (LEQ) (see Fig – 3).
- Extant NASA Deep Space Network (DSN) facilities as primary terrestrial locations for communications and signal processing, with Lunar Exploration Upgrades (LEU).
- Proposed NASA Lunar Exploration Ground Site (LEGS) facilities as extended terrestrial communications

nodes: a combination of government and commercial services, designed to focus on lunar missions, thereby alleviating load on the DSN (which is in high demand).

- A possible "base camp" or outpost in the southern polar region of the Moon. According to NASA's extensive long-term plans, the establishment of this facility will support "…longer expeditions on the lunar surface… and in-situ resource utilization systems" [1].

While multiple additional spacecraft orbits and trajectories were included in the simulation for completeness, not all were extensively utilized to perform access interval and latency computations. Principle calculations focused on spacecraft in NRHO, SELFO, and L1 orbits mainly because:

1. The baseline LunaNet architectures in cited references – which are focused on covering the Moon's South Pole – will initially probably rely on SELFO relays.
2. The L1 vantage point offered a possible alternative solution to address gaps in early baseline LunaNet constellations and was some worth added attention.
3. A more conservative estimation of access and PD constraints – centered on a few key orbits – was desired given the limited scope of this paper.

Nevertheless, it should be noted that additional orbits are currently being used or investigated for cislunar communications. These will almost certainly be integrated into future NASA, commercial, and international constellations to enable robust exploration and coverage of the Moon, including the lunar farside. These include:

- Lagrange halo orbit variants. Example: China's Queqiao-1 L2 communications satellite [33, 34, 35, 36].
- Variations of inclined elliptical orbits. Examples: China's Queqiao-2, Tiandu-1, and Tiandu-2 lunar communications/navigations satellites [34, 37].
- Lunar distant retrograde orbit (DRO). Examples: China's DRO-A and DRO-B spacecraft performing for operations in/around DRO (i.e., CDROE) [38, 39, 40].

In fact, in a 2024 article published in the journal *Chinese Space Science and Technology*, Chinese scientists outline a very robust "cislunar space infrastructure" to provide positioning, navigation, and timing (PNT) services, communications, and space situational monitoring capability via incremental deployment of spacecraft in various Earth-Moon orbits [41, 42]. The paper by M. Yang et al. [42] suggests initial utilization of spacecraft in ELFO during "Phase I", followed by multiple satellites around each Earth-Moon Lagrange point (e.g., L1 through L5), in NRHO, and in DRO for "Phase II" and "Phase III". The authors even suggested the possibility of two "cislunar space stations" in Earth-GEO and outline the basic network architecture associated with the overall system (see Fig – 4). China may be well on its way with this plan, since it has already stationed spacecraft in ELFO (e.g., Queqiao-2, Tiandu-1 and -2), around L2 (Queqiao-1), and in DRO [34, 37, 38, 39].

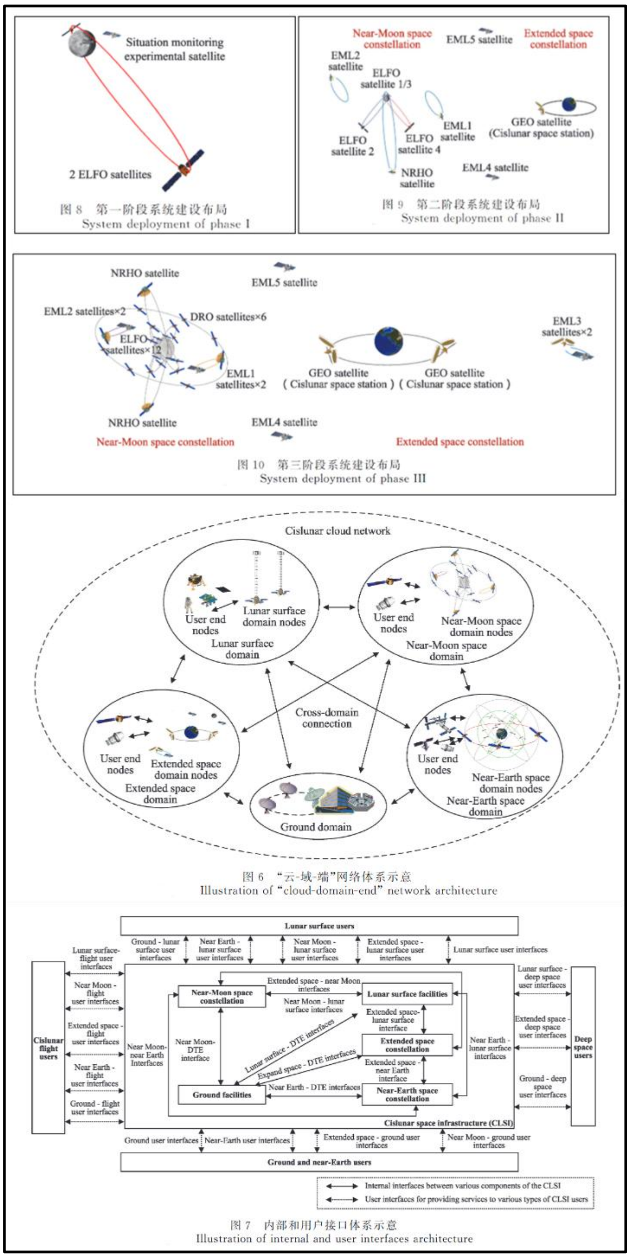


Fig – 4: Cislunar space infrastructure proposed by M. Yang et al. [42]

3. CISLUNAR STK SCENARIO MODELING

Systems ToolKit (STK), produced by Ansys Government Initiatives (AGI), is widely considered to be an industry standard for physics-based simulation, analytics, pre-mission planning, and monitoring of space operations [26]. For this paper, STK was used under academic licensing to build a scenario that facilitated visualization of key orbits for spacecraft included in proposed cislunar mission architectures. The software also allowed for the determination of access intervals and estimation of latencies associated with communications paths between individual spacecraft, spacecraft constellations, and ground stations. Whenever possible, ephemerides (position/velocity information) for actual Earth-orbiting and lunar missions were used as a basis to create notional spacecraft for the simulation. However, if no current or historic missions existed from which to create initial states for trajectory propagation, then basic orbit modeling techniques were used to construct surrogate spacecraft.

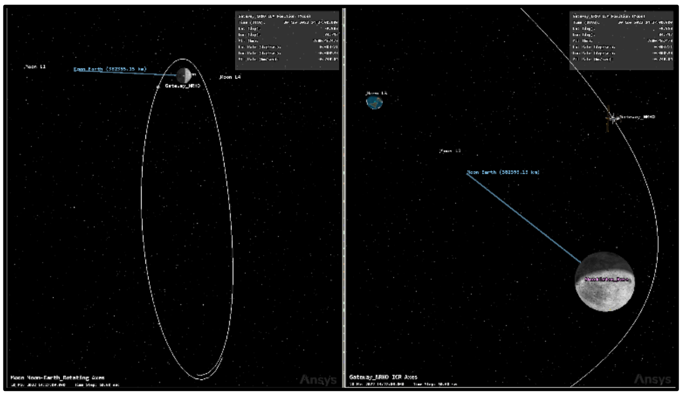


Fig – 5: Gateway NRHO orbit modeled after CAPSTONE.

Spacecraft orbits and trajectories were simulated within a scenario that spanned a period of 30 days between 17 November and 17 December 2022. These dates were selected primarily because NASA's Artemis I and CAPSTONE missions were active in cislunar space during that time frame; analogs based on their trajectories provided convenient "anchors" around which to model other satellites in the simulation. There was also some overlap in ephemerides for additional spacecraft operating near the Moon during that period that assisted with contextual visualization of other lunar orbits (e.g., NASA THEMIS in Lissajous orbits, LRO in lunar polar orbit) [43].

Positional data for Solar System objects (e.g., asteroids and planets) and select spacecraft beyond terrestrial orbit conducting scientific missions can be accessed via the NASA Jet Propulsion Laboratory's Horizons system [43]. The Horizons web interface was used to isolate and download ephemerides for historic and current missions to the Moon that demonstrated lunar trajectories/orbits similar to those discussed in LunaNet studies. These orbital elements were then used to provide initial states for simulated spacecraft in STK, enabling the creation of scenarios that incorporated surrogates for the future Gateway station, notional LunaNet constellations, and trajectories for in- and out-bound spacecraft visiting the Moon. Actual missions and simulated analogs are as follows:

- NASA CAPSTONE: Launched on 28 June 2022 [43]. Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE). CAPSTONE tested the operation of spacecraft in NRHO and was the first spacecraft to achieve and function in this orbit. On 13 November 2022, CAPSTONE entered into an orbit very similar to the one that NASA intends to use for the Gateway station, namely a 9:2 resonant, southern L2 NRHO (Gardner et al., 2023). Consequently, for this paper, CAPSTONE ephemerides were the basis for the NRHO Gateway analog in our scenario (see Fig – 5).
- NASA ARTEMIS-P1 (THEMIS-B) and ARTEMIS-P2 (THEMIS-C): Launched on 17 February 2007 [43]. Originally designated Time History of Events and Macroscale Interactions during Substorms (THEMIS); renamed Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) when the mission shifted to studying the lunar environment in 2009. ARTEMIS-P1/P2 were the first spacecraft to operate at the lunar Lagrange points, functioning in Lissajous orbits for a portion of their mission timelines. The spacecraft also operated in highly elliptical orbits (HEO) around the Moon. Of note, ARTEMIS-P1 was the first spacecraft to orbit an Earth-Moon Lagrange point (L2) and the first to orbit both the Earth-Moon L1 and L2 points. For this study, ARTEMIS-P1/P2 ephemerides were used to create initial analog spacecraft around Earth-Moon L1/L2 and in HEO. This helped visualize and understand differences between Lissajous orbits and halo orbits and assisted with modeling alternative components of LunaNet (beyond baseline) around these locations and in HEO.
- NASA LRO: Launched on 18 June 2009 [43]. The Lunar Reconnaissance Orbiter (LRO) generally operated in an elliptical low polar orbit (LPO) of about 50 km, conducting high-resolution color imaging of the lunar surface and other measurements that facilitated the development of a global lunar geodetic grid. It also gathered data on day-night temperature variations and UV albedo. Mission emphasis was placed on observations of the southern polar regions for assessment of in situ resource availability (i.e., water ice). As of early 2024, the spacecraft was performing an extended mission as a south pole observation platform and communication relay in a low-maintenance (i.e., stable) orbit. Ephemerides for LRO were used to create an LPO satellite surrogate, mainly for completeness of the representative lunar constellation model for this paper.
- NASA Artemis I: Launched on 16 November 2022 [1, 43]. Artemis I was NASA's first integrated, uncrewed test of the *Artemis* lunar exploration program. The mission evaluated the launch procedures of the Orion spacecraft using the Space Launch System (SLS) expendable launch vehicle, spaceflight performance of the capsule, and reentry/splashdown of the crew module. For a portion of this successful 26-day mission, Artemis I operated in a lunar distant retrograde orbit (DRO), about 64 000 km beyond the Moon at its farthest point; this highly stable orbit enabled rigorous testing of the vehicle in a deep space environment [1, 44]. If needed, Artemis I trajectory data were available as analogs for transiting spacecraft, or those operating in DRO (e.g., Artemis-X and Artemis-X_DRO).

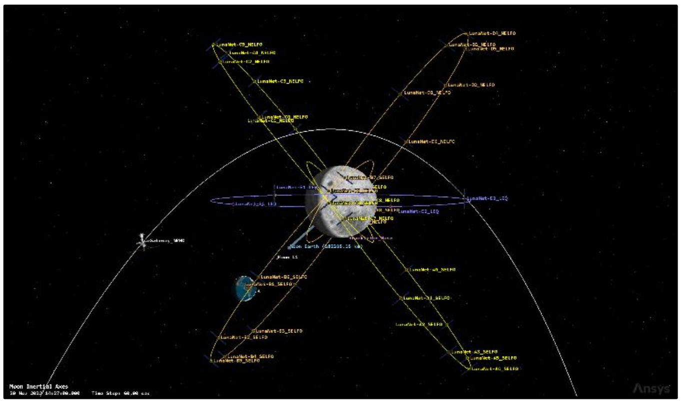


Fig – 6: Fully populated LunaNet constellation model.

3.1 Lunar Elliptical and Equatorial Orbits

We began by constructing a hypothetical, fully populated constellation of LunaNet analogs in southern and northern elliptical frozen orbits (e.g., SELFO and NELFO). Guidance was taken from [3], which studied the effectiveness of various constellations of lunar navigation and communication satellites in ELFO by varying the orbital parameters, number of orbit planes, and satellites per plane. LunaNet ELFO surrogates were constructed with the following baseline parameters: a = 6143 km, i = 51.7 deg, e = .06. Planes were "rotated" around the Moon by shifting the right ascension of the ascending node (RAAN, Ω) by 180 deg. The location of periapsis was established by the combination of RAAN and argument of perigee, which were each shifted by 180 deg. This resulted in four planes of satellites in SELFO and NEFO, designated as follows:

- SELFO Plane A (SELFO A): ω = 90 deg, Ω = 0 deg
- SELFO Plane B (SELFO B): ω = 90 deg, Ω = 180 deg
- NELFO Plane C (NELFO C): ω = 270 deg, Ω = 0 deg
- NELFO Plane D (NELFO D): ω = 270 deg, Ω = 180 deg

Satellites were phased in each orbital plane by varying the mean anomaly (M) which measures the fraction of the period that has elapsed since the spacecraft has passed periapsis in an elliptical orbit. Ultimately, each plane was populated with 8 spacecraft, separated by 45 deg. The first two spacecraft in each plane were phased 180 deg apart, since – in terms of providing essential coverage – these were the most significant satellites the constellations; remaining satellites were filled in at regular 45 deg increments. Spacecraft designations were assigned based on orbit hemisphere, plane, and orbital position. As examples, consider the following spacecraft and associated parameters associated with the SELFO A plane:

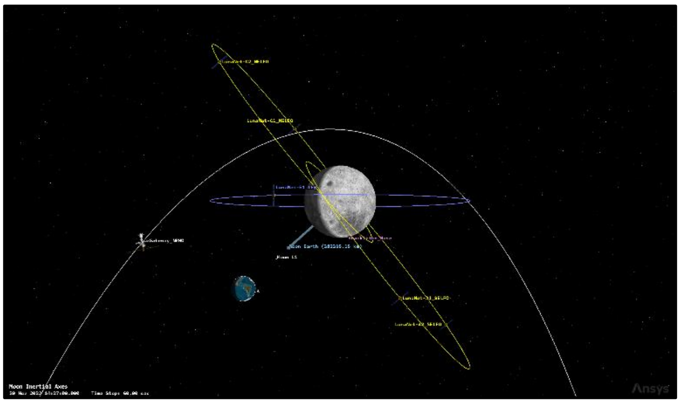


Fig – 7: "LunaNet Baseline" constellation model.

- LunaNet-A1_SELFO: ω = 90 deg, Ω = 0 deg, M = 0 deg
- LunaNet-A2_SELFO: ω = 90 deg, Ω = 0 deg, M = 180 deg
- LunaNet-A3_SELFO: ω = 90 deg, Ω = 0 deg, M = 90 deg
- LunaNet-A4_SELFO: ω = 90 deg, Ω = 0 deg, M = 135 deg
- LunaNet-A5_SELFO: ω = 90 deg, Ω = 0 deg, M = 225 deg
- LunaNet-A6_SELFO: ω = 90 deg, Ω = 0 deg, M = 270 deg
- LunaNet-A7_SELFO: ω = 90 deg, Ω = 0 deg, M = 270 deg
- LunaNet-A8_SELFO: ω = 90 deg, Ω = 0 deg, M = 315 deg

The SELFO B plane follows a similar pattern, with RAAN shifted by 180 deg. Likewise, the NELFO configurations vary mean anomaly with the respective arguments of perigee and RAAN for each plane to set up complementary constellations to the southern counterparts (see Fig – 6). Note that spaces are not allowed in STK object naming conventions; consequently, within the actual scenario construct, "LunaNet-A1_SELFO", for example, is used to represent the "LunaNet A1" spacecraft.

Basic orbit modeling techniques were used to create LunaNet spacecraft operating in lunar equatorial orbit (LEQ). An initial orbit was established with a semi-major axis (a) of 6142.5 km (lunar altitude of approximately 4405 km), inclination (i) of 0 deg, eccentricity (e) of 0, achieve a 12-hour circular orbit as suggested by [8]. When required, additional satellites in this regime were modeled by varying argument of perigee (ω), which is the angle between the ascending node and periapsis (see Fig – 6).

Finally, for the purposes of examining access intervals and PD associated with a more "minimal constellation" – as described by [8], for example – we pared down the full complement of spacecraft to a "LunaNet Baseline" consisting of two satellites in SELFO, 2 satellites in NELFO, one satellite in LEQ, and Gateway in NRHO (see Fig – 7 and Table – 1).

Table – 1: Baseline LunaNet STK Scenario Elements

Asset	Location
Shackleton Base (Moon)	-89.017 deg 126.273 deg
Gateway Station	Lunar Near-Rectilinear Halo Orbit (Southern L2)
LunaNet Baseline	
LunaNet-A1_SELFO	Lunar Southern Elliptical Frozen Orbit
LunaNet-A2_SELFO	Lunar Southern Elliptical Frozen Orbit
LunaNet-C1_NELFO	Lunar Northern Elliptical Frozen Orbit
LunaNet-C1_NELFO	Lunar Northern Elliptical Frozen Orbit
LunaNet-E1_LEQ	Lunar Equatorial Orbit
NASA Deep Space Network (Earth, DSN)	
DSN 01: Barstow/GDSCC	35.43 deg -116.890 deg
DSN 02: Canberra/CDSCC	-35.40 deg 148.982 deg
DSN 03: Madrid/MDSCC	40.43 deg -4.250 deg
NASA Lunar Exploration Ground Stations (LEGS)	
LEGS 01: White Sands/WSC	35.43 deg -106.61 deg
LEGS 02: Matjiesfontein/SANSA	-33.23 deg 20.58 deg
LEGS 03: Geraldton/ASA	-28.70 deg 114.84 deg

3.2 Ground Segments

Communications support for NASA *Artemis* program spacecraft in the cislunar region will primarily be provided via the DSN and, later, also via LEGS [1, 31, 45, 46, 47, 48, 49]. Consequently, in terms of terrestrial communications nodes, the cislunar scenario built for our study incorporated locations for existing NASA DSN ground stations and proposed LEGS ground stations as follows (see Table – 1 and Fig – 8) [31]:

- Goldstone Deep Space Communications Complex (GDSC, 35.43 deg -116.89 deg) – located near Barstow, CA, USA. Scenario Name: NASA_DSN_01_Barstow_GDSCC.
- Canberra Deep Space Communication Complex (CDSCC,) – located 40 km from Canberra, Australia. Scenario Name: NASA_DSN_02_Canberra_CDSCC.

  Madrid Deep Space Communications Complex (MDSCC, 40.43 deg -4.25 deg) – located 60 km from Madrid, Spain. Scenario Name: NASA_DSN_03_Madrid_MDSCC.

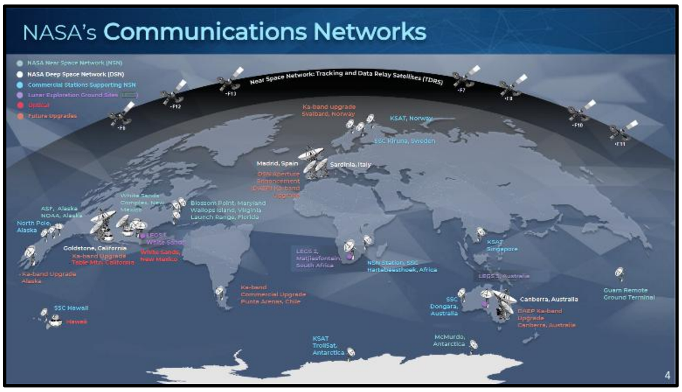


Fig – 8: DSN and (proposed) LEGS ground stations. [31]

- LEGS Site #1 - White Sands Complex (WSC, 35.43 deg -106.61 deg) – Scenario Name: NASA_LEGS_01_White-Sands_WSC.
- LEGS Site #2: Matijiesfontein, South Africa Government (MTJ, -33.23 deg 20.58 deg) – Scenario Name: NASA_LEGS_02_Matjiesfontein_SANSA.
- LEGS Site #3: Geraldton, Australia Government (ASA, -28.70 deg 114.84 deg) – Scenario Name: NASA_LEGS_03_Geraldton_ASA.

Finally, a notional lunar base camp called "Shackleton Base" was placed on the lunar surface, in the South Pole Aitken-Basin (SPAB), at -89.01701 deg 126.27302 deg. This location – the "Peak Near Shackleton" – is one of the areas selected by NASA as a candidate landing site for Artemis III and possible permanent or mobile/transportable lunar base camp [1, 50, 51, 52].

3.2 Lagrange Orbits

Cislunar Lagrange points, L1 through L5, represent positions (more accurately, trajectories) that are "fixed" within the rotating Earth-Moon reference frame as a result of the gravitational forces exerted by each of these two relatively large masses [53]. Our intention in modeling Lagrange orbits was to see how spacecraft in this domain could provide persistent coverage of the southern polar regions of the Moon by themselves (i.e., without SELFO or LEQ satellites). We thought this might provide an alternative constellation for study – i.e., a "Lagrange-Centric" LunaNet. Due to their relative complexity and instability, more advanced techniques were applied to model spacecraft in halo orbits around the Earth-Moon Lagrange points, namely the use of AGI's Astrogator cislunar and interplanetary trajectory and orbit propagation module for STK. Astrogator integrates special propagators and the use of a multi-segment Mission Control Sequence (MCS) to specify targeted parameters and variables as inputs to differential correctors, which seek to "converge" on the desired trajectories and orbits [54, 55, 56, 57]. Astrogator can be complex, but it is powerful and particularly useful for designing cislunar and interplanetary mission sequences.

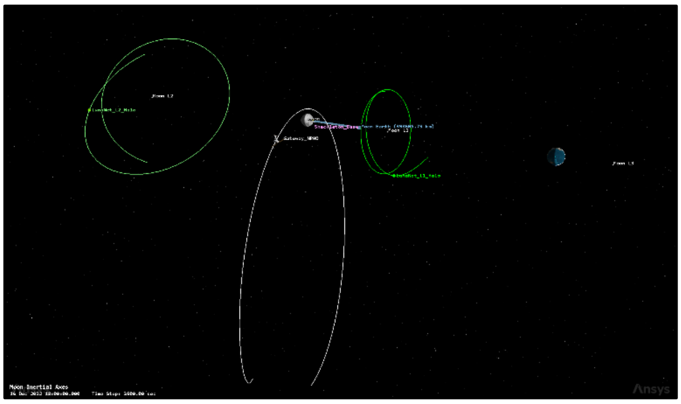


Fig – 9: Initial L1 and L2 orbits.

Initially, full-force trajectories for spacecraft transiting from Earth and entering into orbit near/around L1 and L2 were designed Astrogator. Mission Control Sequences were constructed for spacecraft travelling to L1 and L2, including launch, coast, translunar injection (TLI), propagation, and Lagrange point insertion segments. The tutorial published by [54] was referenced extensively to build these trajectories. However, modifications were made to target final orbits with Z-axis amplitudes (i.e., distances) in the relative L1 and L2 frames of 13 000 km; this was done to approximate the orbit of the Queqiao-1 satellite, which has operated in this regime in support of China's cislunar missions, including the Chang'e-4 lunar farside lander/rover and Chang'e-5 sample return missions [33, 34, 35, 36]. Resulting L1 and L2 analog spacecraft were represented in our scenario as LunaNet-L1_Halo and LunaNet-L2_Halo (see Fig - 9). However – these initial spacecraft did not offer the desired degree of independent, persistent South Pole coverage. We therefore pursued modeling of alternative orbits.

Lester and Thronson [18, 22] posited as early as 2011 that spacecraft located at L1 and L2 with distances around 60 000 km from the lunar surface would have persistent coverage to the near- or far sides of the Moon, with roughly constant RTT values to the surface of about 400 ms; notably these values are within the delay times and "cognitive thresholds" to permit low-latency telepresence (LLT) control of surface robotics [11].

Accordingly, for our case, it was presumed that since L1 is between the Earth and the Moon this location might also provide shorter PD and RTT values; and, most significantly, persistent access between terrestrial resources, spacecraft in lunar orbit, and facilities on the Moon's surface (i.e., near the South Pole). Consequently, we set out to examine "variant L1 orbits" at greater distances. Modeling this additional spacecraft required the use of a specialized prototype STK module called Cislunar Orbit Designer (CODE), developed by Ansys, Inc. in 2024 and released in the middle of that year to a select group of users involved in cislunar mission analysis for beta testing [58, 59, 60].

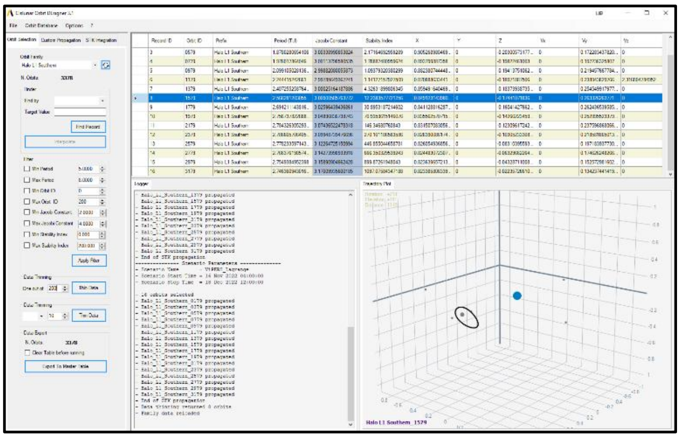


Fig – 10: AGI's Cislunar Orbit Designer (CODE). [55]

CODE works with STK to streamline the modeling of highly complex orbits in a dynamic Earth-Moon environment. The software provides a filterable database of dozens of different cislunar orbit families, representing thousands of variations organized and accessed according to parameters such as stability and period (see Fig – 10 and Fig - 11). CODE automates the construction of an STK scenario based on the canonical circular restricted three-body problem (CR3BP) configuration: this consists of an idealized analog for the Moon called "Luna", which follows a circular versus elliptical orbit around the Earth, and an Earth-Luna rotating (i.e., synodic) reference frame centered on the system's barycenter [58, 59, 60, 61]. Typically, this method is somewhat involved, but it is helpful in establishing the initial states for cislunar trajectories such as those in L1 halo orbits [61, 62]. CODE simplifies the process and produces preliminary spacecraft that can then be introduced into the Astrogator module for propagation using "full-force" algorithms in a more physically accurate Earth-Moon system. CODE was provided to the authors by Ansys/AGI to conduct this study, and others like it, and provide feedback on its utility.

Author John Carrico Jr. – designer of AGI's STK/Astrogator software, Chief Technology Officer of Space Exploration Engineering, and renown space professional – contributed assistance with using CODE to help design our alternative "Lagrange-Centric" LunaNet constellation [57, 63]. His expertise was instrumental, given the inherent complexity associated with the design and optimization of Lagrange halo orbits.

For this project, we sought to create three spacecraft in complementary halo orbits "around" L1, phased such that the constellation could provide continuous connectivity between Gateway and Shackleton. As stated by J. Carrico:

"…this is possible, but really not that easy to figure out… The answer will be using 'receding horizons' which is only a little bit in the literature... But not hard once you see it." [64]

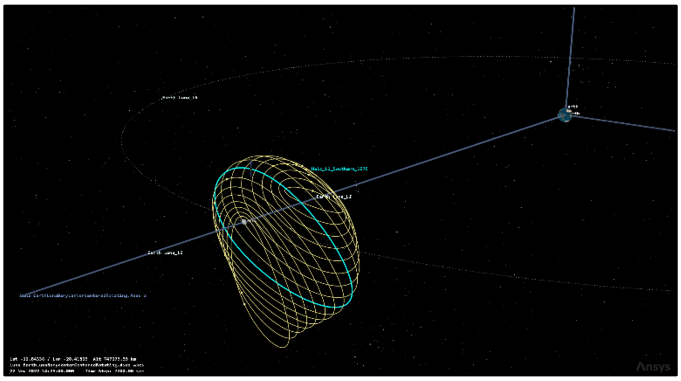


Fig – 11: Family of L1 halo orbits (filtered) in CODE. [55]

As related by J. Carrico, the technique called the "Receding Horizons Method" is something that he and colleagues used at NASA's Goddard Space Flight center (GSFC) in the 1990s to support the International Solar-Terrestrial Physics Science Initiative (ISTP) program [64] The method, as applied to NRHO orbits, is documented in [65] and [66]. As indicated by Williams et al. [66]:

"The receding horizon approach takes advantage of the knowledge that the rotating x component of velocity, Vx, is equal to zero at the Ry = 0 plane crossing for a periodic halo orbit in the CR3BP. The initial state from an NRHO converged for several revolutions in the higher-fidelity force model is selected as an input for the algorithm. The initial state is propagated to periapsis, where a differential corrector targets a maneuver to achieve Vx = 0 at the Ry = 0 plane crossing some number n_{rev} of revolutions downstream (i.e. the "horizon"). The spacecraft is then propagated to the next periapsis, and the process is repeated. " [66]

Commenting on this approach, J. Carrico added:

"The Vx = 0 constraint is a representation of these libration point periodic orbits having perpendicular plane crossings. But, because of transferring from the CR3BP to the full ephemeris model, a perpendicular plane crossing is just used as a first guess for the subsequent plane crossing, and therefore the constraint at crossing n is not held when targeting crossing n+1." [64]

J. Carrico [64] outlined and stepped through the following general process as we attempted to apply the approach toward creating and maintaining suitable L1 halo orbits:

- Utilize CODE [47] to identify an appropriate L1 halo orbit in the idealized C3RP "Earth-Luna" reference frame that could provide preliminary parameters for further propagation. There are particular "X-Z pairs" – i.e., amplitudes/distances about L1 in the X and Z planes – that afford some element of "bounded" stability; CODE enables a user to select from this continuum. In our case, there are 3378 orbits in the L1 Southern Orbit Family as represented in the CODE database; these data were "thinned down" to 1 out of 200 trajectories, to make the set more manageable. Finally, the "Halo_L1_Southern_1579" orbit was selected as most appropriate for our purposes (see Fig – 10 and Fig – 11).
- Transfer/convert this idealized orbit into an "Earth-Moon" reference frame and use the idealized parameters as initial state inputs for the Astrogator "full-force" cislunar propagator.
- Set up differential correctors in the Astrogator that target the plane crossings in the L1-frame, conducting maneuvers at these points and propagating to maintain the desired trajectory.
- Repeat this for additional spacecraft, phasing their orbits to provide desired coverage.

Note that the foundational orbit selected from CODE (Halo_L1_Southern_1579) is not "around" L1, per se. Rather, it orbits between the Moon/Luna and L1, with an inclination toward the Lagrange point when in view of the lunar southern polar region. The Z-axis amplitude ranges from about 28 000 km (positive) to 67 000 km (negative) from the Earth-Luna X-axis, which passes through L1, with a synodic period of roughly 11 days (see Fig – 10 and Fig – 11).

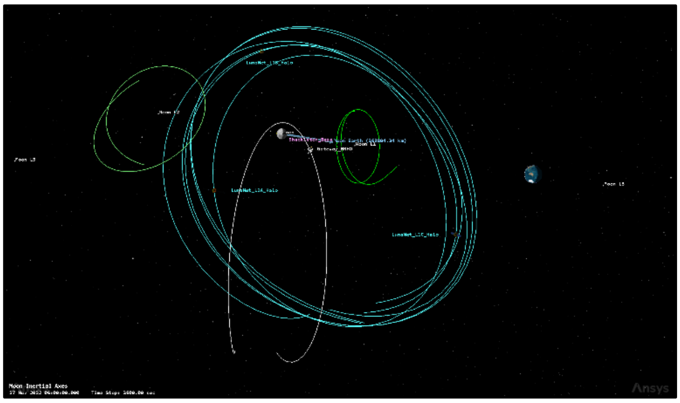


Fig – 12: "L1 Southern" alternative "Lagrange-Centric relay constellation developed with CODE/Astrogator.

This process facilitated the creation of three additional hypothetical LunaNet spacecraft in L1 halo orbit – LunaNet L1A, L1B, and L1C; we called this the "L1 Southern" constellation (see Fig – 12). An investigation of access and path delay associated with a "Lagrange-Centric" relay constellation was thereby possible, as an alternative to a "baseline" architecture that (at least initially) focuses on spacecraft in ELFO and LEQ [3, 4, 8, 10]. It is important to emphasize that the resulting orbits and phasing of these spacecraft are challenging to maintain over long periods of time without consistent, periodic adjustments. This is accentuated by the significant assistance that Mr. Carrico – an expert Astrogator – provided in creating and fine-tuning the Mission Control Sequences and associated impulsive maneuvers required to craft this constellation [57, 63].

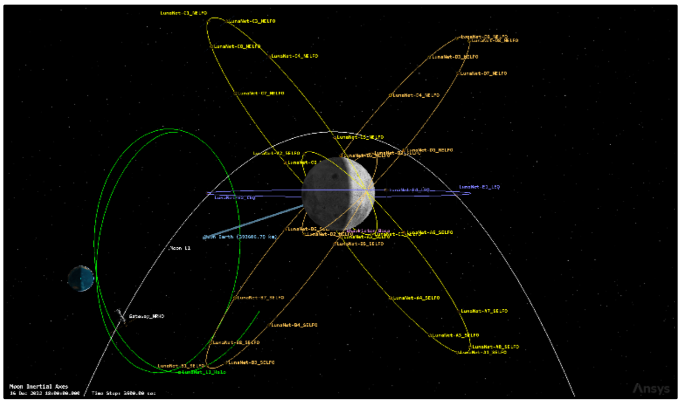


Fig – 13: Fully modeled cislunar orbits/constellations.

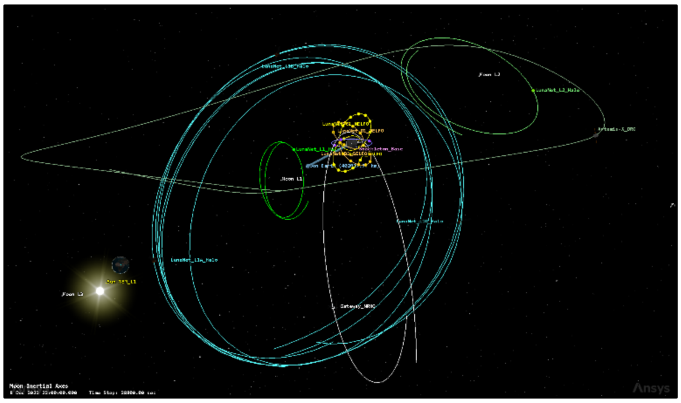


Fig – 14: Fully modeled cislunar orbits/constellations.

The full complement of spacecraft and constellations are illustrated in Fig – 13 and Fig – 14. Generic 3D satellite models (i.e., .MDL, .DAE. or .GBL files) as natively available in STK were used for the visual representations of the spacecraft in the scenario at higher magnifications. One exception is the model of the Gateway station, which was designed by Andreas Engevold [67], and used with permission under Creative Commons license.

4. LUNANET BASELINE: ACCESS INTERVALS/ DURATIONS AND PATH DELAYS

As implied in available literature, it is assumed that the U.S. cislunar communications architecture will scale as the human presence in that domain grows [1, 2, 3, 4, 5, 6, 7,8, 9, 10]. Early explorers near Shackleton Crater – whether during a short-term expedition or at a permanent base – may have no available relays in lunar orbit; hence they would be dependent upon direct LOS conditions for communication with terrestrial NASA ground stations. However, as Gateway and/or LunaNet spacecraft are deployed, communications opportunities between the Moon's surface, astronauts in lunar orbit, and researchers on Earth will increase in terms of frequency and duration.

The ideal scenario for multi-user, interactive, collaborative exploration – and the most stressing – is one in which in situ explorers, astronauts in lunar orbit on the Gateway station, *and* Earth-based researchers can collaborate simultaneously, as dynamically as possible, with the least interruptions and with minimal latency. Working toward that scenario highlights several critical links that can be realized via direct LOS communications or via spacecraft relay (i.e., via LunaNet):

- Shackleton Base to Gateway Station
- Shackleton Base to Earth (DSN/LEGS)
- Gateway to Earth (DSN/LEGS)
- LunaNet to Gateway
- LunaNet to LunaNet (i.e., intersatellite links)

The basic STK construct we devised allowed us to compute and visualize communications opportunities and estimate path delays between these key spacecraft and ground stations. Computation of access intervals helped determine how frequently two spacecraft and/or ground stations were within view of each other to facilitate direct communications. The *chain access* function enabled determination of multi-element links – that is, when more scenario components could make contact via relay by other available assets in series (e.g., "Ground Station-A-to Satellite X-to-Ground Station B"). This functionality is important, for instance, in determining how often – and for how long – the Gateway station has LOS and/or LunaNet-relayed communications opportunities with Shackleton Base over a given period of time. Also – as another example – when Shackleton Base can communicate with terrestrial NASA DSN/LEGS ground stations directly; or, with *both* DSN/LEGS and Gateway simultaneously, and for what periods of time, with and without relays.

Communications access intervals/durations and PD between Earth ground stations (i.e., DSN and LEGS), Shackelton Base, Gateway station, and other lunar orbiting spacecraft were estimated for several different scenarios representing phased deployment of relay satellites as recommended in LunaNet studies. Results are summarized below and in Table – 2 through Table – 7 and illustrated in Fig – 15 through Fig – 22. In the discussion, figures, and tables, these scenarios are referenced according to their constituents and links:

- Direct (No Relay): Represents a configuration/situation in which one resource can communicate directly with another, without an intermediate relay. For example, when the Shackleton Base has LOS visibility with the NASA DSN/LEGS network, or directly with the Gateway Station in lunar orbit. This may often be the case in the early stages of exploration, i.e., when LunaNet has not yet been robustly deployed. (Basic access computations.)
- Gateway: Represents a situation in which the Gateway station is operational and can also function as a relay between explorers in and around Shackleton Base and Earth. (Chain access to determine relay opportunities.)
-

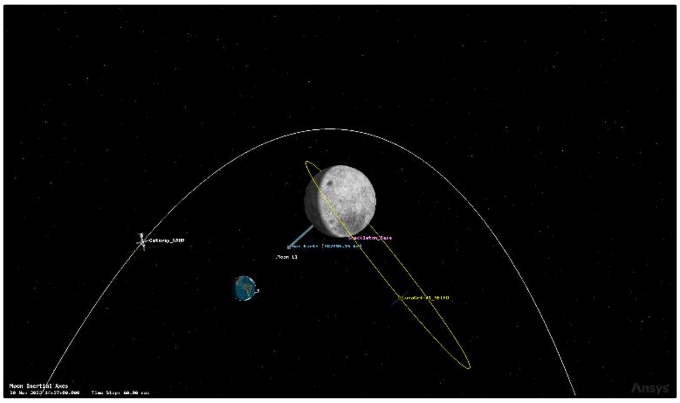


Fig – 15: Gateway + LunaNet A1.

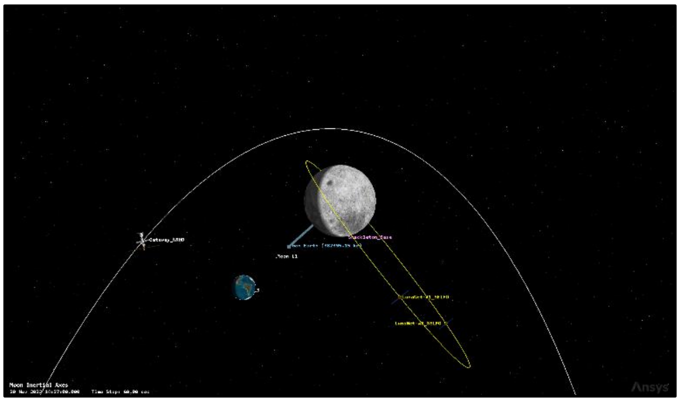


Fig – 16: Gateway + LunaNet A1/A2 (SELFO).

- LunaNet A1: Assumes that a single LunaNet spacecraft has been deployed in SELFO, but Gateway Station is not yet operational.
- Gateway + LunaNet A1 (as in Fig – 15): Incorporates both Gateway station and a single LunaNet spacecraft in SELFO.

  LunaNet A1 + LunaNet A2 (Fig – 16): Adds an additional LunaNet spacecraft in SELFO, phased 180 deg in mean anomaly from the first.
- LunaNet Baseline (Table 1, Fig – 7): The LunaNet Baseline architecture assumes that Gateway station and Shackleton Base are augmented by two communications spacecraft in lunar SELFO (LunaNet A1 and A2), two in lunar NELFO (LunaNet C1 and C2), and one in lunar equatorial orbit (LunaNet E1). This has been suggested by NASA's J. Schier [8], Chief Architect of NASA's Space Communications and Navigation (SCaN) Program, as a minimal constellation to provide "full coverage" of the Moon.

Note that all computations are generalized, based on idealized line-of-sight parameters; they do not consider factors such as terrain restrictions, antenna pointing (i.e., elevation) constraints, and other environmental or operational limitations. Neither does this study consider methods that could mitigate outages between Shackleton Base and the DSN/LEGS network; for instance, the deployment of antennas across the Moon's surface at advantageous points that would vastly improve communications [27]. Further, we focus on <u>maximum</u> PD/RTT, because this effort was primarily directed at understanding the most limiting conditions for access frequencies/durations and space-associated delay times; deeper analysis can be pursued in future research.

4.2 LunaNet Baseline Access Intervals: Details

Access intervals relate to the potential overall "up-time" of a collaborative exploration network; if there is no access between Earth-based explorers, astronauts in lunar orbit, and personnel on the surface, the ability for full, dynamic interaction in an immersive environment across the spectrum of possible users is effectively negated.

The simulation was first used to verify that the lunar NRHO proposed for the Gateway station would allow for near-continuous visibility/communications to NASA ground stations, with calculated access durations of 29.995 days for the DSN, and a full 30 days for DSN/LEGS. This is significant not just for astronauts aboard the station but also for explorers near Shackleton Base, since the station itself can serve as a relay to Earth.

Tangentially, calculations indicated that a LunaNet spacecraft in SELFO would have slightly less visibility to Earth than Gateway, with a total of 29.121 days of access to DSN/LEGS, for example, in a 30-day period; this highlights the value of the NRHO. So, from a technical perspective, a single dedicated LunaNet spacecraft might offer more in terms of tailored (technical) communications capacity, but – in this idealized SELFO – visibility to Earth is less than what Gateway can offer.

Without Gateway or LunaNet, Shackleton Base would have LOS communications with NASA ground stations for a little over half the 30-day period studied; 16.292 days for NASA DSN, and 16.743 days when LEGS stations are added to the terrestrial ground station architecture (see Table – 2).

This reflects the fact that the Moon's orbital inclination (i.e., the tilt of its orbit around Earth) and its obliquity (the axial tilt of its rotational axis) preclude direct visibility of the lunar southern pole from Earth for roughly half of each sidereal (inertially referenced) month [68, 69]. Again, this analysis is within our simplistic model – placing the outpost near -89.01701 deg 126.27302 deg, and neglecting consideration of terrain constraints, alternate basing options, positioning of surface antennas, etc. [27, 50, 51, 52]. Also note that since current proposed locations for NASA's LEGS facilities are in similar geographic regions to the current DSN nodes, their inclusion did not significantly impact access times. However, as indicated by [8] and [31], the primary intention of LEGS is to provide additional capacity for lunar missions and reduce contention for high-demand DSN resources.

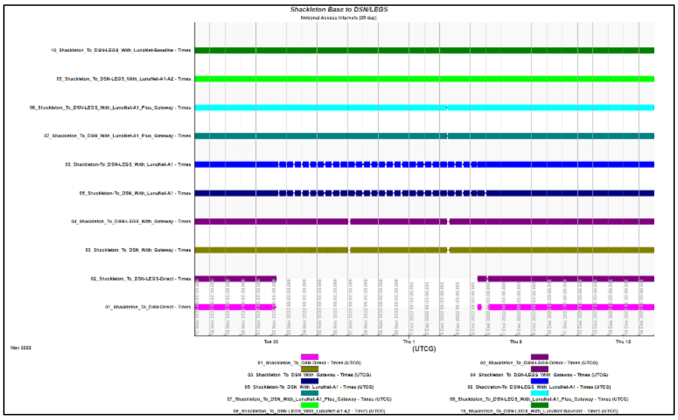


Fig – 17: Shackleton Base to Earth:
Access (days of coverage, 30-day period).

Table – 2: Shackleton Base to Earth: Access (days of coverage, 30-day period).

Cislunar Relay	NASA DSN	NASA DSN/LEGS
Direct (No Relay)	16.292	16.743
Gateway	29.655	29.659
LunaNet A1	26.755	26.876
Gateway + LunaNet A1	29.880	29.880
LunaNet A1 + LunaNet A2	30.000	30.000
LunaNet Baseline	30.000	30.000
***Alternative* LunaNet L1 Southern**	30.000	30.000

As expected, access intervals/durations between the area near Shackleton Base and Earth increased significantly as additional relays in lunar orbit were added to the scenario (see Fig – 17 and Table – 2).

When Gateway is deployed, Shackleton achieves up to 29.659 days of relay-enabled communications to NASA DSN/LEGS, with just a few access gaps (see Fig – 17 and Table – 2); this is a significant improvement on the roughly 50% “up-time” a collaborative exploration system would have in the absence of the station. Interestingly, owing to the orbital mechanics and long dwell time of the NRHO over the Moon’s southern hemisphere, Gateway provides roughly three more days of coverage than a configuration that includes a single LunaNet spacecraft (i.e., LunaNet A1) in SELFO (26.875 days). When LunaNet A1 complements Gateway, Shackleton Base achieves 29.880 out of 30 days of access to Earth.

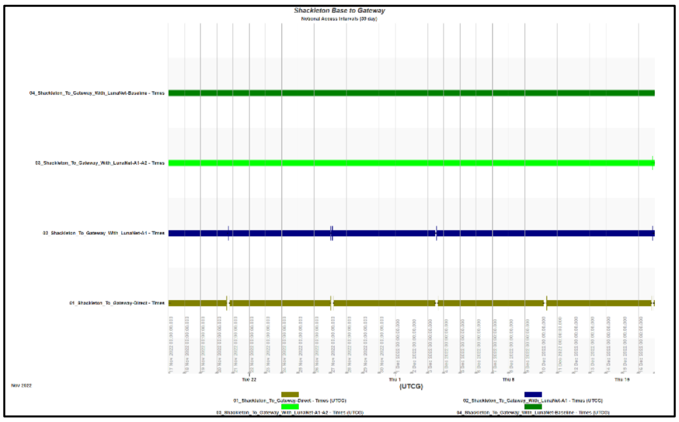


Fig – 18: Shackleton Base to Gateway:
Access (days of coverage, 30-day period).

Table – 3: Shackleton Base to Gateway: Access (days of coverage, 30-day period).

Cislunar Relay	Number of Days
Direct (No Relay)	29.159
LunaNet A1	29.799
LunaNet A1 + LunaNet A2	29.986
LunaNet Baseline	30.000
***Alternative*: LunaNet L1 Southern**	30.000

Finally, the possibility for uninterrupted connectivity between the base and terrestrial researchers is realized when both LunaNet A1 and A2 are deployed, yielding one month of continuous, relay-enabled access (see Fig – 17 and Table – 2). This 30-day coverage is maintained with inclusion of LunaNet C1 and C2 NELFO (i.e., LunaNet Baseline), presumably providing additional access pathways by virtue of the increased potential for intersatellite relay.

Access intervals/durations between Shackleton Base and the Gateway station under LOS and different LunaNet relay-enabled conditions were similarly computed (see Fig – 18 and Table – 3). Again, as a result of the southern hemisphere dwell afforded by the Gateway’s NRHO, Shackleton Base can have 29.159 days of LOS communications with the station, with several small gaps; over the one-month period; these interruptions occur mainly when the spacecraft swings through periapsis over the northern hemisphere of the Moon. The duration and frequency of these interruptions are reduced with the addition of LunaNet A1 (29.799 days) and A2 (29.986 days), and a full 30 days of availability is achieved if LunaNet Baseline is implemented. Under that final scenario, the additional NELFO and equatorial spacecraft close the remaining gaps by providing relay-enabled connectivity during the relatively short periods of time that Gateway passes through periapsis.

4.2 LunaNet Baseline Path Delays: Details

Higher one-way PD/LTT affects the propagation round-trip time (RTT) and the perceived "lag" in an interactive "user experience". For the 30-day simulation, PD was measured between:

- Gateway Station and Shackleton Base
- Gateway and the NASA DSN/LEGS
- Shackleton and the NASA DSN/LEGS, and
- Several combinations of idealized LunaNet spacecraft

While we can consider dynamic, minute-by-minute PD for each "strand" of the chain accesses calculated in our scenario, that is not necessarily useful/required in bounding our expectations for additional cislunar propagation delays. Focus was placed on determining the maximum PD associated with these links, since these probably represent limiting constraints and "worst-case scenarios" when considering user "quality of experience" associated with lag/latency.

Table – 4: Maximum PD/LTT (sec) between Gateway (GW), Shackleton Base (Base), DSN/LEGS (DSN), and LunaNet Baseline or alternative L1 Southern (L1) constellation.

From/To	GW	Base	LunaNet Baseline	L1	DSN
GW		0.233	0.263	0.339	1.408
Base	0.233		0.028	0.334	1.353
LunaNet Baseline	0.263	0.028	0.048		1.376
L1	0.339	0.334		0.377	1.329
DSN	1.408	1.353	1.376	1.329	

Intersatellite Delay

Table – 5: Maximum RTT (sec) between Gateway (GW), Shackleton Base (Base), DSN/LEGS (DSN), and LunaNet Baseline or alternative L1 Southern (L1) constellation.

From/To	GW	Base	LunaNet Baseline	L1	DSN
GW		0.466	0.526	0.678	2.816
Base	0.466		0.056	0.668	2.706
LunaNet Baseline	0.526	0.056	0.096		2.752
L1	0.678	0.668		0.754	2.658
DSN	2.816	2.706	2.752	2.658	

Intersatellite Delay

Table – 4 and Table 5 list the calculated maximum PD and RTT values for periods when there is access between scenario elements. Note that the maximum delay computed between Shackleton Base (i.e., "Base") and the NASA DSN/LEGS on Earth (i.e., "DSN") is about 1.353 s, or roughly 2.706 s round-trip; this is very close to the canonical 2.6 s RTT value generally accepted for the lunar surface Moon [18, 22]. Maximum PD between Gateway (i.e., "GW") and Earth is slightly longer at 1.408 s (2.816 s RTT); this is owing to the additional distance required for a signal to travel to reach the more remote portions of the NRHO. Maximum PD between baseline LunaNet spacecraft (SELFO, NELFO and LEQ orbits) and Earth splits these values at about 1.376 s (2.752 s RTT).

Closer to the Moon, PD values between Shackleton Base and spacecraft in lunar orbit are much lower. One-way latency between the base and Gateway station is about 0.233 s (0.466 s RTT). The maximum delay between Gateway and elements of the baseline LunaNet constellation is about 0.263 s (0.526 s RTT), and the longest intersatellite lag between LunaNet spacecraft is about 0.048 s (0.096 s RTT).

4.3 LunaNet Baseline: Access/Path Delay Example

Examining a specific "edge case" in our cislunar model can illustrate the significance for users on Earth and at the Moon of the additional communications relays. In particular, looking at what happens during the portion of the Gateway orbit that the station moves through periapsis is helpful. This occurs about four times in our 30-day simulation, notably at the following approximate times, reflecting the roughly 6- to 7-day period of NASA's reference Gateway NRHO orbit:

- 20 Nov 2022 16:56
- 27 Nov 2022 02:38
- 3 Dec 2022 13:12
- 10 Dec 2022 05:58
- 16 Dec 2022 21:04

During this time LOS communications to the base are "blocked" by the Moon itself, and the station would not have connectivity to Shackleton Base without either routing communications through terrestrial resources such as DSN/LEGS or a relay spacecraft (i.e., LunaNet). This lack of direct linkage would add latency to interactions between users at the station and base as a result of Earth-relayed communications, presumably complicating simultaneous, dynamic sessions between all participants (terrestrial, orbital, and Moon-based) in a collaborative system.

To visualize these conditions, we can "play through" 20 November 2022 in our scenario; during this "day in the life" of Gateway and Shackleton, the station transitions from its long dwell over the southern polar region of the Moon toward its close approach with the lunar surface over the northern hemisphere. On this day, without relay via Earth and/or lunar orbiting communications satellites, the two facilities temporarily lose direct contact.

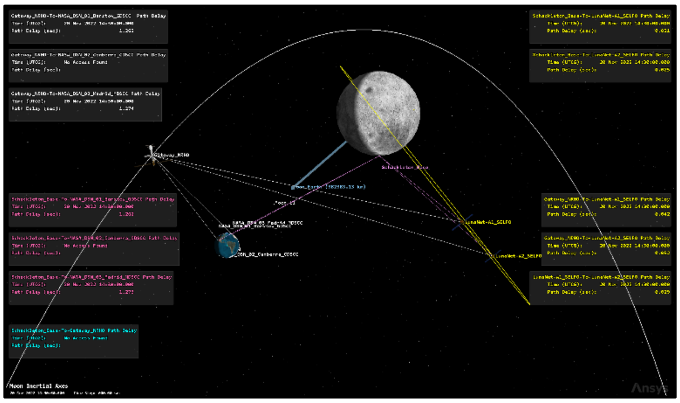


Fig – 19: Accesses and PD (20 Nov 2022/14:30 UTC): Gateway-Shackleton loss of LOS communications.

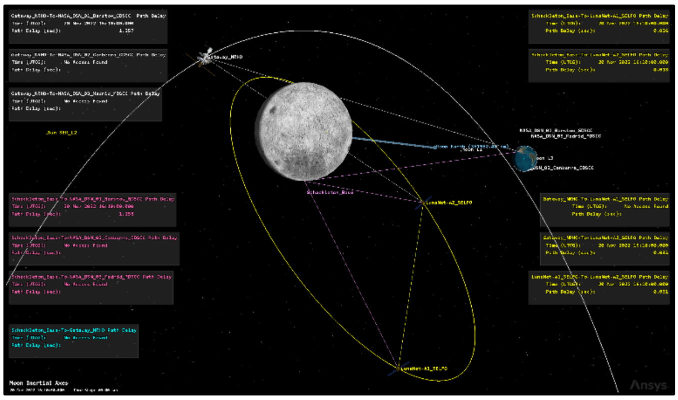


Fig – 20: Accesses and PD (20 Nov 2022/16:10 UTC): Loss of LOS between Gateway and LunaNet-A1 – satellite relay dependent on LunaNet A2.

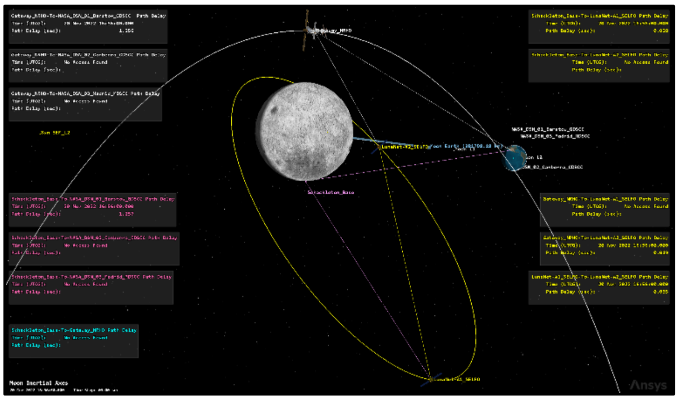


Fig – 21: Accesses and PD (20 Nov 2022/16:56 UTC): Gateway periapsis – communications dependent upon LunaNet A2-LunaNet A1 intersatellite relay.

Incrementally stepping through this day shows how availability of LunaNet spacecraft – specifically addition of LunaNet A1 and A2 in SELFO, optimized for southern polar coverage – can impact access intervals, durations, and PD/LTT (i.e., one half the total RTT) between the components. Particular attention is paid to the time around periapsis (i.e., 14:00 – 19:00 UTC), as this is the period wherein satellite relays become most important if "high-delay" routing through the DSN, for instance, is to be avoided; results are illustrated in Fig – 19 through Fig 21 and summarized in Table - 6. Note that intervals can begin or end in periods of "No Access"(i.e., N/A), and that PD/LTT values decrease as the components move toward each other (reducing range) and increase as they move farther apart.

The access interval and path delay calculations show that we begin the period with LOS visibility between the Gateway station and Shackleton Base, and one-way PD/LTT on the order of a tenth of a second. This delay gets even shorter as the station swings through its local point of closest approach (PCA) with the base, just before direct connectivity is lost at approximately 14:30 UTC (see Fig - 19). In the absence of satellite relays in lunar orbit (and, as mentioned earlier, any relay antennas on the surface), personnel aboard the station and base could communicate via the DSN until LOS visibility is re-established at about 18:50 UTC. However, throughout this time, the terrestrial link would impose a roughly 2.5 s PD/LTT between the spacecraft and the surface (i.e., Gateway-DSN-Shackleton path).

Alternatively, if LunaNet A1 and A2 are available, continuous contact with lower latency can be maintained when Gateway is out of LOS contact with the Moon's South Pole while passing through periapsis (see Table – 6 and Fig – 21). Values for PD/LTT as relayed via LunaNet during this approximate 4 hr 20 min period can be maintained at less than a tenth of a second.

Of interest, with the established orbital parameters for the spacecraft in this model, there is about 47 min between 16:10 and 16:57 UTC during which LunaNet-A2 is essential to continuous communication between the station and the base without relying on DSN/LEGS for relay. This is because Gateway loses LOS visibility to LunaNet-A1 at the beginning of that interval, and communications must pass via LunaNet A2, and/or A2-A1 intersatellite relay (see Fig – 20 and Fig – 21; Table - 6). Gateway passes through periapsis at about 16:56 UTC , and shortly thereafter regains contact with LunaNet-A1. Of course, it may be possible to obviate dependency on a second relay satellite with different phasing between LunaNet-A1 and Gateway.

Alternatively – the addition of LunaNet spacecraft in northern elliptical frozen orbits – such as LunaNet C1 and C2 – could provide substitute pathways between Gateway and Shackleton Base, occasionally at lower PD. For instance, at 17:46 UTC in our model, the inclusion of LunaNet C2 enables a relay link between Gateway and Shackleton with an aggregate PD of 0.025 s, as opposed to 0.061 s via LunaNet A1 (see Fig - 22). However, the NELFO spacecraft are optimized for northern latitude coverage, with periapsis near the south pole; consequently, the availability of these communications paths is more transient. More importantly, this overall "day-in-the-life" example illustrates how – under some conditions – at least two relay spacecraft may be required to maintain uninterrupted, low latency contact specifically between Gateway and a SPAB outpost.

Table – 6: Access and PD/LTT (sec) between Gateway and Shackleton Base near station periapsis (20 Nov 2022), considering availability of LunaNet A1 and A2 relays.

Interval Start Time (UTC)	Minimum Gateway-Shackleton PD/LTT (Route)	Comments
14:00	0.034 (LOS)	- Shackleton-A1 LOS acquired at 13:24
14:30	0.063 (via A1)	- Gateway-Shackleton LOS lost at 14:28 UTC
15:00	0.066 (via A1)	
15:30	0.064 (via A2)	
16:00	0.055 (via A2)	- Need A2 for continued non-DSN connectivity
16:10	0.049 (via A2)	- Need A2 for continued non-DSN connectivity during this interval - Gateway-A1 LOS lost at 16:10
16:35	0.086 (via A2-A1)	- Shackleton-A2 LOS lost at 16:35 - Since A2-Shackleton LOS lost at 16:35, can route from Gateway-A2-A1-Shackleton if available (0.086 s) - Or Gateway-DSN-Shackleton (2.514 s)
16:55	0.083 (via A2-A1)	- Since A2-Shackleton LOS lost at 16:35, can route from Gateway-A2-A1-Shackleton if available (0.083 s) - Or Gateway-DSN-Shackleton (2.513 s)
16:56		**Gateway Periapsis**
16:57	0.070 (via A1)	- Gateway-A1 LOS acquired at 16:57 - Can route Gatweay-A1-Shackleton (0.070s)
17:00	0.069 (via A1)	
17:30	0.064 (via A1)	
18:00	0.058 (via A1)	- A1-A2 intersatellite LOS lost at 17:39 - Gateway-A2 LOS lost at 18:02, regain at 18:25
18:30	0.052 (via A1)	- A1-A2 intersatellite LOS acquired at 18:24
18:50	0.025 (LOS)	- Gateway-Shackleton LOS acquired at 18:50

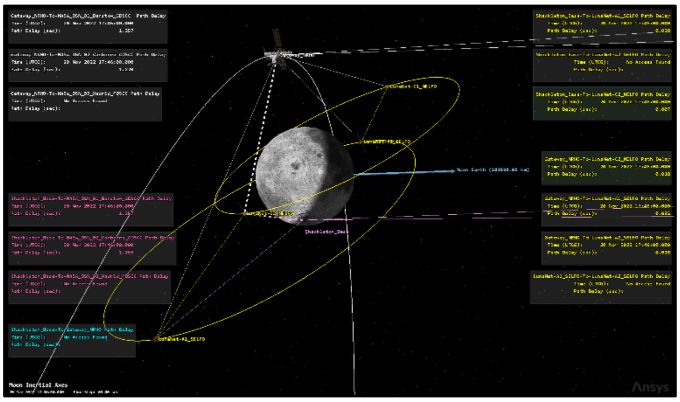


Fig – 22: Accesses and PD (20 Nov 2022/17:46 UTC): Alternate path with inclusion of LunaNet C2 NELFO.

5. ALTERNATIVE “LAGRANGE-CENTRIC” LUNANET CONSTELLATION

The alternative LunaNet “L1 Southern” constellation we constructed can be used to examine the implications on path delay and access intervals if a Lagrange-centric LunaNet constellation were pursued versus a system that is primarily based on relays in ELFO. Notably, by placing three spacecraft in L1 halo variant orbits, persistent relay-enable access between Gateway, Shackleton Base, and the NASA DSN/LEGS can be achieved throughout the one-month test period examined in this paper. Interval extent is listed in Table- 2 and Table – 3 and illustrated in Fig – 23 and Fig - 24.

Maximum PD and RTT values for the L1 Southern constellation (i.e., “L1”) are provided in Table – 4 and Table - 5. Recall that these spacecraft trajectories are based on the “Halo_L1_Southern_1579” orbit generated from the Ansys CODE cislunar orbit database, which has a period of about 11 days and is fairly large in terms of spatial extent (around 28,000 km to 67,000 km distance from the Earth-Moon X-axis). Consequently, the maximum PD values are higher for this constellation for intersatellite relay (about 0.377 s vs. 0.048 s for LunaNet Baseline), between the spacecraft and Shackleton (0.334 s vs. 0.028 s), and between the spacecraft and Gateway (0.339 s vs. 0.263 s). But, since the orbits are closer to Earth – i.e., toward L1 on the “Earth-facing” side of the Moon – the maximum PD between L1 spacecraft and the DSN/LEGS is slightly lower than for LunaNet baseline (1.329 s vs. 1.376 s).

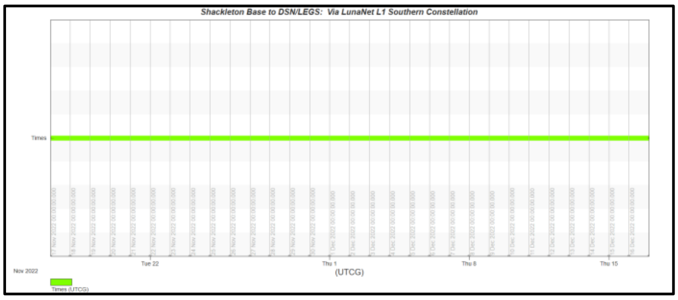


Fig – 23: Shackleton Base to Earth: Access (days of coverage, 30-day period), via L1 Southern constellation.

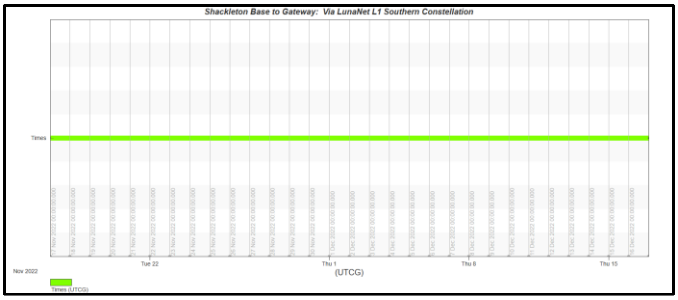


Fig – 24: Shackleton Base to Gateway: Access (days of coverage, 30-day period), via L1 Southern constellation.

As a general illustration of what this configuration might look like during an actual "contact session" see Fig – 25 and Fig – 26, showing the period of Gateway periapsis on 27 November 2022; this is the next periapsis following the "day in the life" example provided earlier. Interestingly, on this day, the location of Shackleton Base would be in the midst of a period during which direct (i.e., LOS) communications with Earth would not be possible for an extended period of time (about 2 weeks) without relays or distributed ground antennas. This is owing to the inclination and obliquity of the Moon's orbit. In effect, Shakleton is essentially "tilted away" from Earth.

At 02:38 UTC Gateway would be over the Moon's northern hemisphere at its closest point to the surface (periapsis), with no LOS communications to Shackleton Base due to lunar obstruction. If the L1 Southern constellation were available, the base would be able to communicate with the station with a total PD of 0.339 s and RTT of 0.678 s – i.e., via the Shackleton-LunaNet L1A-Gateway link. Similarly, Shackleton can connect to the DSN/LEGS via either LunaNet L1A-Canberra (PD 1.291 s, RTT 2.582) or LunaNet L1C-Canberra (PD 1.303 s, RTT 2.606 s). Gateway's minimum PD and RTT to the DSN would be 1.194 s and 2.388 s, respectively, to Canberra. Note, these times are higher than the roughly 400 ms RTT cited by [18]; however, recall that they were investigating control of a telerobotic system from L1 or L2, whereas we are exploring the delays associated with utilizing these locations as relays between the surface, Gateway, and Earth.

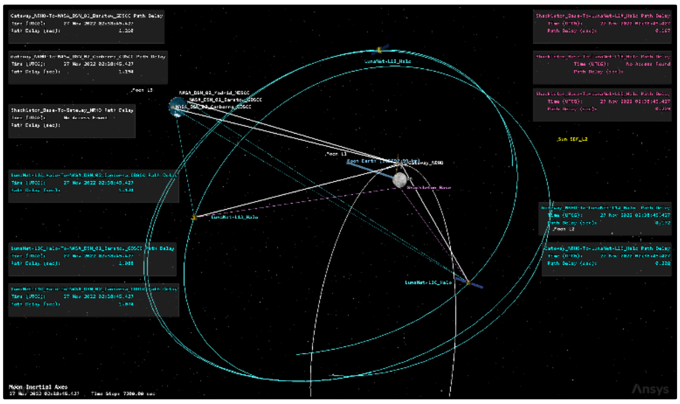


Fig – 25: Accesses and PD (27 Nov 2022/02:38 UTC): Gateway periapsis – access and PD via alternative L1 Southern constellation.

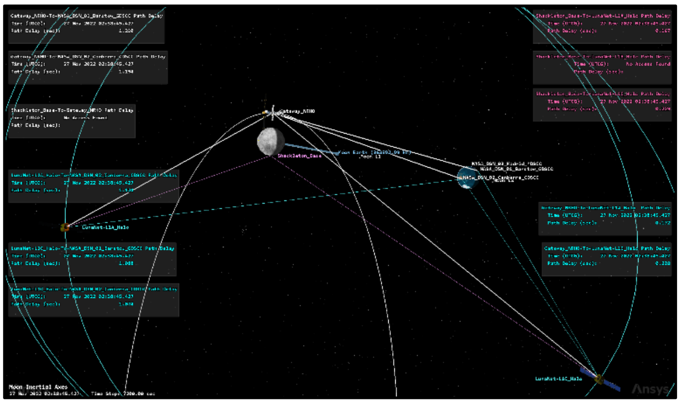


Fig – 26: Accesses and PD (27 Nov 2022/02:38 UTC): Gateway periapsis – access and PD via alternative L1 Southern constellation.

If LunaNet A1 and A2 were available at this time there would be also continuous access between Shackelton and Gateway, with a minimum PD of 0.056 s and RTT of 0.112 s – i.e., via the Shackleton-LunaNet A1-Gateway link. Shackleton could link to DSN Canberra via Luna Net A1 with a PD of 1.224 s and RTT of 2.448 s, and Gateway's times to the DSN remain unchanged (see Fig – 27 and Fig – 28).

Table – 7 provides a summary of the comparative PD/RTT times for the LunaNet Baseline and L1 Southern constellations during this particular periapsis time. Again, we provide the L1 Southern configuration solely as an example of a potential alternative – a "What If?" scenario – to help define latency expectations for the purposes of this paper. The construct is more complicated than the LunaNet Baseline architecture in terms of the astrodynamics required to achieve and maintain the orbits and phasing of the L1 spacecraft (as evidenced by the expertise required to help model it in STK for this general study).

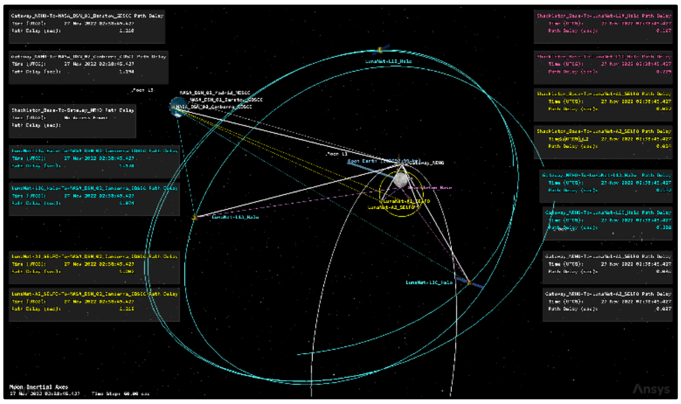


Fig – 27: Accesses and PD (27 Nov 2022/02:38 UTC): Gateway periapsis – LunaNet Baseline LunaNet and L1 Southern constellation, access and PD comparison.

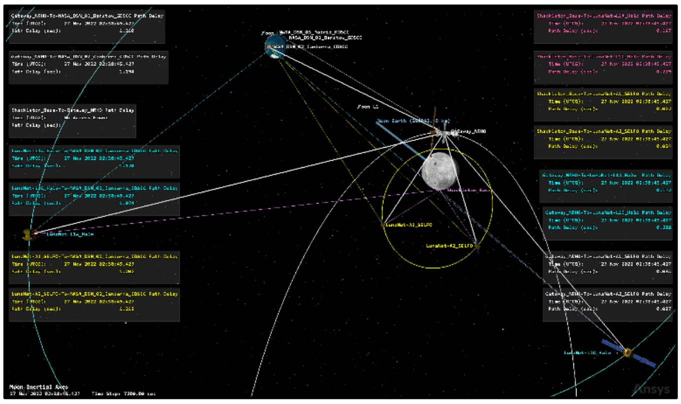


Fig – 28: Accesses and PD (27 Nov 2022/02:38 UTC): Gateway periapsis – LunaNet Baseline LunaNet and L1Southern constellation, access and PD comparison.

Table – 7: Gateway Periapsis – 02:38 UTC / 27 Nov 2022: Comparative PD/RTT (sec) between Gateway and Shackleton Base with LunaNet Baseline or alternative L1 Southern (L1) constellations.

	Gateway to Shackleton	Shackleton To DSN	Gateway to DSN
LunaNet Baseline	0.056 / 0.112	1.224 / 2.448	1.194 / 2.388
L1	0.339 / 0.678	1.291 / 2.582	1.194 / 2.388

Faster

Further, while maximum PD between L1 spacecraft and Earth (i.e., the DSN/LEGS) can be slightly lower than for ELFO satellites orbiting closer to the Moon (1.329 s vs. 1.376 s), the “in-system”/circumlunar transmission times using a Lagrange-centric constellation can be significantly higher (see Table – 4 and Table – 5). This is particularly true when large L1 orbit amplitudes/distances are adopted (as in our case) to provide good, continuous visibility to the southern polar region.

That being said, positioning relay satellites around L1 in this manner may offer some advantages in terms of tracking and communicating with the spacecraft from Earth. Also, although the overall PD/RTT between Shackleton and the DSN/LEGS and Shackleton and Gateway might be longer when using L1 relays, the times and access intervals might be more consistent and predictable. Consequently, it is likely that Lagrange spacecraft will be components of a more robust LunaNet system. While we do not engage in an exhaustive discussion of the possible benefits, limitations, and constraints of the L1 Southern constellation in this paper, it would be interesting to explore it in more detail in the future.

6. CONCLUSIONS

In this article we discuss the use of AGI STK software and associated modules (i.e., Astrogator and CODE) to model two hypothetical cislunar satellite communications constellations and study associated access intervals and path delays (i.e., light travel times). We examined a constellation based on NASA LunaNet plans (i.e., LunaNet Baseline) and an alternative “Lagrange-Centric” construct (L1 Southern). Focusing on periapsis conditions for the planned Gateway lunar space station, we illustrated the dependence on lunar satellite relays to maintain low latency contact between orbiting astronauts and surface explorers at the Moon’s South Pole. Further, we found that idealized round-trip signal times between a notional South Pole outpost, Earth, and Gateway were shorter using relays in elliptical orbits than via those in our Lagrange model.

This study was done to become more familiar with satellite relay dependencies in two different cislunar constellations, each with possible advantages. We also sought to establish some conservative expectations for path associated “lag” when considering options for dynamic, simultaneous interaction between participants on Earth, in lunar orbit, and on the Moon’s surface. The experience and findings will contextualize future work in conceptualizing virtual environments for collaborative, interactive, immersive multi-user cislunar and interplanetary space exploration.

ACKNOWLEDGEMENT

The authors would like to thank Ansys Government Initiatives (AGI) for academic licensing and the use of Systems ToolKit (STK), Astrogator, and the Cislunar Orbit Designer (CODE) during this study.

Additionally, the authors would like to thank their families and Capitol Technology University for supporting this research.

REFERENCES

[1] NASA, “NASA’s Lunar Exploration Program Overview,” NASA, NP-2020-05-2853-HQ, Sep. 2020. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

[2] S. Bhamidipati, T. Mina, and G. X. Gao, “A Case Study Analysis for Designing a Lunar Navigation Satellite System with Time Transfer from the Earth GPS,” *Navigation: Journal of the Institute of Navigation*, vol. 70, no. 4, p. navi.599, Jan. 2023, doi: 10.33012/navi.599.

[3] S. Bhamidipati, T. Mina, A. Sanchez, and G. X. Gao, “Satellite constellation design for a lunar navigation and communication system,” *Navigation: Journal of the Institute of Navigation*, vol. 70, no. 4, p. navi.613, Jan. 2023, doi: 10.33012/navi.613.

[4] D. Israel, N. Abu, and N. Babu, “Draft LunaNet Interoperability Specification (LNIS V005),” NASA, LNIS V005, Aug. 2023. Accessed: Mar. 05, 2024. [Online]. Available: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/lunanet-interoperability-specification/

[5] Johnson, Mortensen, Chavez, and Woodland, “Gateway – a communications platform for lunar exploration,” *38th International Communications Satellite Systems Conference (ICSSC 2021)*, pp. 9–16, 2021, doi: 10.1049/icp.2022.0544.

[6] K. Mauldin, D. Israel, L. V. Cooper, and K. Schauer, “LunaNet: A Flexible and Extensible Lunar Exploration Communications and Navigation Infrastructure and the Inclusion of SmallSat Platforms,” *DigitalCommons@USU*, Aug. 2020. Available: https://digitalcommons.usu.edu/smallsat/2020/all2020/171/

[7] M. Murata, K. Iiyama, Japan Aerospace Exploration Agency, and Stanford University, “Lunar Navigation Satellite System (LNSS) and its demonstration mission,” Oct. 2022. Accessed: Mar. 21, 2024. [Online]. Available: https://www.unoosa.org/documents/pdf/icg/2022/ICG16/WG-B/ICG16_WG-B_03.pdf

[8] J. Schier, “LunaNet Overview,” *NASA Engineering and Safety Center Academy (NESCA)*, Jun. 2022. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjx5rXzmd6EAxWRGVkFHZYNCUIQFnoECBMQAQ&url=https%3A%2F%2Fnescacademy.nasa.gov%2FdownloadFile%2F1208&usg=AOvVaw1YqcLTk6Hp9-eeicULkIO_&opi=89978449

[9] J. Schier and C. Dischinger, “Overview of LunaNet & Worksite Design and Lighting,” *NASA Engineering and Safety Center Academy (NESCA)*. Jun. 09, 2022. Accessed: Mar. 06, 2024. [Online]. Available: https://nescacademy.nasa.gov/video/ddf2b306796040828c7b3bba225099cd1d

[10] Schönfeldt, Grenier, Delépaut, Swinden, Giordano, and J. Ventura-Traveset, “Across the lunar landscape: towards a dedicated lunar PNT system,” *Inside GNSS - Global Navigation Satellite Systems Engineering, Policy, and Design*, Inside GNSS, Dec. 08, 2020. Accessed: Mar. 21, 2024. [Online]. Available: https://insidegnss.com/across-the-lunar-landscape-towards-a-dedicated-lunar-pnt-system/

[11] S. Becker and M. Johnson, “Extended Reality In U.S. Spaceflight Operations: A Review Of Historic And Potential Future Applications,” *International Research Journal of Engineering and Technology (IRJET)*, vol. 12, no. 02, pp. 444–469, Feb. 2025, [Online]. Available: https://www.irjet.net/archives/V12/i2/IRJET-V12I262.pdf

[12] KISS, “Space Science Opportunities Augmented by Exploration Telepresence,” W. M. Keck Institute for Space Studies (KISS), 103794, Jun. 2020. doi: 10.7907/w6ma-a113.

[13] T. Fong, “Surface telerobotics: Development and Testing of a Crew Controlled Planetary Rover System,” *National Aeronautics and Space Administration (NASA) Technical Reports Server*, 2016. Available: https://ntrs.nasa.gov/api/citations/20160006511/downloads/20160006511.pdf

[14] H. Thronson, A. Valinia, J. Bleacher, J. Eigenbrode, J. Garvin, and N. Petro, “Low-Latency Science Exploration of Planetary Bodies: A Demonstration using ISS in Support of Mars Human Exploration,” journal-article, 2013. Accessed: Jan. 23, 2025. [Online]. Available: https://ntrs.nasa.gov/api/citations/20140017468/downloads/20140017468.pdf

[15] M. L. Lupisella and M. S. Race, “Low-latency teleoperations, planetary protection, and astrobiology,” *International Journal of Astrobiology*, vol. 17, no. 3, pp. 239–246, Nov. 2017, doi: 10.1017/s1473550417000374.

[16] A. Valinia *et al.*, “LOW-LATENCY TELEROBOTICS FROM MARS ORBIT: THE CASE FOR SYNERGY BETWEEN SCIENCE AND HUMAN EXPLORATION,” *Lunar and Planetary Institute (LPI) Concepts and Approaches for Mars Exploration*, 2012, Accessed: Jan. 21, 2025. [Online]. Available: https://www.lpi.usra.edu/meetings/marsconcepts2012/pdf/4214.pdf

[17] T. Fong, "Telerobotics for Human Exploration Enhancing crew capabilities in deep space," *National Aeronautics and Space Administration (NASA) Technical Reports Server*, 2014. Available: https://ntrs.nasa.gov/api/citations/20140005543/downloads/20140005543.pdf

[18] D. Lester and H. Thronson, "Low-Latency Lunar Surface Telerobotics from Earth-Moon Libration Points," 2011. Accessed: Jan. 23, 2025. [Online]. Available: https://ntrs.nasa.gov/api/citations/20110022582/downloads/20110022582.pdf

[19] Aerospace Corporation, "Project Phantom: Furthering Space Exploration with Virtual and Augmented Reality | The Aerospace Corporation," *Aerospace Corporation*, Dec. 01, 2024. Available: https://aerospace.org/article/project-phantom-furthering-space-exploration-virtual-and-augmented-reality (Accessed Jan. 12, 2025).

[20] D. Haddad, "Responsive Space Environments: New Paradigms in Blending Virtual and Physical Exploration through Human-Robot Operations," PhD Dissertation, Massachusetts Institute of Technology, 2023. [Online]. Available: https://resenv.media.mit.edu/pubs/theses/haddad-ddh-PhD-MAS-2023-thesis.pdf

[21] S. Becker and M. Johnson, "Extended Reality: History, Concepts, and Techniques," *International Research Journal of Engineering and Technology (IRJET)*, vol. 12, no. 02, pp. 237–262, Feb. 2025, [Online]. Available: https://www.irjet.net/archives/V12/i2/IRJET-V12I235.pdf

[22] D. Lester and H. Thronson, "Human space exploration and human spaceflight: Latency and the cognitive scale of the universe," *Space Policy*, vol. 27, no. 2, pp. 89–93, 2011, doi: 10.1016/j.spacepol.2011.02.002.

[23] D. Lester, "Achieving human presence in space exploration," *MIT Press Journals & Magazine | IEEE Xplore*, Nov. 2013, Accessed: May 31, 2022. [Online]. Available: https://ieeexplore.ieee.org/document/6818646

[24] ESA, "Telerobotics: Ground-based Rover's Touch Shared with Astronaut in Space," *Eurpoean Space Agency (ESA) eoPortal.org*, Jul. 27, 2022. Available: https://www.eoportal.org/other-space-activities/telerobotics-1#telerobotics-ground-based-rovers-touch-shared-with-astronaut-in-space (Accessed Jan. 09, 2025).

[25] J. Crusan, "Gateway Update," *NASA Advisory Council / Technology, Innovation and Engineering Committee*, Dec. 07, 202018. Available: https://www.nasa.gov/wp-content/uploads/2015/03/nac_tie_december_2018_jcrusan_gateway.pdf (Accessed Oct. 27, 2023).

[26] AGI, "Welcome to Systems Tool Kit 12," *Ansys Government Initiatives (AGI)*, 2025. Available: https://help.agi.com/stk/ (Accessed Mar. 22, 2024).

[27] M. C. Scardelletti *et al.*, "Lunar Surface Network Relay Terminal: a Lunar communications platform," *NASA Technical Reports Server (NTRS)*, Oct. 23, 2023. Available: https://ntrs.nasa.gov/citations/20230013361 (Accessed Aug. 10, 2024).

[28] ESA, "Moonlight Services: Seeking feedback for updated LunaNet framework," Sep. 25, 2023. Available: https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Moonlight/Moonlight_services_seeking_feedback_for_updated_LunaNet_framework (Accessed Jul. 31, 2024).

[29] SpaceNews, "ESA advances its plan for satellites around the moon," *SpaceNews*, SpaceNews, May 25, 2021. Accessed: Jul. 31, 2024. [Online]. Available: https://spacenews.com/esa-advances-its-plan-for-satellites-around-the-moon/

[30] S. Chang, "SCaN Updates," *National Aeronautics and Space Administration (NASA)*, Nov. 20, 2023. Available: https://www.nasa.gov/wp-content/uploads/2023/12/nac-scan-heo-nac-nov2023-11-20-tagged.pdf

[31] J. Volosin, "SCaN Program Presentation to the National Academies Decadal Survey in Solar and Space Physics/Heliophysics, Working Group on Communications Infrastructure & Innovations," *National Aeronautics and Space Administration (NASA)*, Sep. 07, 2023. Available: https://ntrs.nasa.gov/api/citations/20230013074/downloads/SCaN%20National%20Academies%20Brief%20September%202023%20Final.pdf

[32] T. Gardner *et al.*, "CAPSTONE: a summary of a highly successful mission in the Cislunar environment," Small Satellite Conference, Aug. 2023. Accessed: Apr. 17, 2024. [Online]. Available: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5595&context=smallsat

[33] G. D. Krebs, "Gunter's Space Page," *Gunter's Space Page*, May 01, 2023. Available: https://space.skyrocket.de/doc_sdat/queqiao-1.htm (Accessed Jun. 26, 2024).

[34] NASA GSFC, "NASA Space Science Data Coordinated Archive - Goddard Spaceflight center (GSFC)," *NSSDCA | Spacecraft*, 2022. Available: https://nssdc.gsfc.nasa.gov/nmc/SpacecraftQuery.jsp (Accessed Jun. 26, 2024).

[35] M. Ye *et al.*, "The precise positioning of lunar farside lander using a four-way lander-orbiter relay tracking mode," *Astrophysics and Space Science*, vol. 363, no. 11, Oct. 2018, doi: 10.1007/s10509-018-3421-z.

[36] L. Zhang, "Development and prospect of Chinese lunar relay communication satellite," *Space: Science & Technology*, vol. 2021, Jan. 2021, doi: 10.34133/2021/3471608.

[37] The Planetary Society, "Queqiao-2: China's Bridge for Lunar Exploration," *The Planetary Society*, Mar. 20, 2024. Available: https://www.planetary.org/space-missions/queqiao-2-chinas-bridge-for-lunar-exploration (Accessed Jun. 26, 2024).

[38] A. Jones, "China appears to be trying to save stricken spacecraft from lunar limbo," *SpaceNews*, Mar. 28, 2024. Available: https://spacenews.com/china-appears-to-be-trying-to-save-stricken-spacecraft-from-lunar-limbo/ (Accessed Jun. 26, 2024).

[39] A. Jones, "China rescues stranded lunar satellites," *IEEE Spectrum*, IEEE Spectrum, Feb. 18, 2025. [Online]. Available: https://spectrum.ieee.org/china-saves-dro-moon-mission

[40] S. Li, "High-fidelity Autonomous Navigation Based On DRO-LEO Inter-satellite Links.," *ResearchGate*, Aug. 2022, [Online]. Available: https://www.researchgate.net/publication/366538221_High-fidelity_Autonomous_Navigation_Based_On_DRO-LEO_Inter-satellite_Links

[41] A. Jones, "Chinese scientists outline major cislunar space infrastructure project," *SpaceNews*, Jul. 30, 2024. Available: https://spacenews.com/chinese-scientists-outline-major-cislunar-space-infrastructure-project/

[42] M. Yang *et al.*, "Architecture and development envision of cislunar space infrastructure," *Chinese Space Science and Technology*, vol. 44, no. 3, Jun. 2024, doi: 10.16708/j.cnki.1000-758X.2024.0034.

[43] NASA JPL, "Horizons System," *National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL)*, Dec. 21, 2023. Available: https://ssd.jpl.nasa.gov/horizons/ (Accessed Mar. 22, 2024).

[44] K. Mars, "Orion will go the distance in retrograde orbit during Artemis I - NASA," *NASA*, Apr. 18, 2022. Available: https://www.nasa.gov/missions/orion-will-go-the-distance-in-retrograde-orbit-during-artemis-i/ (Accessed Apr. 03, 2024).

[45] H. Monaghan, "What is the Deep Space Network?," *National Aeronautics and Space Administration (NASA)*, Mar. 30, 2020. Available: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/what-is-the-deep-space-network/ (Accessed Apr. 15, 2024).

[46] NASA, *Space Communications and Navigation (SCAN) overview*. National Aeronautics and Space Administration (NASA), 2022. [Online]. Available: https://explorers.larc.nasa.gov/HPSMEX22/pdf_files/11_HEP22PPC_SCaN_Overview_Hayes.pdf

[47] NASA JPL, "How NASA's deep space network supports the agency's missions," *National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL)*, 2022. Available: https://www.jpl.nasa.gov/news/how-nasas-deep-space-network-supports-the-agencys-missions (Accessed Apr. 15, 2024).

[48] NASA, *Space Communications and Navigation (SCAN) overview*. National Aeronautics and Space Administration (NASA), 2022. [Online]. Available: https://explorers.larc.nasa.gov/HPSMEX22/pdf_files/11_HEP22PPC_SCaN_Overview_Hayes.pdf

[49] N. T. Tillman, "NASA's Deep Space Network: How spacecraft phone home," *Space.com*, Feb. 02, 2018. Available: https://www.space.com/39578-deep-space-network.html (Accessed Apr. 15, 2024).

[50] Boyce, "Research provides details of possible NASA Moon landing sites," *Univerrsity of Alaska Fairbanks (UAF) News and Information*, Univerrsity of Alaska Fairbanks (UAF), Oct. 28, 2022. Accessed: Apr. 19, 2024. [Online]. Available: https://www.uaf.edu/news/research-provides-details-of-possible-nasa-moon-landing-sites.php

[51] NASA, "NASA identifies candidate regions for landing next Americans on Moon," *National Aeronautics and Space Administration (NASA)*, Aug. 19, 2022. Available: https://www.nasa.gov/news-release/nasa-identifies-candidate-regions-for-landing-next-americans-on-moon/ (Accessed Apr. 19, 2024).

[52] S. Gracy and P. Lee, "CANDIDATE LANDING SITES FOR ARTEMIS 3 IN TWO NASA CANDIDATE LANDING REGIONS NEAREST THE LUNAR SOUTH POLE," *55th Lunar and Planetary Science Conference (LPSC) 2024*, Art. no. 1695, Mar. 2024, [Online]. Available: https://www.hou.usra.edu/meetings/lpsc2024/pdf/1695.pdf

[53] NASA, "What are Lagrange Points?," *National Aeronautics and Space Administration (NASA) Science*, Jul. 2012. Available: https://science.nasa.gov/solar-system/resources/faq/what-are-lagrange-points/ (Accessed Oct. 27, 2023).

[54] The Astrogator's Guild, "Trajectory Design with STK/Astrogator Earth-Moon L1 Trajectory," *The Astrogator's Guild*, 2005. Available: https://astrogatorsguild.com/ (Accessed Mar. 06, 2024).

[55] C. Short, P. Ghosh, and A. Claybrook, "Revisiting Trajectory Design with STK Astrogator, Part 1," *Astrodynamics Specialist Conference*, vol. AAS 19-824, Aug. 2019, [Online]. Available: https://www.researchgate.net/publication/336074120_Revisiting_Trajectory_Design_with_STK_Astrogator_Part_1

[56] C. Short, L. Kay-Bunnell, D. Cather, and N. Kinzly, "Revisiting Trajectory Design with STK Astrogator, Part 2," *AAS/AIAA Astrodynamics Specialist Conference*, vol. AAS 21-561, Aug. 2021, [Online]. Available: https://www.researchgate.net/publication/354555431_Revisiting_Trajectory_Design_with_STK_Astrogator_Part_2

[57] J. Carrico, D. Cather, G. Corrao, and J. Woodburn, "Revisiting Trajectory Design with STK Astrogator, Part 3," *AAS Astrodynamics Specialist Conference*, vol. AAS 23-409, Aug. 2023, [Online]. Available: https://www.researchgate.net/publication/373329159_Revisiting_Trajectory_Design_with_STK_Astrogator_Part_3

[58] Ansys, Inc., "Mission Design and Performance Analysis Made Easy with Ansys STK's Cislunar Orbit Designer," *Ansys, Inc.*, Apr. 03, 2024. Available: https://www.ansys.com/blog/mission-design-performance-analysis-stk-cislunar-orbit-designer (Accessed Jul. 17, 2024).

[59] M. Exnicious, C. Short, T. Brooks, and D. Cather, "Exploring an AI/ML Approach to Automating the Transition from the Circular Restricted Three-Body Problem to Higher Fidelity Solutions, Part 1," *AAS Astrodynamics Specialist Conference*, vol. AAS 24-479, Aug. 2024, [Online]. Available: https://www.researchgate.net/publication/384112922_An_Architectural_Concept_for_Multibody_Dynamical_Systems_Trajectory_Design_with_STK_Astrogator

[60] C. Short, M. Exnicious, G. Corrao, and D. Cather, "An Architectural Concept for Multibody Dynamical Systems Trajectory Design with STK Astrogator," *AAS Astrodynamics Specialist Conference*, vol. AAS 24-352, Aug. 2024, [Online]. Available: https://www.researchgate.net/publication/384112922_An_Architectural_Concept_for_Multibody_Dynamical_Systems_Trajectory_Design_with_STK_Astrogator

[61] N. Policht and Ansys, "Ansys Online Training: Astrogator Circular Reistricted Three-Body Problem Configuration," *YouTube*, Apr. 04, 2023. Available: https://www.ansys.com/services/ansys-learning-hub (Accessed Jul. 24, 2024).

[62] C. Short and Ansys, "What's new in Ansys 2023 R2: Cislunar Mission Enhancements," *YouTube*. Jul. 25, 2023. Accessed: Jul. 24, 2024. [Online]. Available: https://www.youtube.com/watch?v=UfGdc9ouzB0

[63] Space Exploration Engineering (SEE), "Space Exploration Engineering | Our Team," *Space Exploration Engineering (SEE)*, 2024. Available: https://see.com/our-team/ (Accessed Jul. 17, 2024).

[64] J. Carrico, "Personal Communication," Jul. 08, 2024.

[65] D. Davis *et al.*, "Orbit Maintenance and navigation of human spacecraft at Cislunar near rectilinear Halo Orbits," in *NASA Technical Reports Server (NTRS)*, San Antonio, Texas, United States of America, Feb. 05, 2017. [Online]. Available: https://ntrs.nasa.gov/citations/20170001347

[66] J. Williams, D. E. Lee, R. J. Whitley, K. A. Bokelmann, D. C. Davis, and C. F. Berry, "Targeting Cislunar Near Rectilinear Halo Orbits for Human Space Exploration," in *NASA Technical Reports Server (NTRS)*, San Antonio, Texas, United States of America, Feb. 05, 2017. [Online]. Available: https://ntrs.nasa.gov/citations/20170001352

[67] A. Engevold [andreas9343], "Gateway Station 3D Model," *Sketchfab*, 2021. Available: https://sketchfab.com/3d-models/gateway-57c6a27313794618a299ebe9ec8c2afd (Accessed May 17, 2024).

[68] NASA, "NASA's Lunar Communications and Navigation Architecture," 2023. Accessed: Aug. 07, 2024. [Online]. Available: https://ntrs.nasa.gov/api/citations/20230016359/downloads/Lunar%20Communications%20and%20Navigation%20Architecture.pdf

[69] NASA Visible Earth, "NASA Visible Earth - Home." Available: https://visibleearth.nasa.gov/

BIOGRAPHIES

Savan C. Becker
Doctoral Student
Department of Engineering
Capitol Technology University
Laurel, MD, USA

Michael E. Johnson, PhD
Adjunct Professor
Department of Engineering
Capitol Technology University
Laurel, MD, USA

John Carrico Jr.
Chief Technology Officer,
Astrogator & Technical Advisor
Space Exploration Engineering
Laurel, MD, USA