Analysis of a LEO Constellation Network as a Ground Station for Lunar Communications

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***Abstract*—This paper presents a systems analysis of a next-generation lunar communication architecture from a wireless engineering perspective. The study evaluates and compares the performance of the NASA Deep Space Network (DSN) and a low Earth orbit (LEO) constellation as ground station options for a lunar communication system consisting of three satellites in distinct 12-hour orbits: a circular equatorial orbit, a north elliptical orbit, and a south elliptical orbit. The DSN comprises ground stations in Goldstone, Madrid, and Canberra, while the LEO constellation is modeled as a 24-satellite Walker Delta configuration at 600 km altitude.**

Simulation results reveal that employing a LEO constellation as a ground station provides significantly greater resilience, with an average of 23 line-of-sight (LOS) links available to the lunar constellation, compared to only 2 LOS links for the DSN. While cone angles were large for both architectures, exceeding 70°, the LEO constellation demonstrated the potential to reduce these angles by leveraging alternative LOS links. Future work will focus on refining RF parameters for the LEO satellites and developing a more optimal LOS link selection algorithm to enhance the reliability and efficiency of the proposed system.

I. Introduction

NASA's renewed interest in the Moon through the Artemis missions [1], along with international competition to establish a sustained presence on the lunar surface, has prompted the need for a next-generation lunar communication architecture capable of providing high capacity and connectivity [2], [3]. While these architectures have been extensively researched from an astrodynamics perspective, few studies offer detailed analysis from a wireless engineering standpoint, particularly concerning the link performance of these proposed systems. Conducting a realistic link analysis for lunar communication satellites, beyond assessing contact times, can yield valuable insights into critical parameters such as mass and power requirements for spacecraft communication systems.

Recent advances in reducing launch vehicle costs have enabled more satellites to be deployed into orbit each year at lower prices. Notably, SpaceX's Starlink network, with over 6,000 satellites at the time of writing, has shifted the satellite communication paradigm from traditional geosynchronous Earth orbit (GEO) systems to low Earth orbit (LEO) constellations. LEO is typically defined as orbits below 2,000 km in altitude, and its satellites provide distinct advantages over GEO, such as reduced latency and lower launch costs. However, LEO systems face challenges such as increased atmospheric drag, limited ground coverage per satellite, and the need for complex handover algorithms to maintain continuous service. By deploying thousands of smaller, cost-efficient satellites, LEO constellations not only overcome these disadvantages but also create a more resilient network that is less reliant on any single satellite for functionality. LEO constellations, therefore, also have potential to improve not only terrestrial communications on Earth, but also communications between Earth and the Moon.

Several different lunar communication architectures have been proposed [4], [5], [6], [7]. One class of orbit considered is Lower Lunar Orbit (LLO), similar to the concept of LEO but applied to the Moon instead of Earth. LLO offers close proximity to the lunar surface, providing advantages like low latency, but also comes with challenges, such as increased station-keeping requirements due to gravitational perturbations and the need for a larger satellite count to ensure coverage [4]. At an altitude of 750 km with inclinations of 27°, 50°, 76°, and 80°, gravitational perturbations can be considered negligible [4].

A second class of orbits under consideration is Halo Orbits (HO), which are orbits around the L1 and L2 Lagrange points between Earth and the Moon [8]. HO offers the advantage of a continuous line of sight (LOS) to Earth, but the distance to the lunar surface can be as much as 72,000 km [4].

A third class of orbits is Lunar Frozen Orbits (LFO), where the orbital elements remain constant over time. These stable orbits provide continuous coverage with minimal station-keeping, but they are not necessarily circular and exist only for limited orbital parameters [9].

Other types of orbits, such as Prograde Circular Orbit (PCO), Elliptical Lunar Orbit (ELO), Near Rectilinear Orbit (NRO), and Distant Retrograde Orbit (DRO), also have been topics of research [6].

In this paper, a systems analysis is presented for a next-generation lunar communication architecture from a wireless engineering perspective. The study evaluates key parameters of the line-of-sight (LOS) links, including the incident signal power at the receiver, elevation angles for ground stations, cone angles for satellites, and coverage times and resilience for a lunar satellite constellation consisting of three satellites in distinct 12-hour orbits. A comparative performance analysis is conducted between the NASA Deep Space Network (DSN) and a low Earth orbit (LEO) constellation as ground station options. The LEO constellation is modeled as an ideal 24-satellite Walker Delta configuration at 600 km altitude, capable of downlinking received data to Earth.

II. System Model

A. Constructing the Orbit Propagator

To investigate the link parameters of a lunar communication system, an orbit propagator was constructed in MATLAB using the *satelliteScenario* object from the Aerospace Toolbox. The properties of the numerical propagator used in this paper are outlined in Table I.

TABLE I
NUMERICAL PROPAGATOR PROPERTIES

Properties	**Value**
Propagator Type	Numerical
Relative Tolerance	1×10^{-6}
Absolute Tolerance	1×10^{-6}
Max Step	60
Third Body Gravities	Sun, Moon, and all Planets
Third Body Gravity Type	Point Mass

Since the aim of this paper is to provide a systems analysis of different configurations of the lunar communication architecture at a broader level, high precision was not used in favor of reducing computational time. Simulations were conducted over a 3-day window, from January 1, 2024 (UTC) to January 3, 2024 (UTC), as an arbitrary time frame to assess general performance.

B. Constructing the Lunar Relay Satellites

Several lunar communication architectures have been proposed. However, the architecture presented in [10] was chosen for analysis in this paper due to its reference in [11], a collaborative report published by ASA (Australia), ASI (Italy), CNES (France), CNSA (China), CSA (Canada), DLR (Germany), ESA (Europe), ISRO (India), JAXA (Japan), KARI (South Korea), NASA (United States), ROSCOSMOS (Russia), and UKSA (United Kingdom). The values provided in [10] for the ideal satellite constellation to ensure coverage of the lunar poles are summarized in Table III.

TABLE II
KEPLERIAN ELEMENTS OF IDEAL LUNAR CONSTELLATION

Lunar Satellite Orbits	12-hr Circular Equatorial	12-hr Elliptical North	12-hr Elliptical South
Semi-major Axis (km)	6142.4	6142.4	6142.4
Eccentricity	0	0.6	0.6
Inclination (deg)	0	57.7	57.7
Ascending node (deg)	0	270	0
Argument of Perilune (deg)	315	270	90
True Anomaly (deg)	adjustable	adjustable	adjustable

C. Constructing the Ground Stations

NASA's Jet Propulsion Laboratory (JPL) Deep Space Network (DSN) was used to construct the ground station scenario. The longitudes and latitudes of the ground stations in Goldstone, Madrid, and Canberra are provided in [12]. For simplicity, the altitude was assumed to be zero.

TABLE III
LOCATIONS OF GROUND STATIONS

Location	Latitude (deg)	Longitude (deg)
Goldstone	35.427	-116.890
Madrid	40.431	-4.248
Canberra	-35.402	148.983

D. Constructing the LEO Constellation

For the LEO constellation effectively serving as a ground station for the lunar relay satellites, a Walker Delta constellation was considered, consisting of 24 satellites in 6 planes, with a phasing factor of 1, an altitude of 600 km, and an inclination of 97.4 degrees. These parameters represent a near-polar Sun-synchronous orbit with global 24-hour revisit times. Since the purpose of this constellation is not to provide global communication to users on Earth, it does not require as many satellites as Starlink. A Sun-synchronous orbit is advantageous as it provides satellites with consistent sunlight, simplifying power generation through solar panels.

E. Calculating Line-of-Sight (LOS)

To determine whether a satellite is LOS with a ground station, the ground station elevation angle needs to be greater than the minimum elevation angle, and the Earth and Moon cannot be causing occultation of the satellites. For the minimum elevation angle, a value of 20.2° was used for all three DSN ground stations to reflect the largest minimum elevation angle defined in [12]. In this model, it is assumed that all of the satellite antennas are pointing in the zenith direction from the body it is orbiting. Mathematically, the conditions for the ground station are given by:

$$\theta_{el} < \theta_{el,min} = 20.2^\circ \quad (1)$$

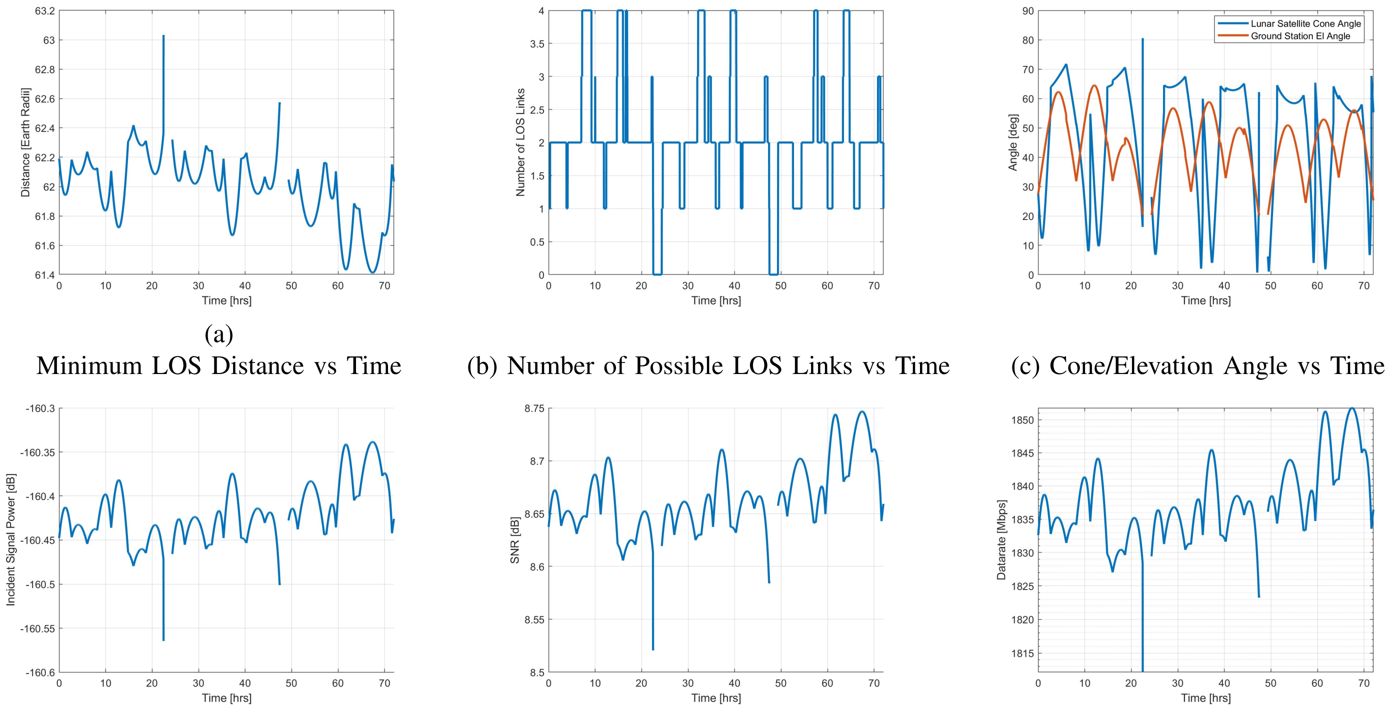
and the conditions for the LOS vector to not be blocked by a circular body can be derived from [13] to yield:

$$\theta_{cone} = cos^{-1}(\hat{r}_{nadir} \cdot \hat{r}_{LOS}) \quad (2)$$

$$\theta_{nadir,min} = sin^{-1}\left(\frac{r_{body}}{d}\right) \quad (3)$$

$$\theta_{cone} > \theta_{nadir,min} \quad (4)$$

where $\hat{r}_{nadir}$ is the satellite's unit vector towards the center of the body, d is the distance between the satellite and center of the body, r_{body} is the radius of body, and θ_{cone} is the angle of separation between the nadir and LOS vector. Ensuring these conditions are met for both the Earth and Moon will generate the contact intervals during which to analyze the link.



(a) Minimum LOS Distance vs Time

(b) Number of Possible LOS Links vs Time

(c) Cone/Elevation Angle vs Time

(d) Incident Signal Power vs Time

(e) SNR vs Time

(f) Maximum Datarate vs Time

Fig. 1. Simulation Results for Communications Between Lunar Relay Satellites and DSN

F. Link Budget

In this paper, link parameters for the downlink of high data-rate communication between Earth and the Moon are considered. While the DSN has existing RF parameters as indicated in [14], proposed values from [11] were used, anticipating a future architecture. This resulted in a center frequency of 22.85 GHz and a bandwidth of 0.6 GHz, with options for OQPSK/GMSK modulation and LDPC coding rates of 1/2, 2/3, 4/5, and 7/8. The transmitter parameters for the lunar satellites are summarized in Table IV. Given the limited time allotted for this paper, generally accepted values were taken from [15] and [5].

TABLE IV
TRANSMITTER RF PARAMETERS

Parameter	Value
Power, P_T (W)	0.3
Antenna Type	Dish
Antenna Diameter, D (m)	1
Antenna Efficiency, η	0.8
Cable Loss (dB)	0.25

The antenna gain can be calculated using:

$$G_{TX}[dB] = 10\,log_{10}\left[\eta\left(\frac{\pi D}{\lambda}\right)^2\right] \tag{5}$$

For the ground station, worst-case parameters were taken from [12]. The receiver parameters are summarized in Table V.

TABLE V
RECEIVER RF PARAMETERS

Parameter	Value
Gain, G_R (dB)	78.7
Pointing & Weather Loss, L_{misc} (dB)	4
System Noise Temperature, T_{sys} (K)	44

With these RF parameters defined, incident signal power at the receiver can be calculated with:

$$P_{incident} = \frac{P_T G_T}{L_T L_{FSPL} L_{misc}} \tag{6}$$

The received signal power can be calculated with:

$$P_{signal} = \frac{P_T G_T G_R}{L_T L_{FSPL} L_{misc}} \tag{7}$$

Noise power can be calculated with:

$$P_{noise} = k T_{sys} B \tag{8}$$

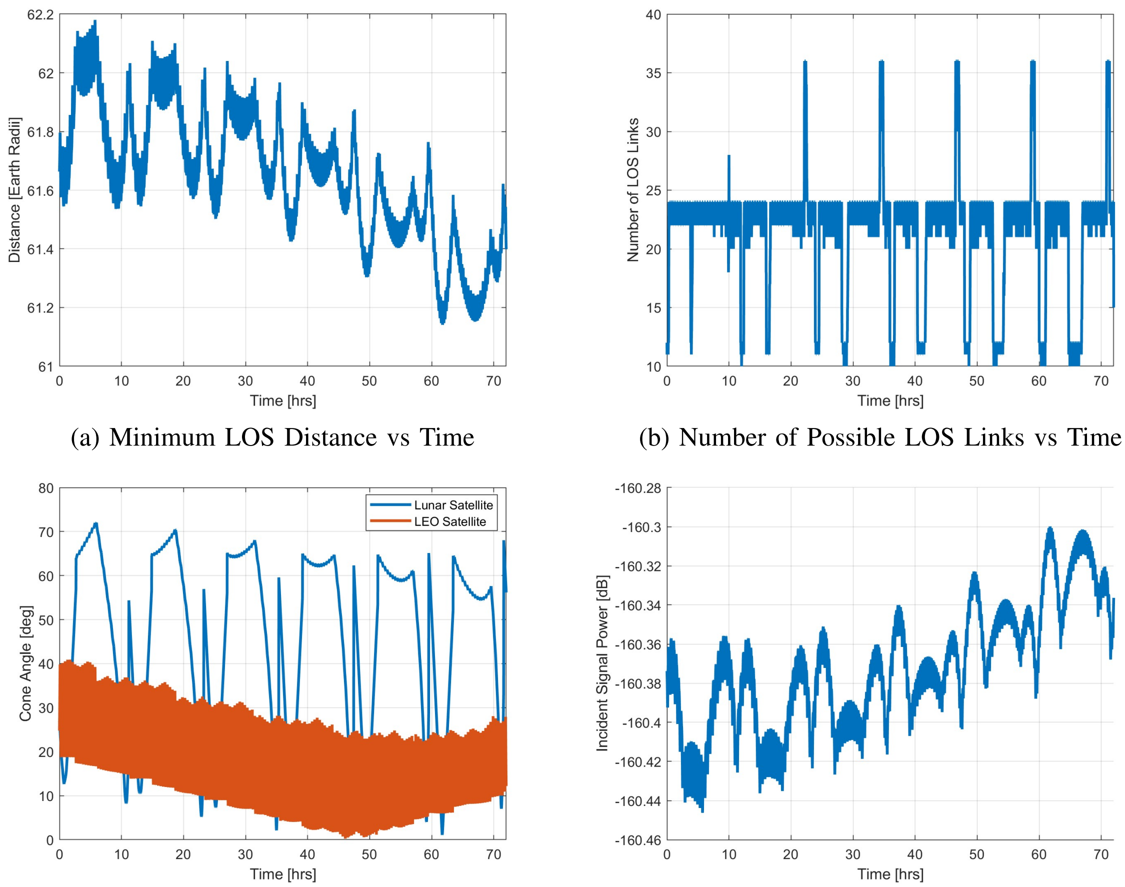
where k is the Boltzmann constant and B is the bandwidth.

Finally, signal-to-noise power can be calculated with:

$$SNR = \frac{P_{signal}}{P_{noise}} \tag{9}$$

Given the SNR, the theoretically achievable maximum data rate can be calculated using the Shannon Capacity Formula:

$$R = B\,log_2(1 + SNR) \tag{10}$$



(a) Minimum LOS Distance vs Time

(b) Number of Possible LOS Links vs Time

(c) Cone Angles vs Time

(d) Incident Signal Power vs Time

Fig. 2. Simulation Results for Communications Between Lunar Relay Satellites and DSN

For the lunar communication architecture with the DSN ground stations, both SNR and maximum capacity will be calculated. However, for the LEO constellation, only the incident signal power will be calculated. The receiver parameters for the LEO constellation will vary significantly based on satellite design, and providing the incident signal power was deemed sufficient for the preliminary analysis, which is the scope of this paper.

III. Contribution

The main contributions of this paper are as follows:

1) A systems analysis of lunar communication architectures, specifically comparing the performance of the Deep Space Network (DSN) and a Low Earth Orbit (LEO) constellation as ground stations for lunar communication.
2) An evaluation of key link parameters, such as line-of-sight availability, cone angles, and signal-to-noise ratio (SNR) for both DSN and LEO constellation configurations, providing insights into their effectiveness for lunar communication.
3) The identification of advantages offered by a LEO constellation, including improved resilience and higher network availability, making it a viable alternative to the DSN for lunar missions.
4) The proposal of a future research direction that includes optimizing link selection algorithms and refining RF parameters for LEO satellite systems to further enhance communication performance.

IV. Results/Evaluation

A. DSN Ground Station Simulation

Simulation results for the lunar relay satellites communicating with the DSN are plotted in Figure 1. Notably, in Figure 1a, there are gaps during times when no link can be established between the lunar relay satellites and the ground stations. It is also observed in Figure 1b that the number of possible LOS links fluctuates around 2. The outages are clearly a result of the elevation angle constraint, but the lunar cone angles are also large, reaching up to 70°, which could be another critical constraint depending on antenna capabilities. Using the minimum LOS distance, the link budget calculations yielded the incident power and SNR graphs, as shown in Figures 1d and 1e. With the calculated SNR, the Shannon Capacity was determined, as shown in Figure 1f. It should be noted that the presence of outages does not conflict with the concept of an ideal constellation defined in [10], which considered additional ground stations and optical links.

B. LEO Constellation Ground Station Simulation

Simulation results for lunar relay satellites communicating with a LEO ground station network are shown in Figure 2. It can be observed in Figure 2a that there are no outages during the 3-day window. Figure 2b shows that there are at least 10 possible LOS links between the lunar satellite and LEO satellites at any given time, with the average number being around 23. Note that, with 3 lunar satellites and 24 LEO satellites, a total of 72 LOS links are possible, compared to just 9 in the DSN case. In Figure 2c, the cone angles of the LEO satellites fluctuate between 0° and 40°, while the cone angles of the lunar satellites fluctuate between 0° and 70°. While the large cone angles of the lunar satellites are a concern, this is a result of using the minimum LOS distance link to compute the cone angle. Future work can address this issue by selecting the most optimal link from the available LOS links that satisfy the cone angle constraints at both ends of the link.

C. Evaluation

From the results of these two lunar communication architectures, the LEO constellation provides a clear advantage over the DSN in delivering continuous and resilient coverage to the lunar relay satellites. This resiliency is particularly important for human-crewed missions where lives are at stake, and may be required to accommodate increased communication demands when multiple lunar missions are taking place simultaneously.

Regarding the lunar satellite cone angles, the lack of alternate LOS links in the DSN ground station case would require the lunar satellites to accept performance losses in gain by using less directional antennas, or necessitate additional mechanical or electrical capabilities on the spacecraft communication system to steer the beam at large angles off-boresight.

V. CONCLUSIONS

In this paper, a systems analysis was presented for a next-generation lunar communication system from a wireless engineering perspective, comparing the performance of the DSN and LEO constellation as ground stations for a lunar communication architecture consisting of three satellites in a 12-hour circular equatorial orbit, a 12-hour elliptical north orbit, and a 12-hour elliptical south orbit. The DSN has ground stations in Goldstone, Madrid, and Canberra, while the LEO constellation is a 24-satellite Walker Delta constellation at an altitude of 600 km.

The results showed that utilizing a LEO constellation as a ground station offers greater resilience in the network, with an average of 23 LOS links available between the lunar constellation compared to just 2 for the DSN. Cone angles were large for both constellations, reaching upwards of 70°, but the LEO constellation has the potential to reduce these angles by selecting alternate LOS links. Further work is needed to establish the RF parameters of the LEO satellites and to implement a more optimal LOS link selector to further validate the preliminary results presented in this paper.

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