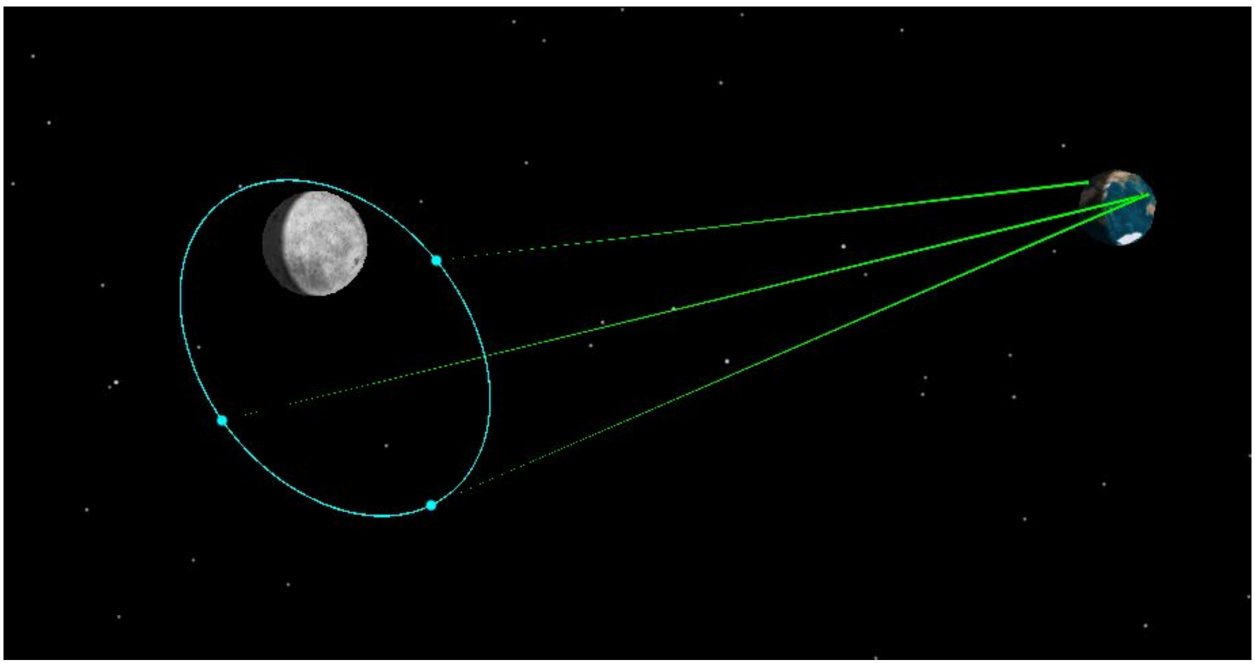
Lunar Polar Communications Network



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Introduction

Among its proponents, the Space Economy has many meanings. To some, it means a new frontier of industry, employing resources beyond Earth to promote and sustain life on Earth. To others, it means a system of transport, facilitating growth and the transfer of resources, information, and people.

To us, the coming Space Economy means the exploration and mastery of our solar system. Once a theme of science fiction, our progress towards becoming a multi-planet species is real and ongoing. Resource excavation, interplanetary transport, colonization, and growth - all of these objectives will play a part in this economy and will contribute immensely to the research and understanding of our universe [1].

The development and success of this economy will depend heavily on a strong communications network; any operation beyond Earth will require its operators to remain organized and well-connected. This report proposes such a network to facilitate lunar operations and expeditions, specifically for the establishment and maintenance of a lunar base. These lunar operations would serve as a foundation for future objectives of the space economy, while also providing solutions to short-term objectives, such as the acquisition of resources, the testing of new technologies, and the provision of a communications hub for deep-space missions.

Resources available from the lunar surface alone offer immense economic benefits, while also serving to sustain surface operations [2]. Water ice, to be separated into hydrogen and oxygen propellants or melted down, would be a key resource for a lunar station. The mining of asteroid remains, Rare Earth Elements and metals, ammonia, and Helium-3, a valuable candidate for nuclear fusion, could also serve to either boost terrestrial economies or enhance production on the Moon, on-orbit, and beyond [3].

A lunar base also offers the possibility of a springboard for development of the Space Economy; it offers a checkpoint from which future missions and growth can be staged. It has potential as a refueling station, to reduce the cost of large missions (such as in Mars exploration), and as a basis of communication: being virtually without atmosphere, it provides a stronger and clearer point of contact for outgoing satellites and manned missions. Such a base would also serve as an invaluable research center; in addition to testing new technologies and procedures for further exploration, research at a lunar outpost would provide a wealth of knowledge in the sciences of astronomy, astrobiology, and planetary geology.

Because of these assets, the proposed communication network is centered around lunar base operations. Our Moon offers us countless opportunities for advancing the Space Economy and is itself an ideal “next stepping stone” in a long, yet valuable, series of steps outward.

System Requirements

As the only dedicated lunar communications network, we believe that the system should provide close to constant contact between the Earth and the desired region of lunar operations. As a case study for such a region, we specifically researched the South Pole-Aitken (SPA) Basin, regarded by NASA as an area of immense interest for both scientific study and potential economic operations. Formed from the heavy bombardment period, SPA is composed of a significant amount of impact melt, lower-lunar crust, and excavated upper mantle. Gamma-ray observations indicate the presence of iron, titanium, and thorium reserves within the basin interior and surrounding highlands, while its many shadowed regions likely contain reserves of ices and other valuable compounds [4].

From a research perspective, the impact melt and any records of water composition would not only corroborate the age of the Moon, but provide astrobiologists with a dataset dating back to the beginning of our solar system.

From an economic standpoint, there is enormous value in the mining of iron, titanium, thorium, and other reserves left behind by asteroid remains; the presence of water ice alone would be a vital factor in lunar exploration and the installation of a lunar base. Mountain peaks, specifically surrounding the Shackleton crater, experience near-constant illumination and could offer consistent solar power for lunar operations [5].

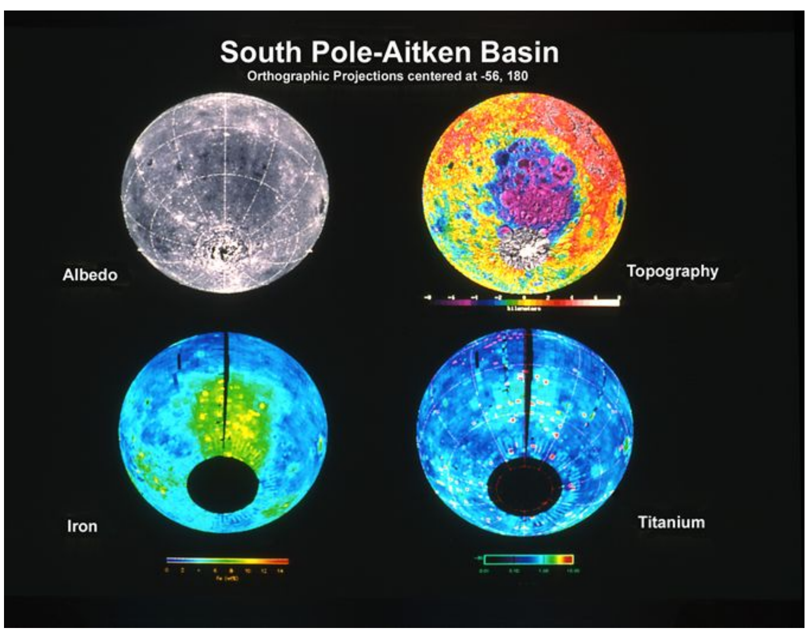

Figure 1: Images of the South Pole-Aitken Basin [6]

The South Pole-Aitken Basin is defined at 22.3°S to 78.4°S latitude from north to south, and 221.3°E to 150.6°E longitude from east to west [7].

Given the large number of proposed use cases for this polar region of the Moon, our system will focus on coverage of the lunar south pole. Our proposed region for which to provide near complete access is below 45°S latitude.

With the mission objective defined, we developed a more specific set of high-level requirements for the system. These requirements were divided into three primary categories. We first considered customer needs: broad descriptions of the mission objectives. Next, we considered technical requirements, which attribute specific and measurable metrics to the customer needs. Finally, we considered target values, which establish a specific numeric value for each technical requirement.

Table 1: High Level Requirements

Customer Needs	Technical Requirements	Target Values
Dedicated southern lunar communications link	Provide a certain percent coverage of a lunar latitude band	> 95% coverage of all regions below -45° latitude throughout operation
Support high data rates throughout operation	Provide downlink data rates	1 Gbps data rate from lunar orbit to Earth ground station
Long-term operational lifespan	Provide estimates for system operational lifetime	20 years of continuous operations

Network Design

Orbital Design

In the realm of the architecture of our system, we discussed many potential orbital configurations within the Earth-Moon system. In comparing these configurations, we considered cost, technological feasibility, complexity, and regulatory obstacles as criteria, placing the foremost emphasis on cost and feasibility.

Lunar L1 Lagrange Relay

We briefly considered placing a relay satellite in a halo orbit around the L1 Lagrange point between the Earth and Moon. This had the potential to reduce the total number of satellites in our system while still maintaining 100% connectivity, thus significantly reducing our overall cost. The Jet Propulsion Laboratory has proposed a similar architecture, with relay satellites placed at L1 and L2 [8]. However, the instability of the halo orbit and the difficult maneuvers necessary to establish it were sources of significant concern, particularly for a commercially operated system.

Moreover, while there have been multiple missions that have successfully placed a payload in a halo orbit around an Earth-Sun Lagrange point, this feat has only been accomplished once for a lunar Lagrange point, through the ARTEMIS extension of the THEMIS mission in 2010 [9]. While ARTEMIS demonstrated the possibility of utilizing lunar Lagrange points, their instability provides unnecessary complications for a system that is meant to be continuously operational for many years. These factors led us to swiftly forego the prospect of a halo orbit.

With the possibility of a halo orbit now rejected, we next considered an overarching system consisting of two subsystems: a subsystem to communicate with the lunar base and a subsystem to communicate with the terrestrial ground station, with potential relay satellites to assist on communications between these two networks.

Lunar Relay Constellation

Although we initially considered placing a constellation of satellites around the Moon, similar to constellations that currently exist around the Earth, we quickly concluded that this was too complicated given our goal of communicating with lunar bases stationed exclusively in the southern polar region. The primary advantage of a satellite constellation is the ability to communicate with many broad locations on the surface of the orbited body, but this is not necessary for our particular network. However, it is worth noting that if a party did seek to establish multiple dispersed lunar bases outside of the southern polar region, a constellation of communications satellites would be very practical.

Polar Lunar Relay

Taking advantage of the relative simplicity of a system that only targets one pole, we discussed a lunar subsystem that would consist of two satellites in a single elliptical polar orbit. This orbit would be oriented such that the apoapsis would occur above the southern polar region and the periapsis above the north.

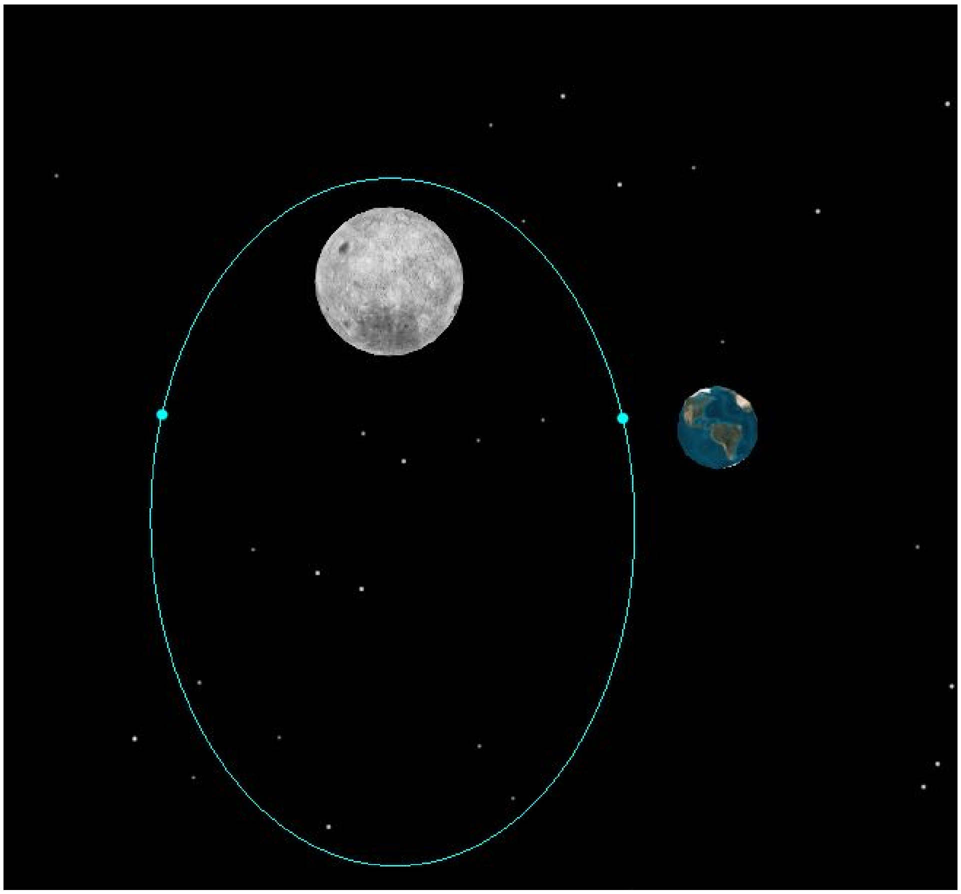

Figure 2: Lunar Polar Relay Architecture (rejected due to orbital instabilities)

By placing the two satellites out of phase in this orbit, we could ensure that the lunar base always has access to at least one of the satellites. However, after further research and analysis, we realized that a high altitude polar orbit around the Moon would be very unstable due to variations in the Moon's gravity and the powerful perturbation of the Earth on the orbiting bodies at apoapsis, with some estimates predicting end-of-life as early as ten days after the orbit is first established.

Frozen Inclined Lunar Relay

In our research we came across a potential solution to this problem proposed by Todd Allan Ely, an engineer at the Jet Propulsion Laboratory. Ely describes a method to enable communications between the Moon's polar region and the Earth using a system of lunar relay satellites. The method consists of placing three satellites in a single eccentric orbit around the Moon. This orbit would have an eccentricity of approximately 0.6, with the apoapsis occurring at the point closest to the southern polar region, extending the period in which this region has access to the satellites. The orbit would also occur at an inclination of 63 degrees relative to the Lunar equator. This inclination would allow for long-term stability while still providing adequate coverage of the southern polar region [10]. Meanwhile, the satellites themselves would be spaced 120 degrees apart in mean anomaly to ensure that the southern polar region can maintain consistent line-of-sight with at least one satellite. The set of orbits librate over time, with the eccentricity, argument of periapsis, and inclination oscillating relative to the Moon. However, multiple sets of initial conditions are identified whose oscillations stay relatively bounded over multiple decades [10].

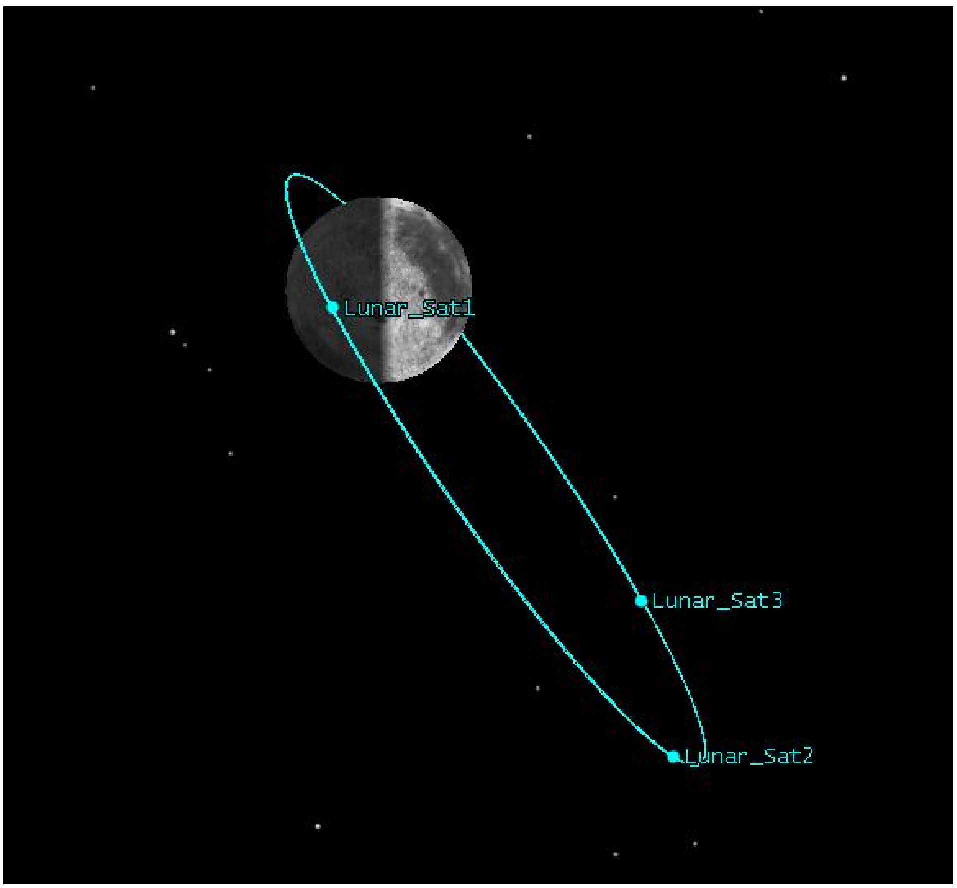

Figure 3: Three-satellite inclined relay design

According to previous analyses, this orbital architecture would remain stable for at least ten years, assuming a small amount of control for baseline perturbations [10].

Although it would be ideal to have fewer than three satellites in our lunar subsystem, we concluded that this was the fewest number of satellites we could deploy while still maintaining consistent line of sight access over long periods of time.

Earth System

We gave significant consideration to various possible arrangements for a subsystem of Earth-orbiting relay satellites. However, we concluded that our system could perform effectively via direct communications between lunar relay satellites and terrestrial ground stations. This decision was based on team research as well as consultation with a communications engineer from Astrobotic, a company working to send commercial payloads to the Moon, and a potential future user of our system. This design decision provides a significant reduction in overall system cost with no significant detriments to performance, given proper communications equipment.

Based on the research of Ely [10], we developed our lunar relay satellites based on the following initial orbital parameters:

Table 2: Constellation Initial Orbital Elements Summary

Satellite	Semi-major Axis	Eccentricity	Inclination*	RAAN*	Argument of Periapsis*	Mean Anomaly
Lunar Satellite 1	6,541.4 km	0.6	79.39°	356.64°	88.39°	30°
Lunar Satellite 2	6,541.4 km	0.6	79.39°	356.64°	88.39°	150°
Lunar Satellite 3	6,541.4 km	0.6	79.39°	356.64°	88.39°	270°

Simulation Epoch: 1 Jan, 2010, 00:00:00 UTC

* Note: The inclination, right ascension of the ascending node (RAAN), and argument of periapsis of these three orbits are defined in the J2000 Earth Equatorial frame.

Communications Design

The only realistic communications architecture that can support the high data rates that we are proposing is one that primarily relies on optical laser communications. For a system that relies on solar power, RF communication is simply not feasible given the data rates we wish to achieve. Optical (laser) communication systems have undergone tremendous progress over the past decade.

In 2005, JAXA's OICETS satellite demonstrated successful two-way optical communication with another satellite, KIRARI, in low-Earth-orbit. In 2006, OICETS took part in the KODEN experiment, which achieved optical communication between a satellite in low-Earth-orbit and an optical ground station on Earth [11]. More recently, in 2013, NASA's LLCD mission utilized laser communications to transmit data from lunar orbit to a terrestrial ground station at a record speed of 622 Mbps [12]. The potential of optical communications for use in space is clear, and the technology will continue to advance with upcoming missions such as NASA's LCRD [13].

However, our system cannot rely on laser communications alone. Including an RF system will assist in the the precise orbital determination that is necessary for the Earth-based tracking stations and the optical transmitter pointing. In addition to this necessary application, the RF system can function as a backup for the laser communication system. A switch to the RF system instead of the optical system would of course not support the high data rates that this network was designed to provide, but is a better option than designing a system with a single point of failure.

In the design of our system, we also do not want to constrain the potential users. While our system architecture relies on laser communications, it is very possible that as commercial access to the Moon increases, many of the companies that will be either directly landing or purchasing payload spots on commercial lunar missions will not include laser communication systems on their payloads. Our lunar relay satellites need to be able to receive RF signals from potential users on the Moon without necessarily targeting them directly. This calls for a low-gain zenith-facing antenna in addition to the high-gain satellite-mounted optical receivers.

Mimicking previous NASA architectures for an RF lunar communications network [14], we propose using Ka band for our RF link between the lunar satellites and Earth. This is a frequency band that is commonly used in satellite communications, and with already mature commercial ground stations.

Our system will also support Ka and S band RF links between the lunar surface and the lunar satellites. This will again ensure that potential users of our system are not constrained in their choice of communication system.

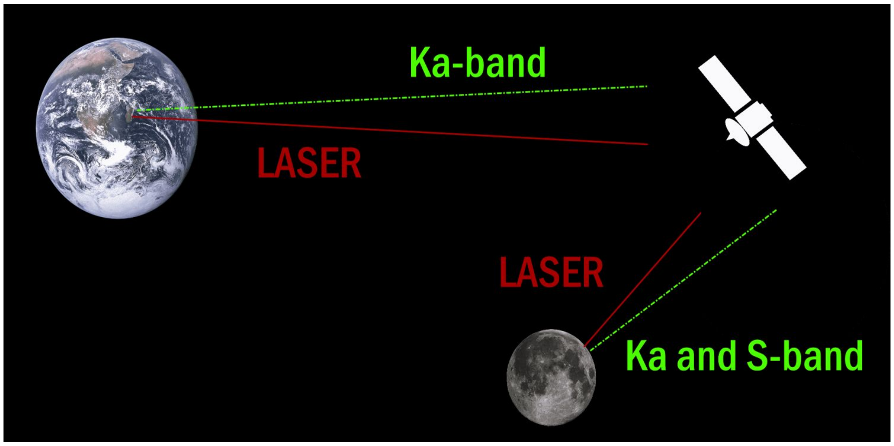

Figure 4: Overall communications architecture

Satellite Hardware

Bus

In order to decrease the total development cost of our system, we decided to use a standardized satellite bus for our three lunar relay satellites.

The GEOStar-2, a small to medium satellite bus produced by Orbital ATK fits the demands of our system very well. It allows for 500 kg of communications payload, and can produce up to 5.5 kW of power over a 15 year lifetime [15]. Orbital ATK has delivered more than 35 of these busses, and the team feels confident that the company will provide a system with the long-term reliability to meet our operational lifetime target of 20 years.

Figure 5: Visualization of GEOStar-2 satellite bus [15]

Table 3: GEOStar-2 Bus Specifications [15]

Bus Dry Mass	Payload Mass Capability	Max Payload Power	Dimensions (HxWxL)	Typical Mission Lifetime
800-1500 kg	500 kg	5500 W (orbit avg. @ 15 yrs)	1.75 m x 1.7 m x 1.8 m	> 15 years

Communications Hardware

Based on the high level communications design outlined in the Network Design section, we identified a set of communications hardware for each of our lunar relay satellites.

Performing basic link budget analyses, we also set the operational conditions for each of these systems.

Table 4: Earth-Facing Assets

System	Transmit Power	Diameter	Gain	Frequency	Data Rate (downlink)
Ka-band Gaussian Antenna	100 W	0.5 m	42.332 dB	30 GHz	3 Mbps
Optical Transmitter	200 W	10.7 cm	110.924 dB	375000 GHz	1 Gbps
Optical Receiver	N/A	10.7 cm	110.924 dB	N/A	N/A

Table 5: Moon-Facing Assets

System	Transmit Power	Diameter	Gain	Frequency
Ka / S-band Gaussian Antenna	100 W	0.1 m	23.03 dB	Variable
Optical Transmitter	200 W	10.7 cm	110.924 dB	375000 GHz
Optical Receiver	N/A	10.7 cm	110.924 dB	N/A

Data rates for the Moon - lunar satellite link were not estimated because again, we do not want to make assumptions or place potential constraints on the users of our system. Instead, we only analyzed the performance of the Earth - lunar satellite link.

Power Generation

To perform analyses that show the functionality of our power subsystem, the team developed a "worst case" power budget. This outlines the absolute maximum power usage under nominal conditions. The maximum communications power draws were estimated, and based on previous missions [16], the power draws for other subsystems were estimated.

Table 6: Power Consumption by Components

Component	Power Draw (W)
Earth-facing optical transmitter	200 W
Moon-facing optical transmitter	200 W
Ka-band Earth-facing transmitter	100 W
Ka/S-band Earth-facing transmitter	100 W
Thermal control	240 W
Electrical power system	120 W
Telemetry, tracking, and command system	275 W
Data processing system	172 W
Attitude determination and control system	275 W
Propulsion system	35 W
Sum	**1.717 kW**
Margin	**x 15%**
Final Sum	**1.974 kW**

To calculate the power required for each spacecraft, we need to predict how much of each orbit is eclipsed by either the Moon or the Earth. Because solar power cannot be collected during eclipse, the system must compensate during periods that it is exposed to the Sun in order to be power positive.

A 1 year simulation period was analyzed with the following results:

Table 7: Satellite Eclipse Periods

Satellite	Fraction of Time Eclipsed
Lunar Satellite 1	2.278 %
Lunar Satellite 2	2.254 %
Lunar Satellite 3	2.262 %

Unlike some satellites constrained by power available, our system will operate at the same power levels inside and outside of eclipse. Given that the analysis above is an average value over an entire year, the team decided to add additional margin to the system, and test the electrical power system with the assumption that our satellites are actually eclipsed 5 percent of the time.

Assuming a 5% eclipse fraction and the power budget in Table 6, each satellite should be expected to collect at least 2.303 kW in order to be power positive. Given that the GEOStar-2 bus is estimated to collect 5.5 kW after 15 years, our system design clearly meets the constraints of the satellite bus.

Performance Analysis

With our conceptual design complete, we conducted various computer simulations of our system in order to assess its predicted performance. These simulations were conducted using FreeFlyer and STK.

Lunar Coverage Analysis

One of the goals of our system was to provide 100% coverage of the Moon below -45 degrees latitude. To analyze the coverage performance of our three lunar relay satellites, we performed a coverage analysis of the entire surface of the Moon. For each area region defined as 1 degree latitude x 1 degree longitude, we calculated the average coverage percentage per day over a one year analysis period. In this analysis, coverage is defined as line-of-sight access to at least one of the lunar relay satellites. These coverage statistics make no assumptions about stationkeeping and orbital adjustment maneuvers.

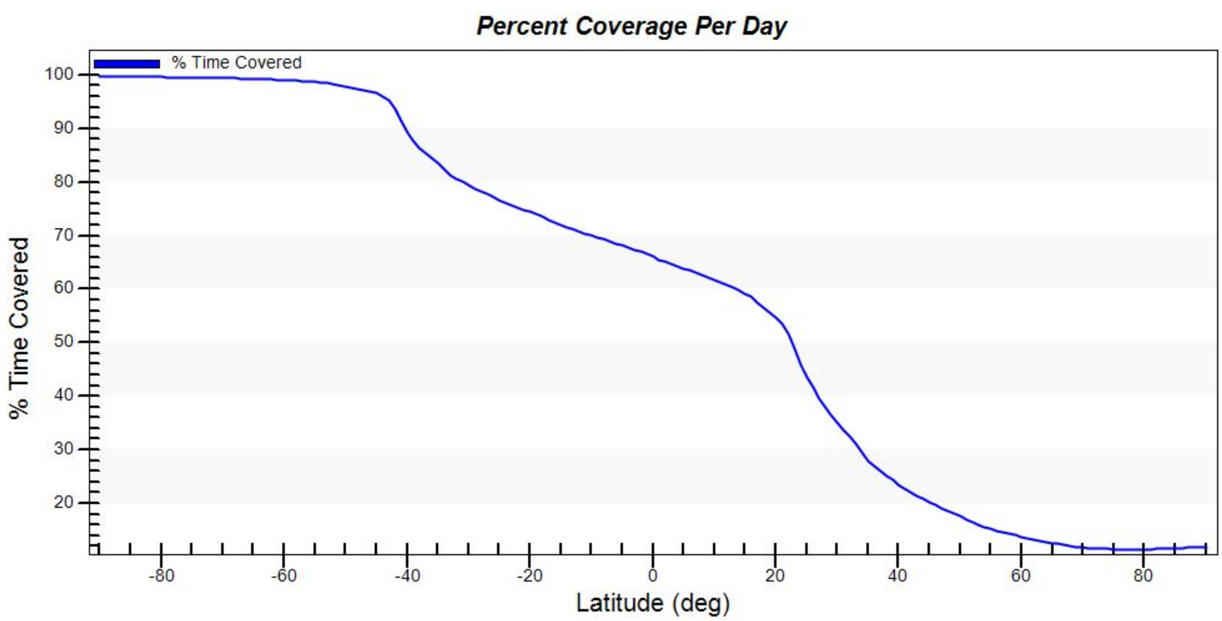

Figure 6: Percent coverage per day as a function of latitude

Table 8: Coverage Simulation Results (Data Table)

Latitude Band (deg)	Average Percent Coverage per Day
-90 to -81	99.663
-80 to -71	99.572

-70 to -61	99.302
-60 to -51	98.693
-50 to -41	96.066
-40 to -31	84.175
-30 to -21	77.078
-20 to -11	72.593
-10 to -1	68.370

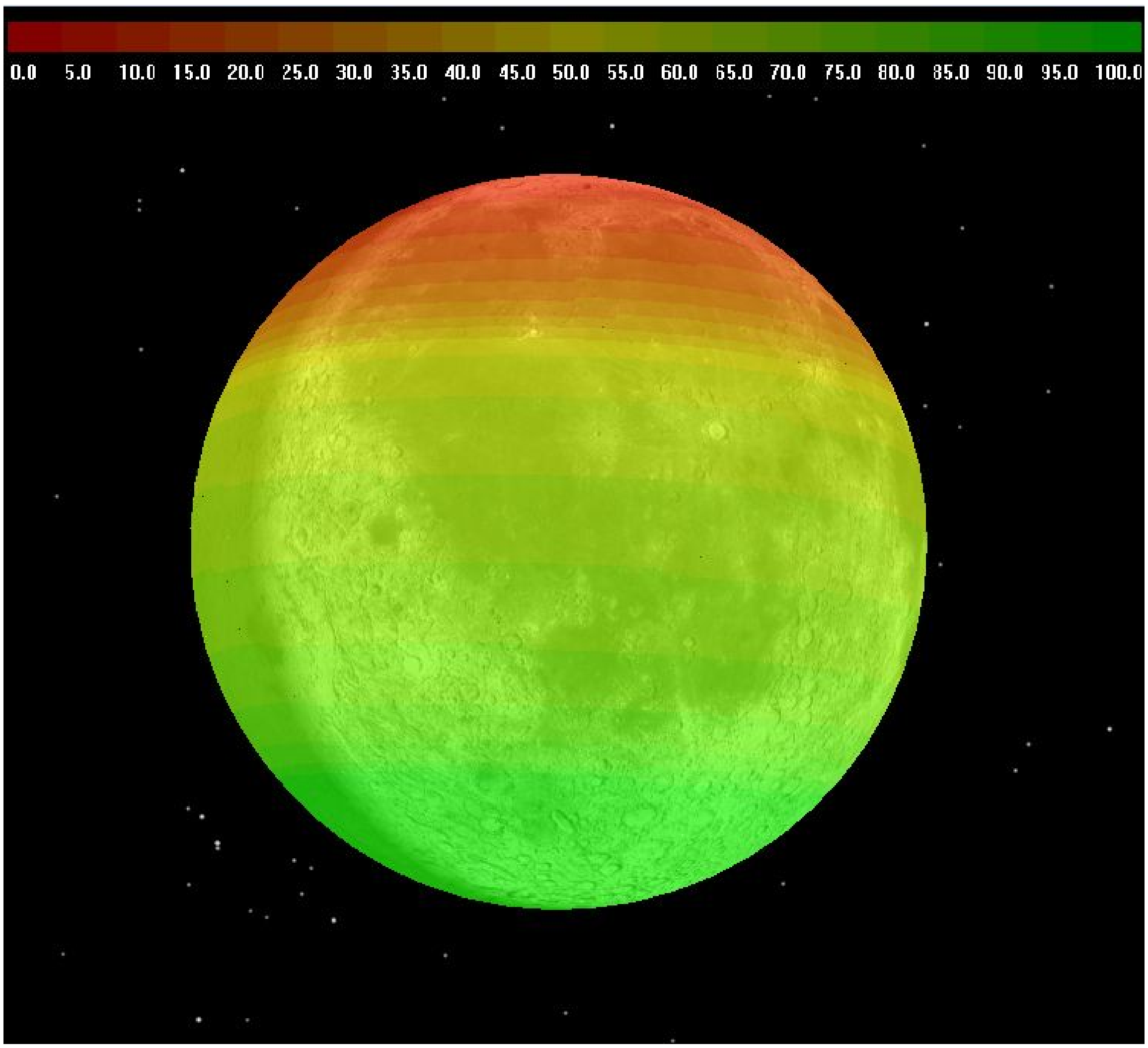

Figure 7: Coverage simulation results (spatial representation)

As this analysis demonstrates, our system performs very well in the southern polar latitudes, maintaining well over 95 percent coverage everywhere below -50 degrees latitude. The miniscule gaps in coverage can be explained by points that are difficult to reach due to the uneven terrain. This analysis confirms that our orbital design was successful in placing the system in a position to provide near continuous coverage between the Earth and southern polar regions of the Moon.

Earth Ground Station Access Analysis

In addition to analyzing the coverage of the lunar surface, in order to provide near continuous connectivity back to Earth, we need to ensure that our system has constant contact with at least one Earth-based ground station.

This analysis is more difficult to perform due to the fact that optical ground networks are still being developed. For our analysis, we considered the placement of a 0.5 m aperture optical receiver (mimicking those currently being installed by BridgeSat [17]) at each of the ground station locations either currently operated by ATLAS Space Operations, or scheduled to open within the next year [18]. More information on each of these companies can be found in the System Lifecycle section. A map of the ground stations used in our analysis is shown below.

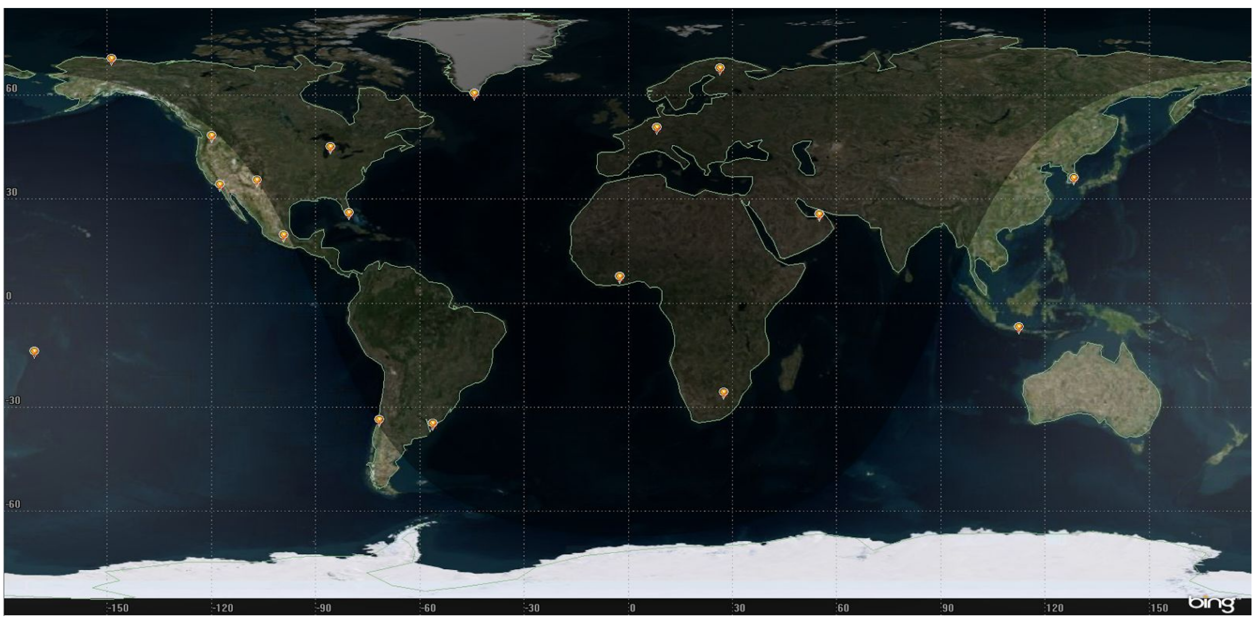

Figure 8: Ground stations used for analysis

Table 9: System Contact with Ground Stations

Satellite	Percent of Time in Contact with Ground Stations
Lunar Satellite 1	97.668
Lunar Satellite 2	97.672
Lunar Satellite 3	97.667

Our analysis showed that over a 1 year test period, each of the three satellites is in contact with at least one of the Earth-based ground stations for over 97.6% of the year. More importantly, there were no situations in which all three satellites were not in contact with any of our assumed ground stations. This means that there is a continuous communications link between our assets in lunar orbit and at least one ground station on Earth. An example of this analysis is shown below:

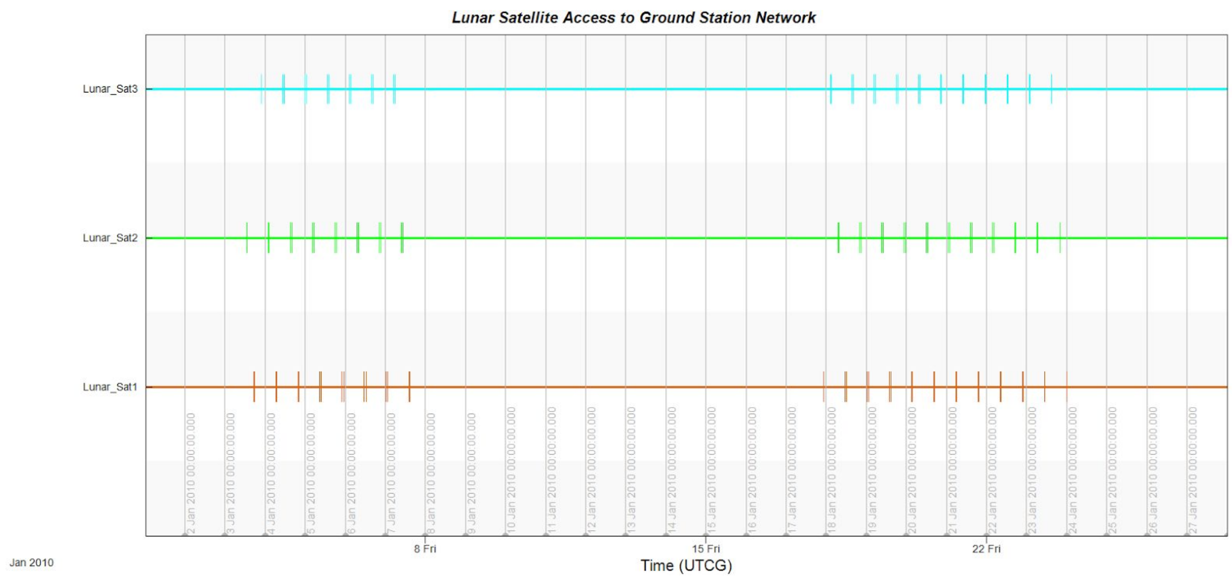

Figure 9: A Plot of Ground Network Access vs Time for the 3 Lunar Satellites

For a one lunar month test period, this is an analysis of the line-of-sight access between each lunar satellite and any one of the ground stations in the network. As shown here, there is never a point where all three satellites are without access, i.e. there is always access between our ground network and at least one of our lunar satellites. This analysis was performed for the first year of operations, but for clarity, only the first month of data was included here.

Communications Analysis

Over a one year analysis period, we generated link budgets to test the performance of our optical communications system. In analyzing the links between each satellite and each individual ground station, the results were very similar. The parameter Eb/No (in dB) was very poor upon the first line of sight access due to the longer path length through the atmosphere. This is a common occurrence in optical communications links. Once the satellite appears at a higher elevation angle (from the point of view of the ground station), the link quality improves.

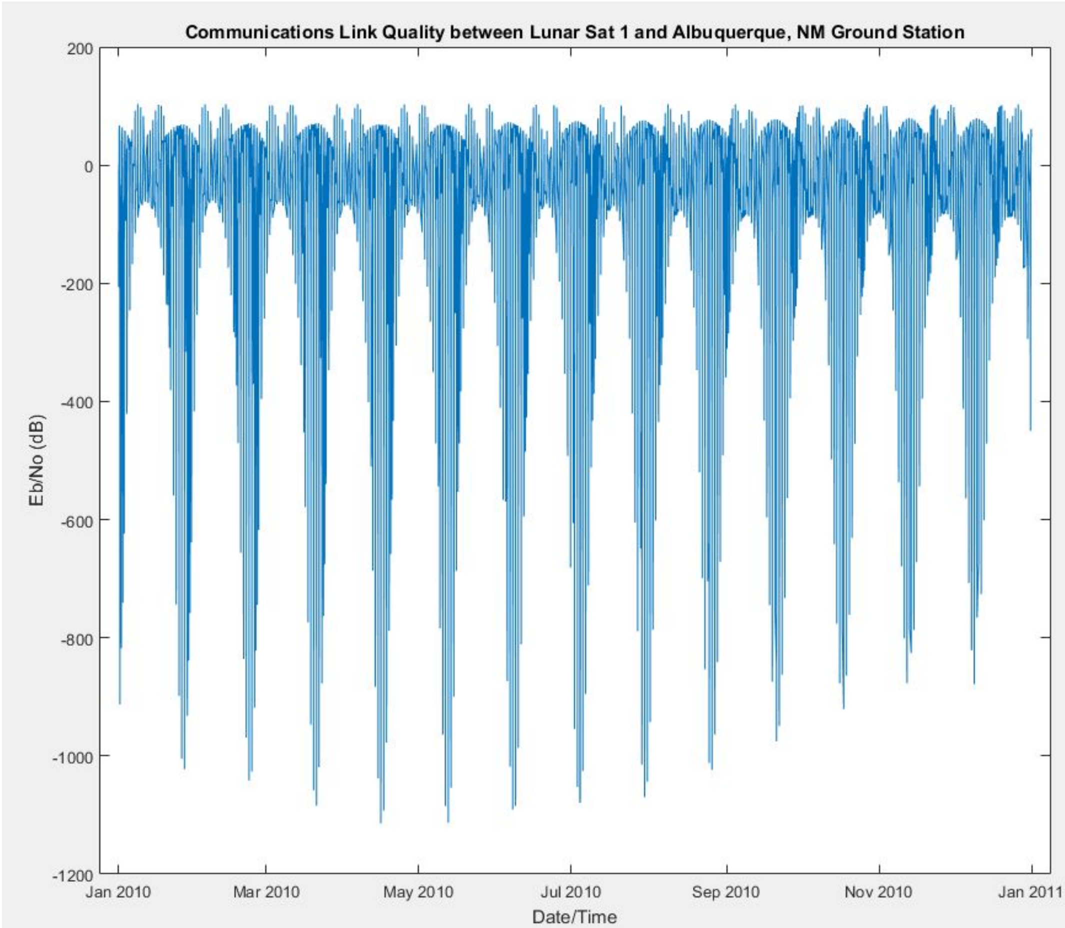

Figure 10: Eb/No for the Lunar Sat 1 - Alburquerque Optical Link

This plot can be cropped to create a better view of the link performance for when Eb/No is greater than -5 dB.

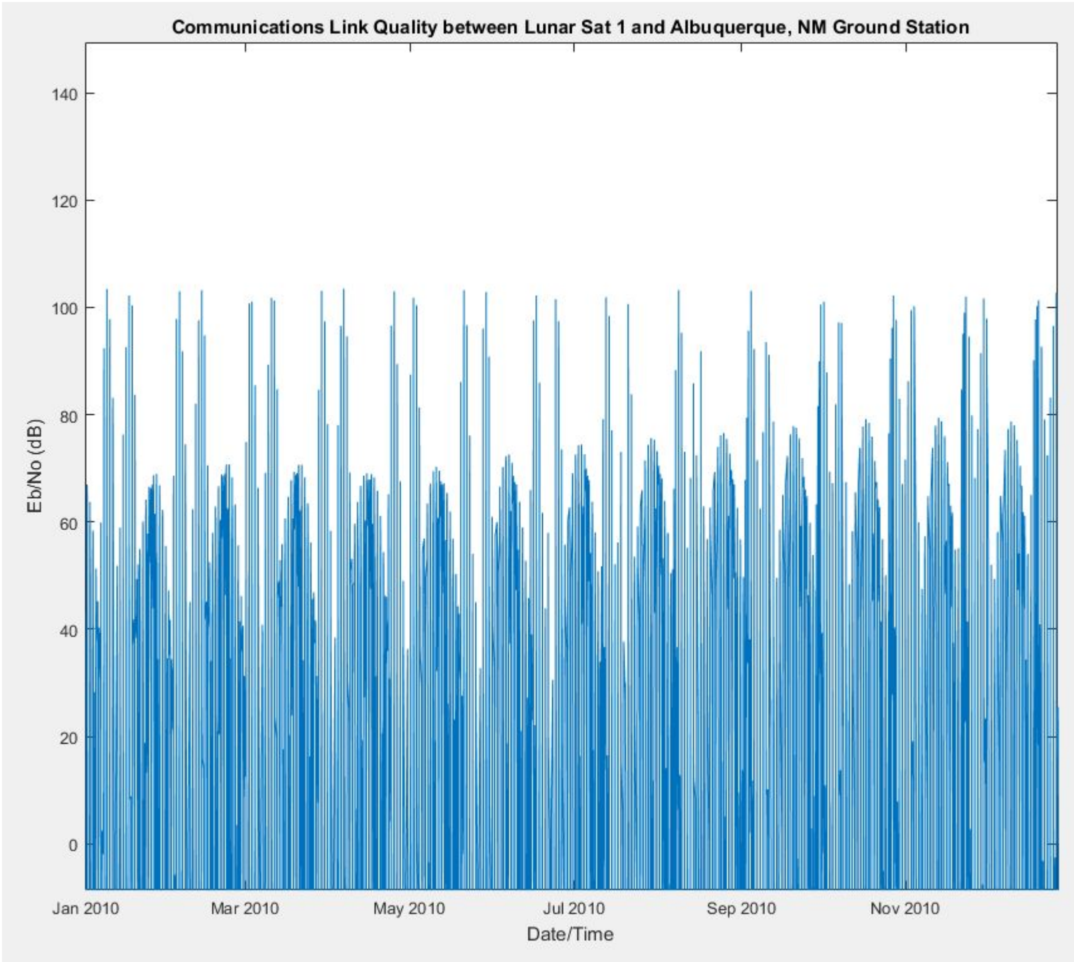

Figure 11: Eb/No for the Lunar Sat 1 - Alburquerque Optical Link (values greater than -5 dB)

The periods of poor link performance while each satellite is at a very low elevation angle is where the importance of our multiple ground stations comes into play. Even if the performance between a single ground station and single satellite may be poor due to low elevation angles, the satellite will always be in view of another ground station where the link performance is better. This fact can be seen by overlaying plots of the performance of one satellite with *each* of the ground stations.

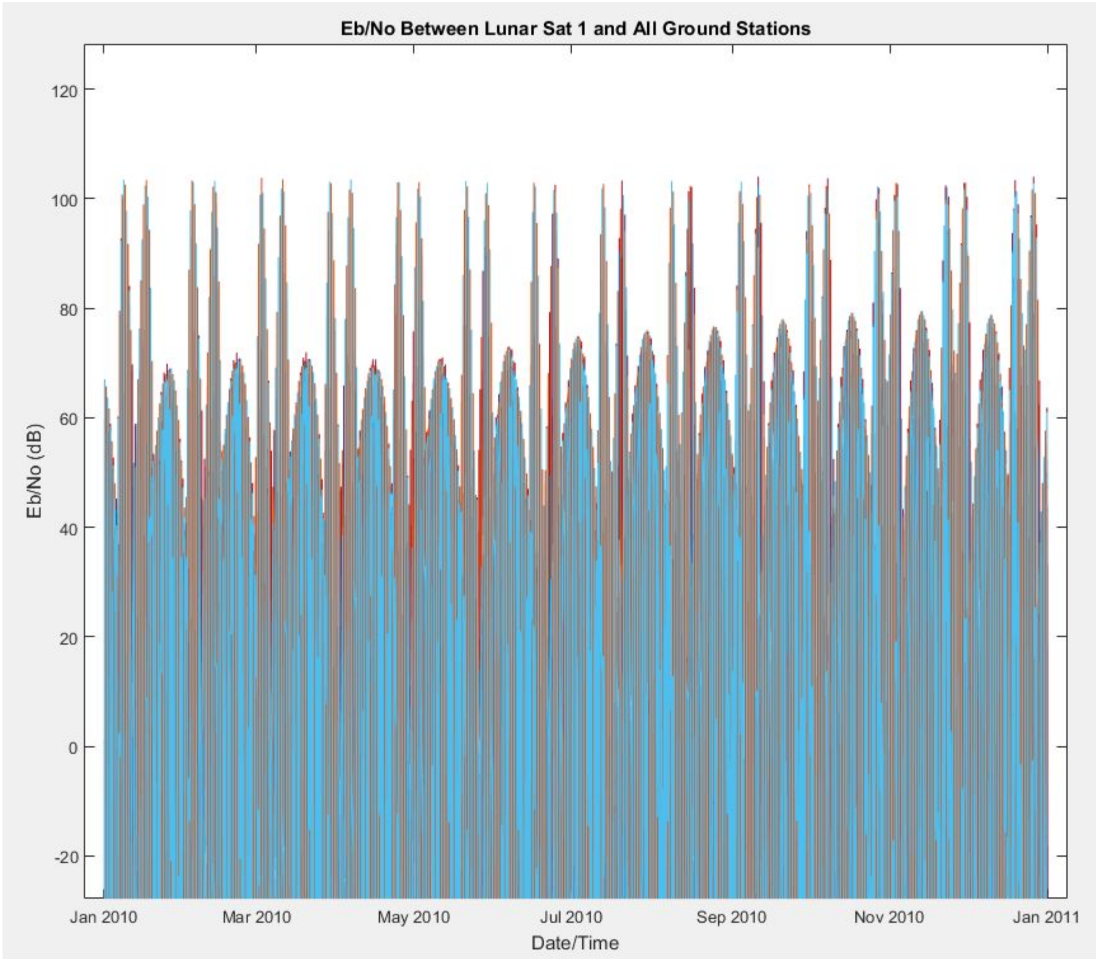

Figure 12: Eb/No for all optical links between Lunar Sat 1 and Earth ground stations (values greater than -20 dB)

This plot (cropped to only show values greater than -20 dB) shows the true performance of our system. While the link performance between any one satellite and one ground station may suffer gaps, our network of ground stations is resilient in maintaining consistently high link quality. For this one year of analysis, when all ground stations are considered, Eb/No never drops below 40 dB.

Orbital Analysis

As explained in the Orbital Design section, the orbits of the lunar relay satellites librate over time. Most high-altitude lunar orbits are inherently unstable due to the perturbations from the Earth. However, due to the specific orbital parameters of our satellites, the librations occur within a small range, and the orbits remain suitable for communications for many years. The target lifetime of our system is 20 years, so this was the period for our orbital analysis.

We performed orbital simulations, taking into account Earth harmonics up to J4, lunar gravity, and solar gravity. To view the evolution of the orbits over time, plots of the semi-major axis, eccentricity, argument of periapsis, and periapsis altitude above the lunar surface were created for all three lunar relay satellites.

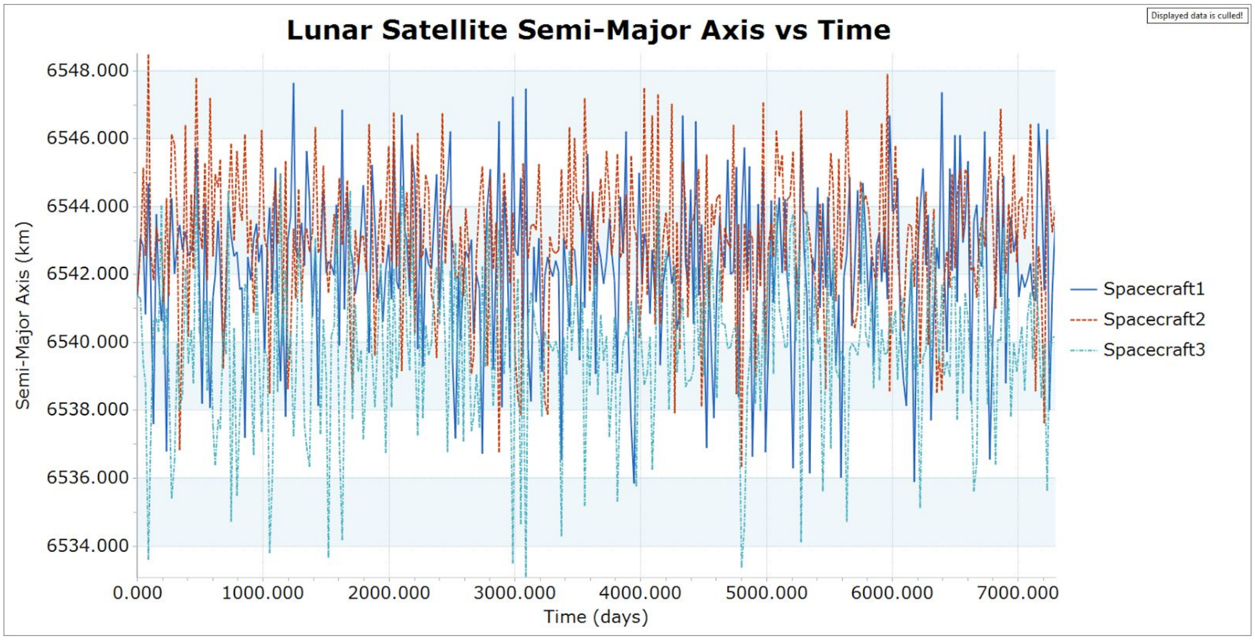

Figure 13: Semi-major axis 20 year simulation

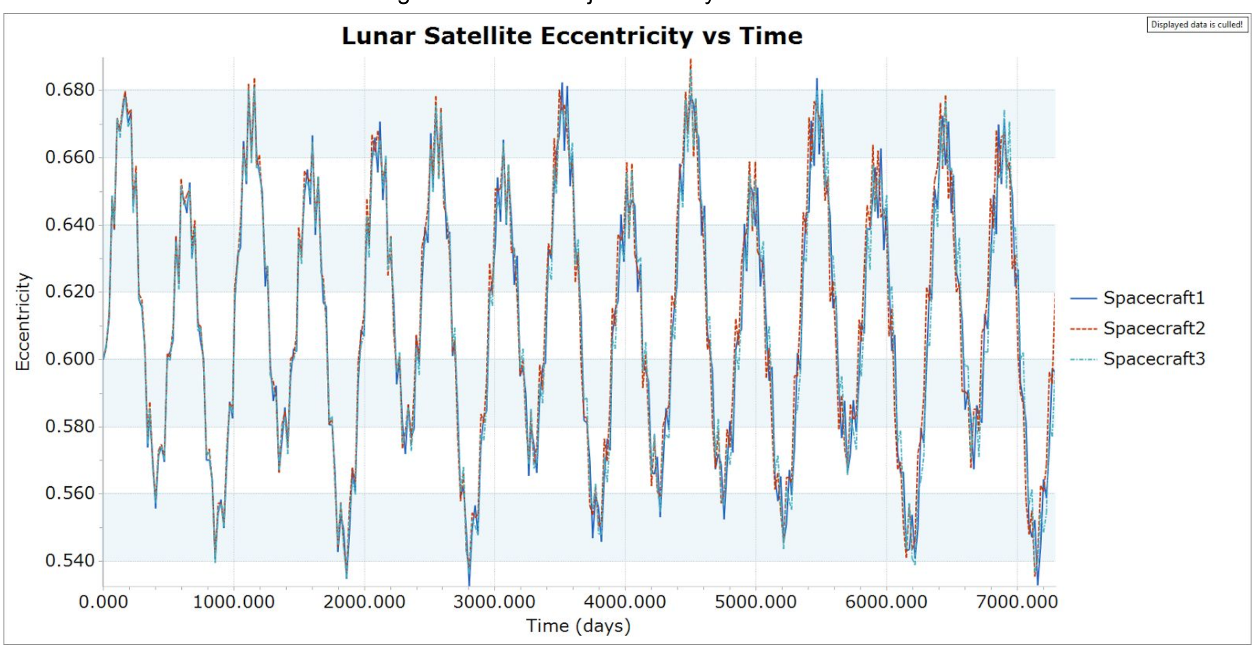

Figure 14: Eccentricity 20 year simulation

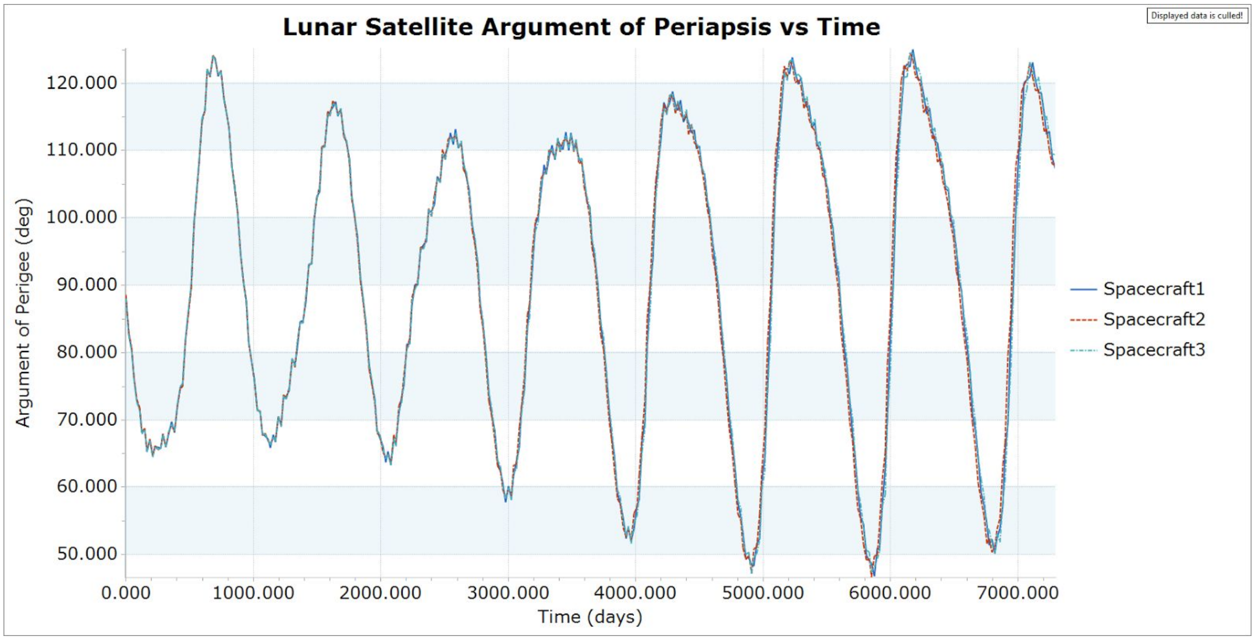

Figure 15: Argument of periapsis 20 year simulation

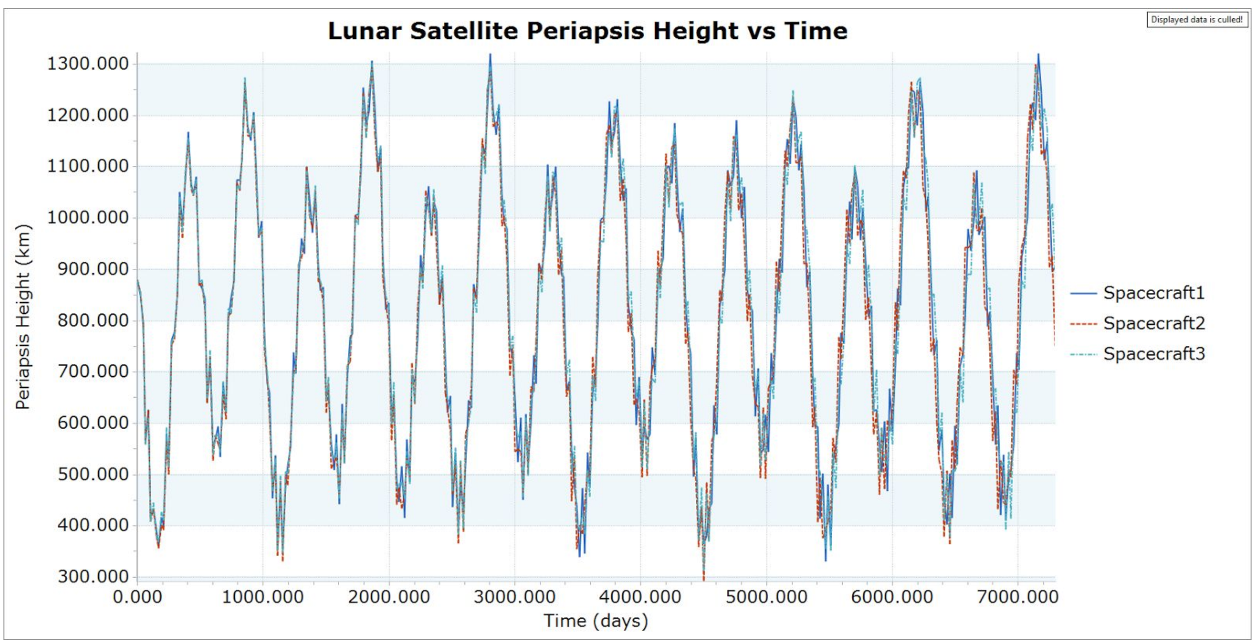

Figure 16: Periapsis height 20 year simulation

As these plots demonstrate, there are major librations in the eccentricity and argument of periapsis; however these librations are constrained to a relatively constant range. Despite the inherent instability of high altitude lunar orbits, our design stays marginally stable for the entire lifetime of 20 years without any needed orbital adjustments. The satellites neither crash into the Moon or leave the sphere of influence on a hyperbolic trajectory. There is no signifigant secular trend of the semi-major axis of the orbits, showing that the energy of the orbits remain practically constant over time.

One significant orbital behavior discovered in our analysis is that of growing oscillations in argument of periapsis. While these start off relatively contained, oscillating between approximately 65 and 120 degrees, by the end of the analysis period they have grown to between 50 and 120 degrees. Despite the growth in these oscillations, due to the eccentricity of our orbital design, even these larger off-nominal values for argument of periapsis yield adequate geometries for communication between southern lunar regions and ground networks on Earth. In addition to this, our analysis assumes that there are no orbital maneuvers or stationkeeping over the entire lifetime of the three satellites. These oscillations that slowly grow over the 20 year lifetime could be offset with basic infrequent stationkeeping maneuvers if desired.

System Lifecycle

Required Ground Infrastructure

One of the most significant barriers to a system like this becoming a reality in the very short term is a lack of optical communication ground infrastructure. While there are a number of commercial ground facilities for RF uplink and downlink all over the world, the number of optical receivers for commercial use is very limited for a fully operational system. If we want to create high-speed lunar communications networks for commercial applications, a ground network of dedicated optical receivers needs to be developed in the next five to ten years.

One specific group that is developing optical ground infrastructure is an American company called BridgeSat [17]. They are constructing a network of 10 ground stations with half-meter aperture receivers [17]. These half meter receivers were the baseline for our communications analysis. Set to be complete in 2019 [17], this will be the first system of its kind for commercial users, and it could easily handle the requirement of continuous downlink from our satellite network.

Other companies such as ATLAS Space Operations already operate and maintain global RF receiver networks for commercial satellite operators [18], and have proposed moving towards integrating optical technologies into their existing RF sites.

Due to the ongoing development of optical ground infrastructure, our analysis assumes that by the time a system like ours could be developed and implemented, the necessary ground infrastructure will exist for continuous operations. Our system will of course occur costs for the utilization of the ground infrastructure, but costs for developing the global system of ground receivers were not analyzed. These are costs that are currently being covered by other commercial entities.

Lifetime Limitations

The primary lifetime limitation on our system (like most communications satellites) is the amount of fuel that it can carry. However, in contrast with a typical communications satellite in GEO, true “stationkeeping” is not required. Instead, the satellites in our system require precise attitude control to allow the onboard transmitters and receivers to point at their “targets”. The satellite bus our system will use allows for attitude control through chemical propulsion, electric propulsion, and reaction wheels.

Unfortunately, despite the recent advances in communications satellite refueling and servicing, (especially given our use of an Orbital ATK bus,) lunar orbit is simply too far to consider satellite servicing a viable option for extending the lifetime of our system. In the nominal case, running out of fuel should be the limiting factor in the lifetime of our system.

A secondary lifetime limitation on our system is imposed by solar cell degradation, which is caused by cell exposure to high radiation levels. Previous research has estimated an average cell output degradation of 2 - 3% per year in lunar orbit [19]. Given the power surplus over the lifetime of our system, this is not a major concern over 20 years, but could potentially pose a problem if the lifetime was extended.

End of Life Scenarios

Due to our orbital design, the orbit of the three satellites librates over time. While numerical simulations have shown the orbit to be stable over a period of multiple decades [10], there is no natural orbital decay around the Moon as there is with the Earth's atmosphere. Given the increasing problem of orbital debris, and the possibility of our system being pulled out of the Moon's sphere of influence (and thus into the Earth's sphere) over a period of many decades, a strategy for end-of-life beyond simply leaving all three non-operational satellites in their lunar orbit is required.

Crashing spacecraft into the Moon has been a disposal strategy for multiple past lunar missions. Both the GRAIL mission, carried out by the Ebb and Flow twin probes, and the LADEE mission were retired in such a way, as they lacked the fuel required to maintain long-term orbits and thus sustain scientific operations [20][21]. This end-of-life option also offers the opportunity for further scientific research, as lunar geology can be studied through the geometry of the resulting impact crater. Given the eccentric orbit of the three satellites, the periapsis of their orbit could be lowered into the lunar surface with a very small maneuver at apoapsis.

Cost Analysis and Launch Vehicle Selection

Satellite Cost

Based on the cost of communications satellites today, and previous lunar science missions, we believe that we can produce each satellite at a cost of $300 million each.

In terms of communications satellites, our system is of relatively average size. It is the communications payload that truly sets it apart. Past optical communication demonstration missions, performed both by commercial companies and national space organizations have not had significantly high costs, but this is of course a mission risk.

Launch Vehicle Selection

After studying options for launch vehicles, we came to the conclusion that the best one for our purposes would be the SpaceX Falcon 9. This is primarily due to the accessible cost of the Falcon 9 in comparison to other currently available launch vehicles with similar capacities.

Overall Cost Analysis

Table 10: System Pricing

Component	Individual Price	Quantity	Total Cost
Lunar relay satellite	$300M	3	900M
Falcon 9	$62M	3	186M
Total ($)	-	-	1086M

Ground Infrastructure

The ground infrastructure that would process the data is not included in our budget as we are assuming that it already exists, leaving us to merely hire the services of the of the ground infrastructure.

Risk Analysis

The team performed a risk analysis to identify potential hazards to the system. The analysis uses a common 5x5 risk matrix with the following criteria for each axis:

Table 11: Risk Probability Scale

Rating	Description	Likelihood*
1	Very Low	< 1%
2	Low	1% - 10%
3	Moderate	10% - 33%
4	High	33% - 50%
5	Very Likely	> 50%

*Likelihood refers to the probability of occurrence at any point during the operational lifetime of the system.

Table 12: Risk Consequence Scale

Rating	Description	Details
1	Minimal Impact	Little to no impact on the functionality of the system
2	Minor Impact	Short term reduction in data integrity or rates
3	Moderate Impact	Temporary loss of continuous communications between Earth and Lunar Site OR Long term reduction in data integrity or rates
4	Major Impact	Irrecoverable, permanent loss of continuous communications between Earth and Lunar Site
5	Mission Catastrophic	Irrecoverable, permanent loss of all communications between Earth and Lunar Site

Table 13: Risk Priority Ranking

Probability / Consequence	Minimal Impact	Minor Impact	Moderate Impact	Major Impact	Mission Catastrophic
Very Likely					
High					
Moderate					
Low					
Very Low					

Each risk is assigned a value for probability and mission impact to evaluate the overall risk to the mission. Once the overall risk is determined, the team developed mitigation strategies, giving priority to risks that were viewed as the highest priority.

Table 14: Risk Analysis Summary

Risk	Probability	Consequence	Priority	Mitigation Strategies
Launch vehicle catastrophic failure	1	5		Prioritize reliability in launch vehicle provider selection.
Individual satellite attitude control system failure	2	4		Build redundancy into the system: Allow for attitude control through multiple systems.
Loss of pointing accuracy in satellite-based optical transmitter	2	3		Recalibrate (if possible), otherwise switch to RF system.
Loss of pointing accuracy in satellite-based optical receiver	2	3		Recalibrate (if possible), otherwise switch to RF system.
Satellite collides with orbital debris or foreign object	1	5		Calculate probability of collision, and perform evasive maneuvers as necessary.
Earth optical receivers are not ready to receive optical signals from our system.	2	3		We are depending on the commercial ground networks to process our signal. If this fails, we would switch to our backup RF system, and use it until signal processing is enabled.

Solar power system failure	1	3		Use energy stored by Solar Panels until depleted. Since we produce more power than we need, we can sustain a partial failure.
Propulsion system failure	1	5		Once in place, our orbital design ensures the system can operate without propulsive maneuvers.
Launch vehicle delivers payload to incorrect orbit	2	2		Add adequate margin to delta-v budget for satellite-powered orbital maneuvers.
Network interferes with operations of other satellites	1	3		Ensure compliance with ITU frequency allocation regulations.
Location of satellites and/or communication system could cause political issues	1	1		Analyze political regulations prior to satellite launch, in order to avoid these scenarios in the first place.
Space Weather Effects (e.g. solar flares, coronal mass ejections, solar radio bursts)	1	2-4 Depends on severity of "Weather".		Depending on the severity of the situation, different mitigation strategies could be taken.

After assigning probability and consequence/severity to each of the risks, the team concluded that two particular risks are of high priority for consideration. These are: individual lunar satellite attitude control system failure; and loss of pointing accuracy in satellite-based optical transmitters/receivers.

In the event of an attitude control system failure, we would allow either the reaction wheels or chemical thrusters to take control over the attitude system, giving us three possible methods to deal with this issue if it ever presents itself. In case we end up losing pointing accuracy in either optical transmitter, receiver, or both, we would attempt to re-calibrate it, and if this doesn't work, we would switch to our RF system. This last one doesn't depend on us, but it is a risk that we have to consider, since laser tech is not the most developed at the moment. In case this happens, switching to the RF system until signal processing is enabled is our best option.

Conclusions

As the Space Economy develops from science fiction to reality, we believe that one of the most crucial factors in this development will be lunar operations. Several use cases exist for a return to the Moon, while companies and countries across the globe are beginning to attribute great value to the market for lunar operations. However, in spite of the opportunity, no dedicated network exists to facilitate communication between the Earth and the Moon.

Our proposed system is designed to meet this need by offering a high-speed, high-reliability communications link to and from the Moon. This network could open up markets for lunar operations and trigger tremendous growth in the space industry, while also sustaining that growth for decades to come.

Lunar operations offer significant returns on investment in several forms: in terms of material resources, scientific research, and the accompanying revolution in technology and innovation. With the installation of a dependable, powerful communications network, all of these opportunities become more attainable, and in establishing this connection, humankind can once again place its feet on the Moon - this time to stay.

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