Investigation and Analysis into Establishing a Cislunar PNT System and Performing a Soft Landing on the Lunar Surface

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With an expected increase in human activity in and around the lunar environment, Georgia Tech, along with GTRI, has proposed two projects to get involved in this sector. One project focuses on Cislunar PNT, which attempts to establish a satellite architecture for PNT in the Cislunar environment. The other project is Lunar ISRU, which desires to soft land a spacecraft on the lunar surface to perform energy capture resource utilization. For an initial phase I study, the Space Systems Design Laboratory (SSDL) team investigated currently proposed requirements and architectures from literature for a Cislunar PNT architecture. Additionally, analysis was performed to simulate a transfer from a NRHO orbit to the lunar surface through an intermediate low lunar parking orbit for Lunar ISRU. From this research, the goal for a more detailed analysis is to create a navigation algorithm simulation package to apply to the chosen system architecture for Cislunar PNT and achieve an optimal and efficient landing for the Lunar ISRU spacecraft on the Moon's surface.

I. Nomenclature

PNT	Position, Navigation, and Timing
GNSS	Global Navigation Satellite System
DSN	Deep Space Network
(P, G) DOP	(Position, Geometric) Dilution of Precision
ISECG	International Space Exploration Coordination Group
LLO	Low Lunar Orbiter
NRHO	Near Rectilinear Halo Orbit
ISRU	In Situ Resource Utilization
L2	Second Lagrange Point

II. Introduction

Over the next decade, there will be an expected increase in human activity around the lunar sphere of influence, referred to throughout this paper as Cislunar space. This growth is motivated by a global interest to return humans to the Moon, as demonstrated in NASA's Artemis mission, along with other projects going to the Moon, such as ESA's Lunar Pathfinder, China's Chang'e, and Russia's Luna missions. This includes an interest to potentially create long-term human colonies at desirable locations, such as the Shackleton crater. However, with such a substantial increase in activity, there is a need for accurate positioning and navigation, along with a need to utilize resources on the Moon to prolong the timespan for lunar operations. As part of this interest in Cislunar space and the lunar surface, GTRI has proposed two projects investigating this area: A Cislunar PNT system and a Lunar ISRU spacecraft. In this report, work performed in the initial stages for both these projects will be covered, along with next steps and goals for future analysis.

III. Cislunar PNT - Overview

Currently, Cislunar missions utilize NASA's DSN to obtain their necessary PNT services, and there have been a few missions currently planned that will utilize "Weak GNSS," which is essentially receiving signals from Earth GNSS satellites to obtain PNT in the cislunar space. While these systems work to satisfy current day requirements, there is a need to achieve a more capable system to provide long term support for more stringent performance requirements and a larger service volume. In this report, an overview of current methods to achieve PNT will be covered. Then some necessary requirements for a future PNT system will be determined, followed by a trade study of architectures that have been in literature.

IV. Cislunar PNT - Current Systems

DSN

The DSN is a NASA operated network that is utilized by a multitude of interplanetary missions to communicate with mission operators back on Earth. However, due to the framework of the network and its capabilities, DSN can only serve a limited quantity of users at a time. DSN is currently operating near its capacity, and with the expected increase in mission downlinks that would need to be supported, as shown in Figure 1, the current DSN infrastructure cannot support the burgeoning interest in cislunar space.[1] This highlights a need for a different source to be used for Cislunar PNT, reserving the DSN to support other distanced interplanetary missions that may not be able to have such a convenient architecture in place.

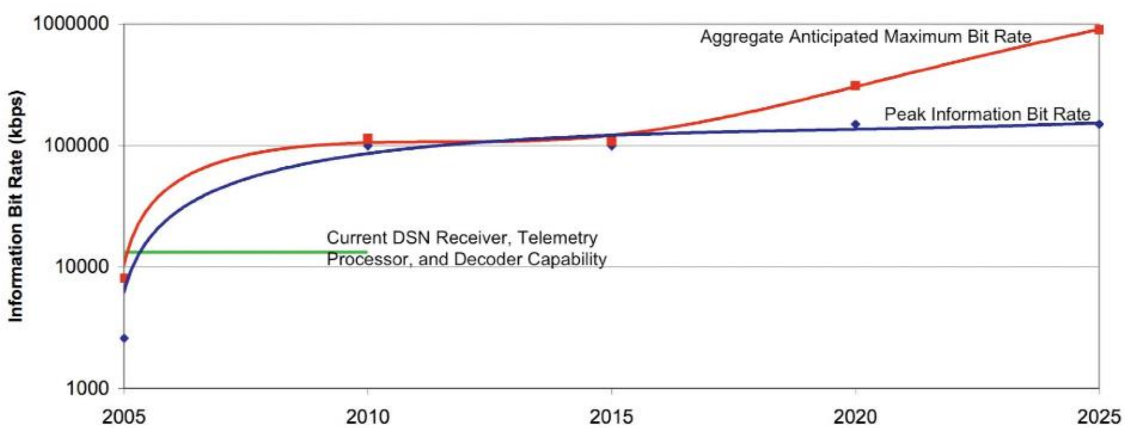

Figure 1. Projections of Needed Mission Downlink vs Current DSN Capabilities[1]

Weak GNSS

Weak GNSS refers to the leveraging of GNSS satellites, belonging to the GPS, Galileo, GLONASS, and/or BeiDou systems, to obtain position, navigation, and timing. While GNSS satellites direct their signals towards Earth, due to a sufficiently large beamwidth[2], these signals can be received from the other side of Earth, and out towards Cislunar space. Therefore, with a large enough antenna and a precise clock[3], accurate 3D positioning can be obtained from the tracking of these GNSS signals that are visible outside of the obstruction of the Earth.

A simulation of the effectiveness of these GNSS signals for the Lunar Gateway mission[4] was completed, with an assumption of 0.1-0.5 cm receiver range errors and 0.3-10 m navigation node errors. The results were that the Lunar Gateway would have between 5-13 satellites in view, at any given time, to receive signals which obtained a position root mean square error (RMSE) ranging from 300 meters to 7 km. Additionally, the results of the PDOP for the Lunar Gateway can be seen below in Figure 2 from the simulation. These numbers showcase that weak GNSS can be used to provide coarse PNT to satellites in Cislunar space, and additionally offers a benefit of reusing current GNSS architecture for future mission demand, without an excessive increase in additional infrastructure cost. However, the requirement of needing large antennas for such missions, combined with the relatively poor DOP provided due to poor satellite geometry, highlight a need for a more accurate and reliable system to be put into place.

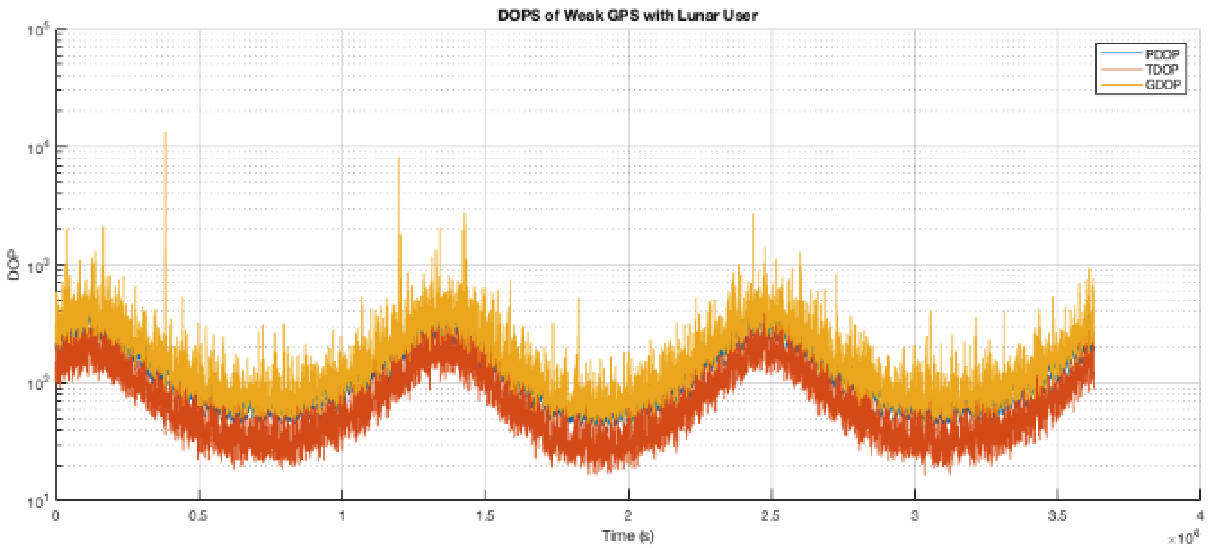

Figure 2. PDOP of Lunar Gateway in simulation for a duration of 50 days[4]

V. Cislunar PNT - System Requirements

When determining the requirements for a comprehensive PNT system, there are two aspects to keep in mind. First are the quantifiable PNT requirements that various users will require to operate in Cislunar space. These requirements will help define the architectures that are suitable to be implemented, along with the navigation algorithms and level of hardware sophistication needed for any mission. Second is a consideration for a phased plan to steadily work towards achieving a complete PNT system. The final PNT system will be unlikely to be deployed immediately or all at once, so there needs to be support and thought behind how the system should be rolled out, based on the level of activity that occurs in that space over time.

PNT Requirements

There are numerous sources that provide different recommendations and suggestions for PNT requirements for an eventual lunar PNT system. The suggestions utilized to establish requirements for this system come from a 2015 report from NASA[5] and a 2019 release from the ISECG[6] regarding what they identified as critical technological needs for space exploration. These two entities were chosen due to the specificities they provided in their desired requirements, combined with their personal stake in operations and missions in the cislunar environment now and in the future.

The ISECG has recommended that a 3-sigma positioning requirement of 90 m for precision landing and 0.4 m absolute and relative positioning requirement for in-space timing and navigation autonomy be achieved. The absolute and relative positioning requirement is stringent and is an expected final goal for a full PNT system, but currently requires space-certified clocks that are 10-100 times more exact than current technologies can obtain[6]. Therefore, this goal is something that can be accomplished within the next decade but is not likely to be obtained soon.

The NASA report has various positioning requirements proposed, all within 3-sigma, of surface operations within 30 meters, precision landing within 100 meters (10 meters less stringent than that by ISECG), 10 meters for surface rendezvous, 100 meters and 10 cm/s velocity error for any lunar constellations, and 50 km and 2 cm/s velocity error for users performing station keeping near libration points, like the L2 Lagrange point. These requirements serve as a good basis for PNT needs from operators looking to work in the Cislunar space.

Phase Requirements

While proposed performance requirements have been established for an eventual PNT system, it will take some time for a final PNT architecture to be fully deployed and put into use. Therefore, there also needs to be an established plan for how and when this PNT system should be deployed. Ideally, the final satellite architecture can be deployed out in blocks, similar to the process for how GPS was rolled out[7], so that continuous improvements to PNT support can be made as time progresses. The idea provided here is motivated from what was proposed by ESA's Moonlight mission[8], which is summarized below in Table 1.

Table 1. Desired performance accuracy for various users under the Moonlight mission. Red signifies lower performance and the green signifies higher performance.[8]

Operational Phase	Earth-Moon Transfer Orbit	Lunar Orbit	Descent, Landing & Ascent	South Pole Lunar surface	Full lunar surface	Integrity
Phase 1: GNSS-only and high-sensitive receivers						
Phase 2: GNSS augmented with LCNS						
Phase 3: Full lunar PNT constellation						

The following summary of per phase requirements were compiled from work done by the SSDL team for Cislunar PNT for this initial analysis and is drawn heavily from suggestions provided by ESA's Moonlight mission. They are presented here for context regarding a case study of the Low Lunar Orbiter in the next section.

First will be "Phase 1", which starts now and should be expected to last until the late 2020s. The goal of this phase is to utilize weak GNSS signals for more missions, testing out the levels of accuracy that can be obtained with high sensitivity receivers, and leverage the usage of DSN as much as possible while it can still support the current Cislunar mission load. In this time, satellites with intended long lifespans in Cislunar space should be provided with the appropriate hardware and software necessary to be compatible with the eventual proposed PNT architecture. This will allow these satellites to operate currently with the less exact weak GNSS measurements but hopefully switch to the more exact positioning once the eventual PNT system has been established. There are also a variety of navigation algorithms that have been proposed to improve positioning with regards to weak GNSS, such as two-way ranging and GNSS-CP[9], which can be tested and utilized during this phase. The emphasis of phase 1 is on low accuracy and opportunistic measurements.

Following in “Phase 2” will be the rolling out of the PNT architecture satellites in blocks. This phase should continue onwards until the early to mid-2030s. These satellites will first be deployed to provide the most desirable coverage towards critical regions of interest such as the South Pole or Shackleton Crater. These regions serve to be the most pertinent due to numerous reasons, including the rumored presence of frozen water and the early desires to begin a human Moon colony centered around these locations[10]. As each block of satellites is developed, the PNT provisions and Moon surface coverage will improve until phase 3 is reached. Additionally, during this phase, with the expected development of a human lunar colony, ground stations should be placed in high-traffic locations (such as the regions mentioned previously) so that more accurate PNT can be obtained at a higher volume over the local region. The emphasis of phase 2 is on high accuracy measurements on select lunar locations, but with reduced global availability.

Finally, in “Phase 3”, the last of satellite blocks should be rolled out and the final PNT architecture should be deployed in the mid to late 2030s. At this point, the combination of the final lunar satellite constellation, along with the presence of numerous ground stations, should be able to provide high accuracy positioning requirements across the entire service volume. These ground stations can serve as communication relays and additionally provide processing of ephemeris data on the ground to obtain precise point positioning[11] in the lunar environment. Finally, the presence of the lunar constellation can help provide weak lunar measurements to satellites in other areas of the cislunar environment such as near libration points.

Low Lunar Orbiter Case Study

In this paper, the low lunar orbiter case study is assumed to be applied for both low lunar orbiters and lunar lander missions. As mentioned earlier, the most stringent initial requirements for low lunar orbiters are the 90 meters positioning requirement. This support is already being met through weak GNSS capabilities, which will be the emphasis for phase 1 of the architecture. A paper simulating the positioning for a Moon transfer orbit, using weak GNSS, was able to achieve a positioning error of 75 meters at closest approach to the Moon with 2 sigma uncertainty by leveraging the E5/L5 band, a frequency band at the bottom of the lower L band for Galileo/GPS, and smoothing out errors with an extended Kalman Filter (EKF).[12]

In phase 2, a lunar satellite architecture is expected to be in place, and there will be less of a need to rely on weak GNSS. For phase 2 for a low lunar orbiter would expect to have improved performance requirements, which were determined by the SSDL team to be on a magnitude of under 25 meters in position error, under 0.02 m/s in velocity error, and within 0.01 ms in clock timing error. This type of accuracy has also been shown to be accomplished in literature. Through the usage of a highly accurate Moon camera and star tracker, satellites were able to achieve 30-meter positioning accuracy in a simulation[13], which could be improved with dynamic filtering methods to meet phase 2 requirements. Additionally, through the usage of LiASION, a linked autonomous orbit determination algorithm that leverages crosslink range measurements[14], a simulation of a 4-satellite constellation near a libration point was able to supply PNT with a root mean square (RMS) positioning error of 23.35 meters and an RMS velocity error of 20.3 mm/s.[15] Therefore, it is reasonable that with the development of a smallscale satellite constellation in phase 2, the specified requirements could be met with currently developed technology.

Finally, in phase 3, the most stringent requirements are expected to be met, which would be on a similar magnitude to what is requested by ISECG for absolute and relative positioning. This phase's requirements, relying on lunar satellite constellations, can be accomplished through an extensive satellite architecture, as will be demonstrated in the section with a 24-satellite constellation. However, with the support of precise point positioning[11] through ephemeris data from lunar ground stations, this level of performance could potentially be achieved with a less extensive satellite system.

VI. Cislunar PNT - Architecture Trade Study

After discussing the necessary requirements for any lunar PNT architecture, it is critical to apply them against a lunar navigation architecture. For the final PNT architecture, there have numerous proposed systems with varying numbers of satellites, orbits, and performance. Through an investigation into these architectures, there were four final proposals that were chosen to be investigated and analyzed. From this, recommendations and intuitions onto the cost-benefit analysis and trade space for the lunar navigation system environment can be determined. The architectures reviewed are Lunar Autonomous PNT System (LAPS)[16], Moonlight's Lunar and Communication Navigation Services (LCNS)[17], Lunar GNSS[18], and CAPSTONE[19]. These architectures, however, are more solely focused on utilizing satellites and the final PNT system would ideally also envision using lunar ground stations to improve PNT performance.

LAPS

LAPS, or Lunar Autonomous PNT System, is a proposed infrastructure to utilize existing lunar assets to provide PNT services to missions. The system is comprised of nodes that can estimate their own state, either through utilizing weak GNSS or DSN, or by interlinking with other nodes. This system was simulated using two test cases. Test case one considered 21 satellites over 3 planes to provide coverage over low altitudes of the Moon, while test case two used 9 satellites over 3 planes to provide coverage of the South pole. The specific geometries of these cases are illustrated below in Figure 3. In case 1, 2-sigma performance of 16 m for position error was achieved and a 2-sigma performance of less than 37 m for position error was achieved for test case 2.

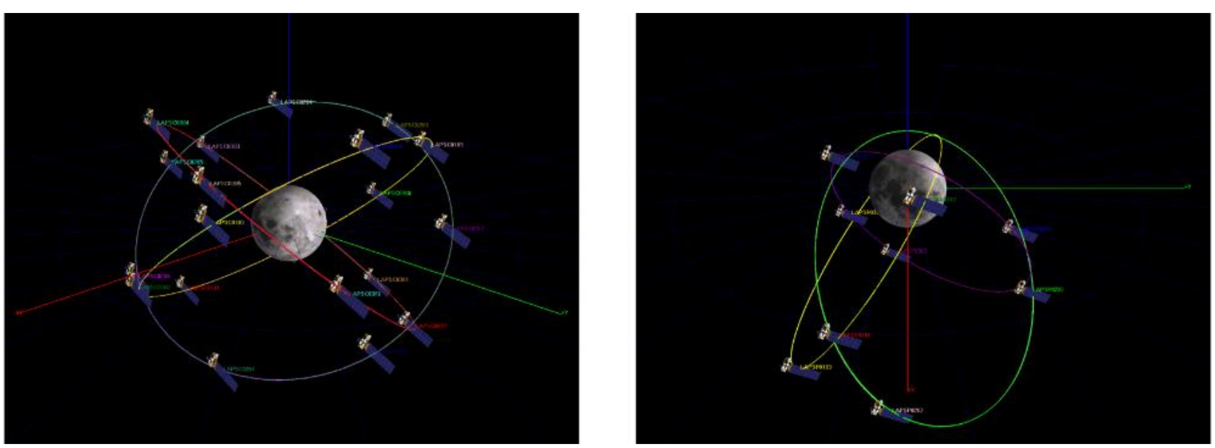

Figure 3. Proposed test cases for the LAPS system. Left: The proposed 21 satellite infrastructure (Test Case 1) Right: Proposed 9 satellite architecture (Test Case 2) [16]

This system provides sufficient enough phase 2 position performance for the regions that were covered in both instances, and additionally consists of a highly scalable architecture that is dependent on new users as new nodes are added for improved coverage. However, the need for at least one external source of positioning can be troubling for a desire to be completely independent of utilizing weak GNSS or the DSN. Additionally, the fact that the simulated architecture only provides coverage over certain regions would be conducive to a phase 2 plan rather than phase 3. However, with the proposed system, it seems reasonable that with enough users in diverse orbits, total coverage of the lunar surface could be accomplished.

LCNS

The Moonlight initiative proposed by ESA is a plan to provide PNT capabilities at the Moon by leveraging current GNSS techniques and technologies in their satellites. To highlight the potential capabilities of such an architecture, a sample scenario of 4 satellites in ELFO (Elliptical lunar frozen orbits) in 2 different orbital planes was proposed, as shown below in Figure 4. Using this architecture, support for a lunar lander scenario was simulated, with a 50 m 1-sigma error assumed for both orbital and clock components. Based on this, a position error of 47 meters was achieved for a single epoch measurement and 27 meters position error was obtained for a multiple epoch measurement, with 3-sigma levels of uncertainty.

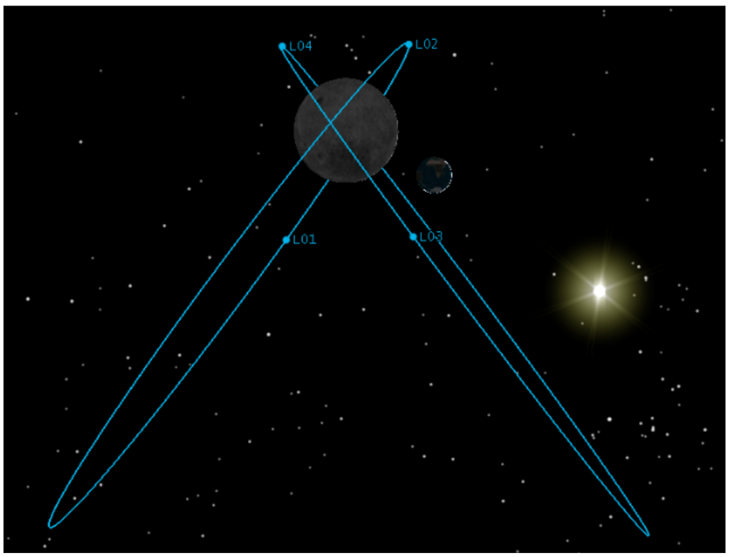

Figure 4. Proposed architecture for Lunar LCNS...Each of the planes will consist of 8 different satellites to obtain global coverage

This design serves to meet the requirements specified for a lunar lander by ISECG of 90 meters positioning error, and only requires a 4-satellite architecture which is fairly light. Additionally, by leveraging GNSS concepts, this could lead to a more rapid development and deployment of such an architecture into practicality. However, the proposed design isn't the most accurate out of all the cases investigated and has relatively poor availability (~68% global average), which could be useful for Phase 2 operations, but necessitates a more comprehensive design for the goals of Phase 3 to achieve total global coverage.

Lunar GNSS

The Lunar GNSS proposed by Pereira and Silva is a 24-satellite constellation on 3 different planes of orbit, as highlighted below in Figure 5. This constellation is a Walker constellation, which is an architecture proposed[20] to “minimize global GDOP, impact of satellite failure, space segment cost, and station keeping delta V”. Since this is a large satellite architecture, deployment is distributed into 3 “epochs”, which is similar to the previously proposed phases, with 8 satellites added per epoch. Each of the satellites required a station keeping of 71 m/s of delta V per year to maintain their orbits.

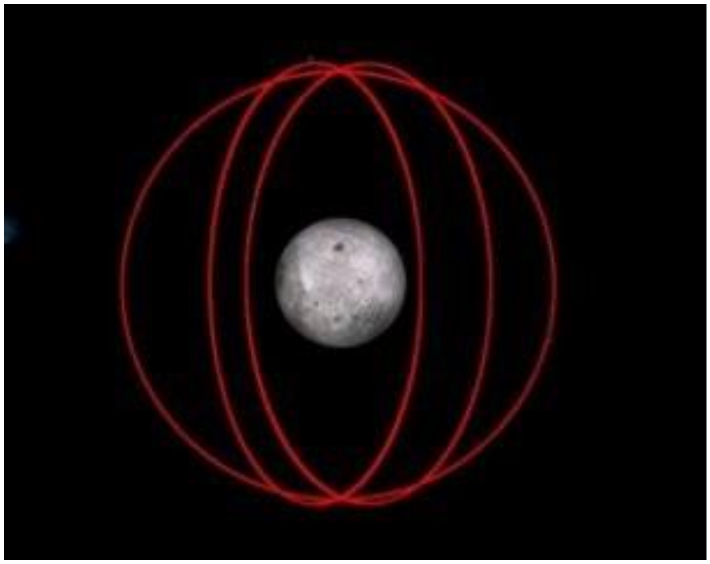

Figure 5. Proposed architecture for Lunar GNSS.Each of the planes will consist of 8 different satellites to obtain global coverage

The performance of this architecture was tested per phase for 3 different users: A surface user in Shackleton crater, which as mentioned previously is a likely location for an initial human base, a surface user in the Marius Hills, which is located near the Moon’s equator to determine global coverage feasibility, and a LLO user. The simulation was performed assuming a utilization of an S-band receiver with 0.159m of noise and clock plus orbital determination errors of 1, 10, and 100 meters. The worst-case scenario investigated was using a temperature compensated crystal oscillator (TXCO) clock which resulted in a 100 m position noise, 10 m/s velocity noise, and 1 microsecond clock bias. The simulation was able to achieve, in the worst-case, 52 m and 1 m/s position and velocity error respectively for a low lunar user and a 10 m position error for the surface users. In the best-case scenario, a position error of 40.4 cm was achieved for the LLO user for a 16-satellite architecture, and a position error of 30.1 cm was achieved for the LLO user for the final 24-satellite architecture.

Therefore, with this architecture, the most stringent positioning requirement desired by ISECG was satisfied in the best-case scenario for the LLO user. Additionally, with a 24-satellite architecture, the Lunar GNSS system could achieve nearly global coverage, providing PDOP availability, which was defined as any region supplied with a PDOP underneath 10, of 99.6%. However, while this system provides a very accurate and reliable PNT system, it requires an extensive 24-satellite architecture which can be difficult to deploy and requires expensive delta V requirements which can be difficult to maintain for a long-term lifespan, as envisioned for this system. This system can be envisioned as an expensive but highly accurate phase 3 solution to a Cislunar PNT system.

CAPSTONE

CAPSTONE is an upcoming CubeSat mission proposing to go to a NRHO orbit and test the capabilities of the Cislunar Autonomous Positioning System (CAPS). CAPS is a navigation software that can be utilized to perform autonomous navigation through crosslink measurements or one-way uplink with a ground station. The one-way uplink can be accomplished through communications with DSN, or eventually with a developed lunar ground station, but its crosslink measurements can be leveraged through communications with other spacecraft to obtain absolute position and velocity.

A simulation was performed between CAPSTONE and the Lunar Reconnaissance Orbiter to identify the performance capabilities of CAPS. A 2.5-meter position error and 11 mm/s velocity error were assumed for one way up linking and a 10-meter position error and 2 mm/s velocity error were assumed for two-way crosslinking with LRO. CAPSTONE improves with continuous long-duration operations, and in the best-case scenario investigated, after 3 perilune passages, a 3-sigma position accuracy of 156 meters and 3.32 cm/s were obtained with just crosslink measurements. With the addition of one-way up linking with a ground station, a steady state position error of 124 meters in position and 6.56 mm/s in velocity error was obtained after 1.5 days,

The benefits of this system are that it is highly scalable, since it can support an extensive number of “node” spacecraft, like LAPS, and therefore does not require a dedicated lunar satellite architecture or utilizing weak GNSS or DSN. This measurement with limited architecture is extremely appealing, especially when looking to provide support to missions not located in the local lunar environment, such as at the simulated NRHO orbit. However, for this proposal to work, there is a requirement for every spacecraft to utilize the CAPS software and have the sufficient hardware along with it. This could be undesirable because it adds an extra cost and power requirement to missions, which may not be preferred compared to lunar navigation systems that can provide PNT without any additional cost to the spacecraft. Additionally, for the crosslink measurements to perform optimally, they require spacecraft in asymmetric orbits (Ex. One in NRHO and one in low lunar orbit), which therefore may not be preferred for a system of node spacecraft all located in similar dynamical environment. It is possible CAPSTONE could be integrated into the Cislunar PNT architecture to provide support to spacecraft located in libration points.

VII. Cislunar PNT – Next Steps

The above analysis was performed for an initial study of this project as a precursor to conducting a more in-depth analysis. If the project is continued, there are three main tasks that need to be accomplished by the study team in the future.

First there is a need to clearly establish PNT requirements per phase. Current navigation requirements are established from literature review and estimations are made for relative magnitudes of performance needed for the various phases of architecture deployment. Coming up with exact performance requirements, and how these requirements may adjust based on varying user needs and increases in user volume over the next decade, need to be considered.

Second, there is a need to develop a PNT performance simulation package to enable a more quantitative trade study of architectures. A system to develop and simulate PNT architectures is under development, and there is a need to evaluate the performance of these architectures to see how well they meet the PNT requirements. A modular design that can be readily applied to any created architecture is critical to enable ease of use and an efficient method to compare a wide variety of architectures. This design would take into mind architecture geometry, necessary hardware, and types of measurements when evaluating PNT performance.

Lastly, a final architecture configuration will need to be proposed. From a detailed analysis from all the teams involved and a discussion with all relevant stakeholders, the above tasks will be implemented for the various systems and a more comprehensive trade study can be performed. From there, specific hardware requirements, navigation requirements, and performance metrics can be obtained.

VIII. Lunar ISRU - Overview

This mission focuses on landing a spacecraft on the Moon to perform in situ resource utilization operations. The satellite will focus on extracting materials for energy capture, unlike current research that mainly focuses on extracting oxygen from regolith[21]. However, to perform such a mission, it is necessary to safely land on the Moon to avoid damaging critical components. The objective of this task is to perform an efficient mission design to soft land on the Moon under the necessary mission weight and propulsion requirements. The current mission plan is to deploy from a NRHO orbit around L2, resembling a use case of deploying the spacecraft from Lunar Gateway, inject into a low lunar parking orbit of 100km, and then perform braking to around 1-2 km off the lunar surface, and then a controlled descent to land on the Moon. In this paper, the setup of the NRHO orbit will be explained, along with the initial braking phase analysis for the spacecraft.

IX. Lunar ISRU - NRHO Orbit

The use case for this mission is assuming the lifecycle of the spacecraft would begin from a NRHO orbit, similar to the one that Lunar Gateway will be in. To prepare for future detailed analysis on NRHO to low lunar orbit transfer, an NRHO orbit was created.

This orbit was simulated through propagating the differential equations for the N-body problem. This problem consists of N-bodies and simulates their motion through equations of the acceleration of each body with respect to the other bodies. The geometry of the N-body system is shown below in Figure 6 and the defining equation of motion is shown in Equation 1.[22]

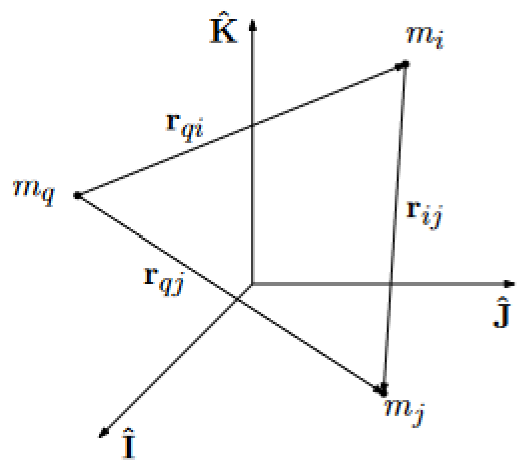

Figure 6. Definition of the geometry for the N-Body problem.[22]

$$\ddot{r}_{qi} = \frac{-G*(m_i+m_c)}{|r_{ci}|^3} r_{ci} + G * \sum_{\substack{j=1 \\ j\neq i,c}}^{N} m_j * \left(\frac{r_{ij}}{|r_{ij}|^3} - \frac{r_{cj}}{|r_{cj}|^3}\right) \tag{1}$$

Where G denotes the universal gravitational constant and the other quantities are consistent to the definitions provided in Figure 6 above. The bodies considered for this problem were the spacecraft's starting position (Ex. Lunar Gateway), Moon, Earth, and the Sun. The N-body problem was propagated by utilizing ephemeris data from NAIF's SPICE toolkit. SPICE is a collection of data, functions, and APIs that can be used for numerous space mission applications.[23] One great benefit that SPICE provides through their data kernels is ephemeris information for various bodies throughout a vast set of times, along with functions to obtain relative positions in a variety of reference frames. Therefore, all position and mass data of these major bodies are directly supplied from SPICE over the time intervals chosen from the initial conditions. In this case, the central body, m_q, was the Moon, the body of interest, m_i, was the starting position of the spacecraft, and the extra bodies, m_j, were the Sun and the Earth. The SPICE position data was collected with respect to the Moon in an inertial Moon reference frame ('IAU_MOON'). The spacecraft mass was assumed to be negligible compared to the mass of the other bodies ($(m_c + m_i) \sim m_i$) and the equations of motion were numerically solved using a 4th order Runge-Kutta method to propagate the spacecraft orbit.

The initial conditions for this orbit were obtained from a paper by Bhamidipati[24] and were specified as [-125.952, 120.961, 4357.681] km for position and [-0.042, 1.468, -0.003] km/s in the IAU frame for the time of November 8, 2025, at 11:22:07 pm in the UTC timeframe. Through this initial condition and above methodology, the orbit was simulated, and Figure 7 below shows one period of the NRHO orbit while Figure 8 shows the starting velocities of the spacecraft through the orbit.

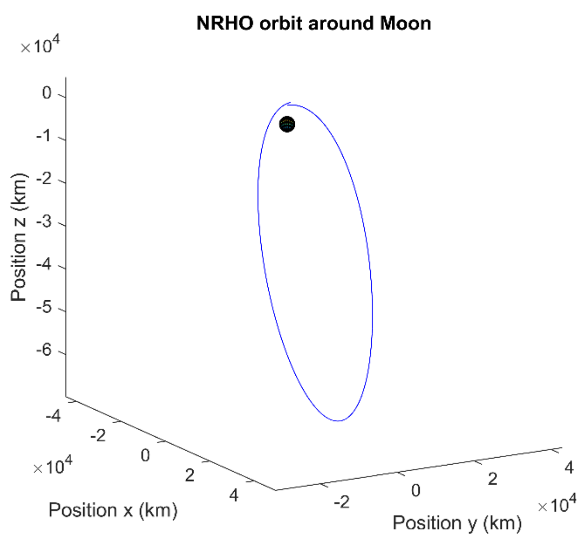

Figure 7. Simulated NRHO orbit from which the spacecraft could be deployed. The central body shown in the figure is the Moon

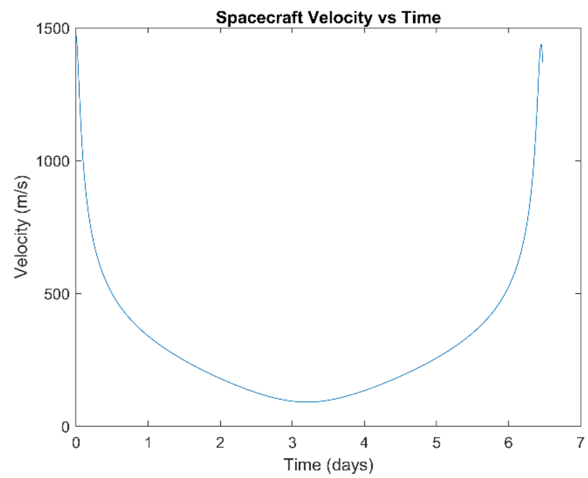

Figure 8. Magnitude of spacecraft velocities throughout the NRHO orbit

However, due to the time constraints presented in performing this initial analysis, much more detailed study on simulating the transfer orbit from NRHO to low lunar orbit was unable to be performed. In the future, the expectation is to utilize a simulation of this NRHO orbit, with various low lunar orbits, and identify the ideal transfer trajectory to minimize delta V.

X. Lunar ISRU - Braking Phase

After arriving at the low lunar parking orbit, the spacecraft will perform some initial identification of landing spots and obtain an ideal descent trajectory based on its desired landing spot and current location in the low lunar orbit. This specification of a desired landing spot, resulting in the optimal trajectory, is reserved for a future analysis and the work done in this report was simulating the direct transfer from low lunar orbit to the controlled descent phase. Along with that, other simplifying assumptions made in the analysis were that the Moon was spherical, with a uniform gravity field, and any external disturbances were ignored. This scenario was treated as a two-body problem, as shown below in Figure 9, with the Moon and the spacecraft, and all equations of motion and values are placed with respect to a Moon centered, Moon fixed reference frame. Lastly, the low lunar orbit, along with the braking phase trajectory, were assumed to be in the same plane, simplifying the problem into a 2-dimensional situation.

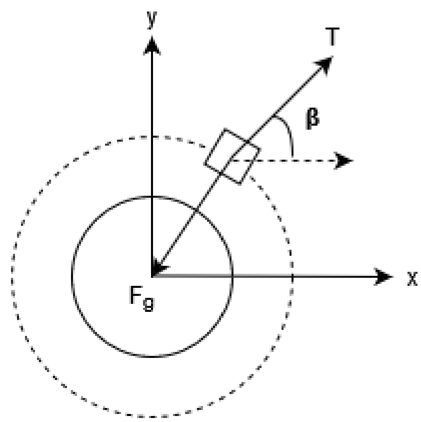

Figure 9. Diagram of the 2-body problem where the central body is the Moon, T resembles thrust, Beta is the thrust angle, F_g is the force of gravity, the dotted line resembles the spacecraft orbit, and the x-y axis belongs to the Moon centered, Moon-fixed reference frame.

In the x-y frame mentioned earlier, the equations 2-7 below were used to determine the change in state of the spacecraft throughout the burn.

$$\ddot{r}_{g,x} = \frac{-\mu * r_x}{(r_x^2 + r_y^2)^{\frac{3}{2}}} \tag{2}$$

$$\ddot{r}_{g,y} = \frac{-\mu * r_y}{(r_x^2 + r_y^2)^{\frac{3}{2}}} \tag{3}$$

$$\ddot{r}_{T,x} = \frac{T}{m} * \cos(\beta) \tag{4}$$

$$\ddot{r}_{T,y} = \frac{T}{m} * \sin(\beta) \tag{5}$$

$$\ddot{r}_x = \ddot{r}_{g,x} + \ddot{r}_{T,x} \tag{6}$$

$$\ddot{r}_y = \ddot{r}_{g,y} + \ddot{r}_{T,y} \tag{7}$$

Where r represents the position of the spacecraft with respect to the Moon center, m is the mass of the spacecraft, μ is the gravitational parameter of the Moon, T is the thrust supplied by the spacecraft and β is the thrust angle of the spacecraft in the Moon centered, Moon fixed reference frame. In this simple analysis, the thrust supplied by the engines was held constant, and the thrust angle was held to be in the opposite direction of the velocity of the spacecraft. Therefore, equation 8 below is used to obtain the angle that the thrust would be fired at.

$$\beta = \tan^{-1}\left(\frac{\dot{r}_y}{\dot{r}_x}\right) + \pi \tag{8}$$

The simulations were run using an ISP of 202 s, similar to that which is achieved by the Lunar Flashlight engines, an initial total mass of the spacecraft of 100 kg at the start of the low lunar orbit, a speed of 1692.7 m/s purely in the x direction, and a position of 100 km of the surface of the Moon purely in the y direction. The final desired state was to achieve a total velocity in the x and y directions of under 5 meters per second.

First, an analysis was done on the ranges of thrust that could work for this problem. From this, the equations of motion were propagated and the Figure 10 (a) and (b) below highlight the fuel fraction consumed during descent and the final altitude till the desired final state was achieved.

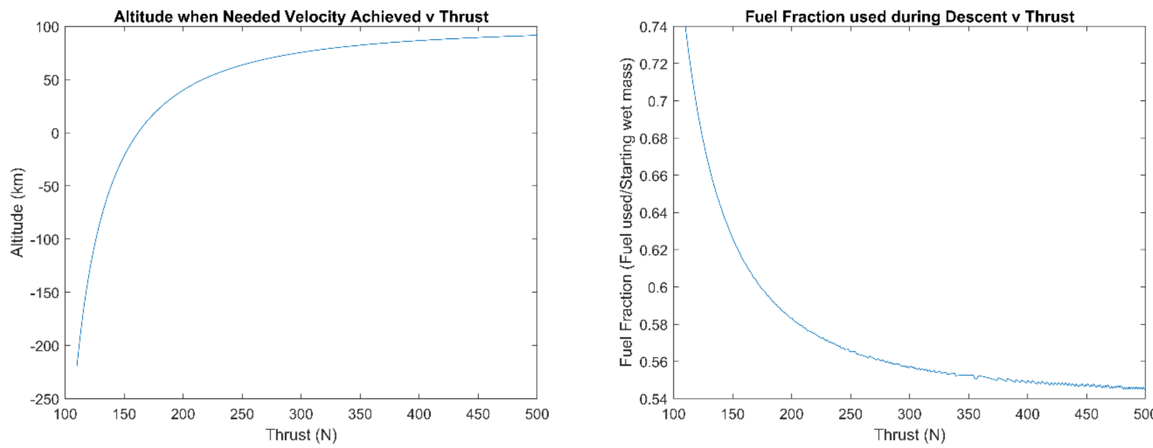

Figure 10. (a) Left: Final altitude of the spacecraft off the lunar surface when x and y velocities were under 5 m/s for various thruster forces (b) Right: Fuel fraction consumed in achieving the final position, compared to the starting mass of 100 kg. The fuel fraction was capped off at 0.74 to leave at least 0.26 for both the dry mass and controlled descent if needed.

As can be seen, there is an optimal thrust level that finds itself at the point of diminishing returns in terms of the fuel fraction, and at an ideal altitude to begin the controlled descent. This thrust was determined to be 155 N. Using this value, the detailed results of the spacecraft motion were obtained and are shown below in Figures 11-13.

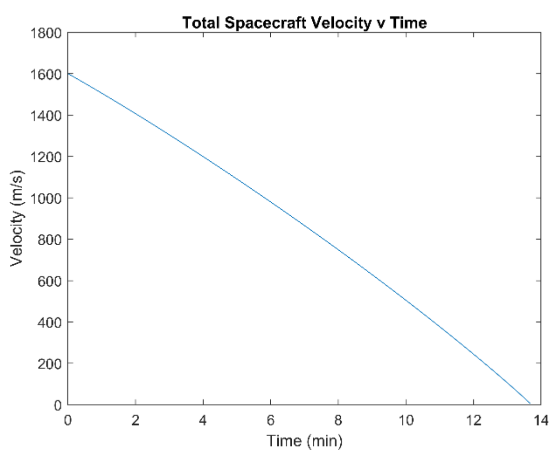

Figure 11. Total Spacecraft velocity over the length of the lunar descent period in meters per second

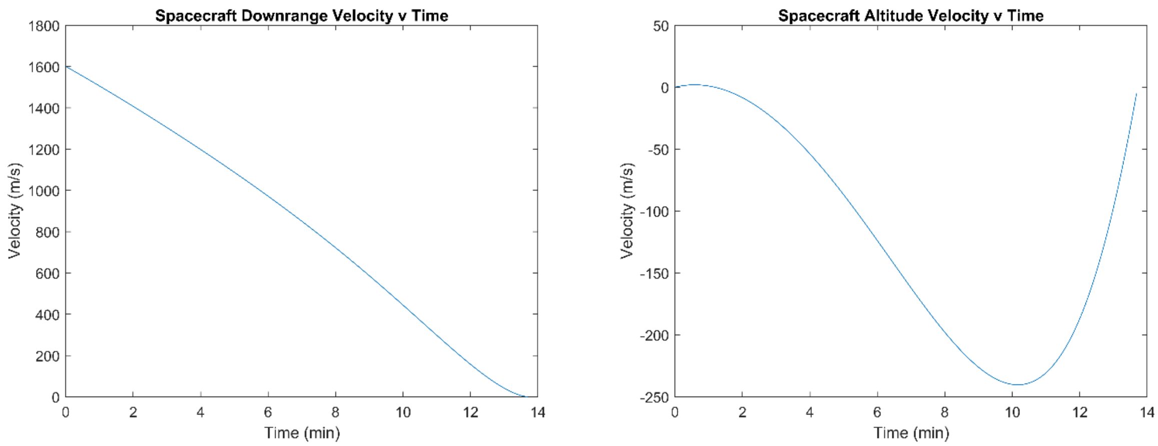

Figure 12. (a) Left: Spacecraft velocity as seen along the surface of the Moon, not in the x and y coordinate system. (b) Right: Spacecraft velocity vertically from the surface of the Moon throughout the length of the descent

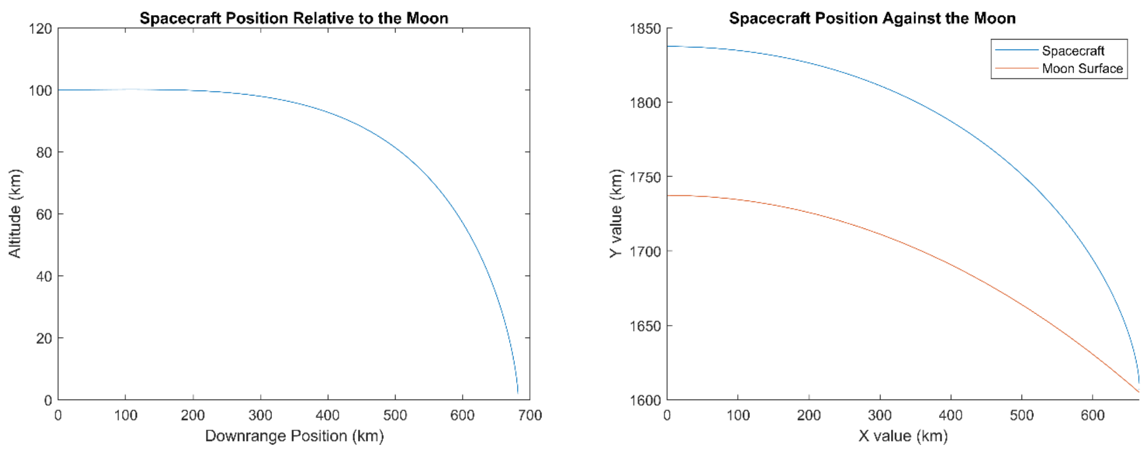

Figure 13. (a) Left: Spacecraft position in a 2-D sense as witnessed from the surface of the Moon. The downrange position is given in respect to a starting position of the Moon's north pole. (b) Right: Spacecraft position given in the x-y coordinate system described earlier

As shown, the 155 N thruster for the 100kg spacecraft can successfully perform the deorbit burn to lead into the controlled descent phase. The burn time is a total of 13.8 minutes and results in a consumption of 64.6 kg of fuel. Through this 13.8-minute descent, the spacecraft ends up at 1508 meters off the surface of the Moon with a downrange speed of 0.2556 m/s and a vertical speed of -4.1371 m/s. From this point onwards, the spacecraft will enter the controlled descent phase to accomplish a soft landing on the lunar surface while descending the remaining 1508 meters.

XI. Lunar ISRU – Next Steps

As was mentioned, there were many simplifying assumptions made in this analysis, either due to lack of information, or to enable a simplified analysis. The next steps are to remove these assumptions to obtain a more realistic mission scenario and an optimal trajectory.

First, there is a need to investigate the performance of various transfer orbits from NRHO to low lunar orbit, and for NRHO to the lunar surface. Currently, the mission design consists of travelling from NRHO to a low lunar parking orbit, and then performing descent to the lunar surface, which matches with suggestions from literature review. However, it will be useful to obtain separate analysis for this specific mission and determine the costs and benefits of pursuing a low lunar parking orbit versus direct descent. Additionally, a determination of performance and requirements for such a trajectory will be useful to obtain for this specific mission scenario rather than relying on literature conclusions for other missions.

Second, simplifying assumptions to the braking phase analysis need to be removed. The situation needs to be translated into a 3-dimensional problem and take into consideration disturbance forces that may be present in a real-life scenario. Additionally, a non-constant thrust approach needs to be considered to identify if this can result in a more optimal usage of fuel to achieve soft landing on the lunar surface. Consideration is being taken on utilizing powered explicit guidance (PEG) equations combined with a sequential engine shutdown method[25] to accomplish this goal. In the meanwhile, a more explicit trajectory control design needs to be implemented to reduce fuel consumption. Work has been made using the Hamiltonian equation and costate variables through optimal control theory[26] to obtain an optimal thrust angle throughout the lunar descent.

Finally, these solutions need to be modular to account for various necessary dry masses and desired landing locations, based on information from the other teams involved in the Lunar ISRU project. The current numbers used for the project were based on approximate values in lieu of having exact specifications on the mission requirements upon landing. Through utilizing the sequential engine shutdown method mentioned earlier, it is possible to adjust the downrange landing location of the spacecraft. Other methods of accomplishing this are altering the low lunar parking orbit the spacecraft ends up in from NRHO and adjusting the starting location of lunar descent from the parking orbit.

XII. Conclusions

The focus of these two studies is motivated from an increasing desire to return humans to the Moon and increase human presence and operations in the Cislunar environment. To accomplish these tasks, support is necessary to provide accurate positioning and timing and for sufficient resources to enable long term presence.

While currently utilized methods for PNT in the Cislunar environment may be sufficient for the current service volume, with the expected increase in future missions planned in Cislunar space, DNS and weak GNSS will soon be unable to supply and/or provide sufficient PNT for operations. Therefore, based on desired requirements for PNT recommended by both NASA and the ISCEG, combined with a phased deployment plan similar to that established by ESA's Moonlight mission, PNT requirements were determined. Various proposed architectures were considered from literature reviews and the costs and benefits to these were considered, along with which phase they would most likely be applied in. The most accurate positioning requirement with high availability was obtained by a 24-satellite architecture, with a 3-sigma positioning requirement of 0.3 m. But with a lower infrastructure requirement, a smaller satellite grouping with less coverage might be preferrable in exchange for a lower level of performance, such as CAPSTONE with a 124 m 3-sigma positioning error. With this information, a hybrid architecture incorporating positives and negatives from all the proposed designs can be created, and then different navigation algorithms can be implemented to try and satisfy the necessary PNT requirements for various cislunar users.

Additionally, with a need to safely land on the Moon to demonstrate ISRU capabilities, a mission design was proposed to travel from a NRHO orbit, envisioning a use case of deploying from Lunar

Gateway, to perform a descent on the Moon. Simulations of a NRHO orbit were performed to enable future detailed analysis on performance of transfer orbits from both NRHO to a low lunar parking orbit, as specified in the current mission overview, and for potentially NRHO directly to lunar descent. Additionally, an initial analysis of the braking orbit, from the 100km low lunar orbit to around 1-2 km off the lunar surface, was performed. Assuming a 100kg spacecraft, the ideal thruster force needed was determined to be 155 N, and the spacecraft was able to complete braking at 1.5 km off the lunar surface with a final velocity magnitude of 4.1 m/s and a consumption of 64.6kg of mass through 13.8 minutes of descent. In the future, consideration will be taken into place of an ideal landing location, removing simplifying assumptions, and developing a guidance control algorithm to improve descent performance.

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