SYSTEM DESIGN AND ANALYSIS FOR CISLUNAR SPACE DOMAIN AWARENESS THROUGH DISTRIBUTED SENSORS

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This paper summarizes an ongoing Georgia Tech effort to provide a cislunar space domain awareness (SDA) solution based on distributed space-based sensors that complement existing Earth-based assets. Distributed space-based SDA architectures complement one another via a diverse constellation geometry to overcome the sensing limitations of any single architecture. Our unique technical approach to this solution focuses on analyzing the links to a "Cislunar Custody Chain" via a diverse team of sensor, policy, and orbital dynamics experts. Our analysis will provide solutions towards creating the best actionable policy knowledge given the challenges of tracking and detecting objects within the Cislunar volume.

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I. INTRODUCTION

Performing the critical tasks of Space Traffic Management (STM) and Space Domain Awareness (SDA) on the cislunar volume is infeasible with any single sensor system. Studies have shown that there is no single sensor that can be positioned in space, on the earth's surface, or on the lunar surface to fully cover the cislunar volume across time [13, 24, 26]. This is due to two major factors: the vast volume of cislunar space, and the time-varying illumination conditions. The distance to the moon is approximately 9 times farther than Geostationary (GEO) orbit, rendering many existing SDA sensors that are capable of monitoring satellites out to GEO useless due to the inverse square law of radiance propagation. Furthermore, the motion of the sun relative to the rotating earth-moon frame and the observer satellite's frame will cause gaps in observability for Electro-Optical (EO) sensors due to solar phase angle considerations [24]. These two issues necessitate the development of a collaborative network of space-based distributed sensors to compliment existing infrastructure and enable persistent and comprehensive cislunar SDA.

This paper summarizes an ongoing effort at Georgia Tech to optimize a cislunar space domain awareness (SDA) solution based on distributed space-based sensors that complement existing Earth-based assets. In this paper, we show initial results proving that distributed space-based SDA architectures are able to overcome the challenges of cislunar SDA monitoring because each sensor can complement one another via a diverse geometry to achieve the coverage and sensing performance that is not possible by a single sensor. The constellation-based SDA capabilities also potentially provide the benefits of flexibility, upgradability, and robustness. To achieve this vision of cislunar SDA through distributed sensors, we will utilize our outlined framework in order to perform high-level trade studies and determines the optimal designs of distributed space-based sensors to maximize the cislunar SDA performance via a Model Based Systems Engineering approach. The result of this effort will inform the design of a space-based sensor configuration that would evolve into an eventual technology demonstration mission to be developed, assembled, and operated by Georgia Tech.

II. TECHNICAL APPROACH: THE CISLUNAR CUSTODY CHAIN

Our technical approach focuses on analyzing the links to the "Cislunar Custody Chain" that are outlined in Fig. 1. This chain has four main links that span all key components from detecting a satellite in the cislunar space to transmitting the information to decision-makers on Earth. If any single chain link is broken then knowledge of a transiting satellite is not maintained by satellite operators and decision makers on the ground. This means that each link is equally critical to spatially-comprehensive and temporally-continuous actionable cislunar surveillance.

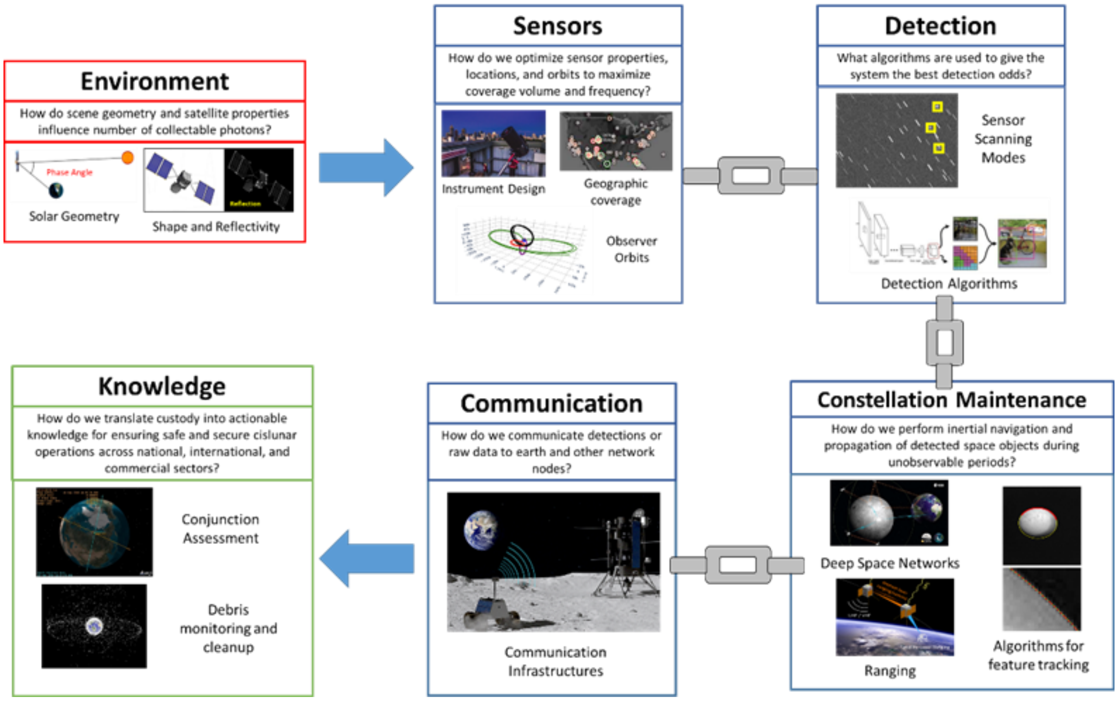


Fig. 1 A diagram of the "Cislunar Custody Chain." A brief description of each chain link and some considerations for each link are shown.

As seen in the diagram, the "Cislunar Custody Chain" decomposes the process of converting unknown environment information into actionable policy knowledge into four main links. The goal of the our model-based systems engineering approach is therefore to optimize each of these links to understand the cislunar environment. In the case of this study, the cislunar environment encompasses all information about the satellites that are not controllable by the operator, but that ultimately dictate how many photons will be scattered into the collecting aperture of the sensor that is detecting the object. These include the time-varying relative orbital dynamics and the reflectivity of the satellite materials.

The links of the "Cislunar Custody Chain" for converting this environmental information into actionable knowledge can be roughly described by the following four categories:

1. ***Sensor*** systems include all potential surveillance satellites and their sensing hardware. Optimizing for the sensor configuration of this network involves fully analyzing the tradeoffs between orbital trajectories, number of sensors, and the payloads on those sensors.
2. ***Detection*** systems encompass factors such as the sky-scanning systems, tasking management schemes, and image processing algorithms that will be used to survey the full cislunar region. These systems attempt to make the best use of the scene and sensor constraints in order to detect and track targets within the cislunar region.
3. ***Constellation Maintenance*** systems include algorithms, sensors, and networks to determine the positioning of the observer satellite in an inertial frame. This is critical information for propagating the detected satellite's position forward in time and eventually maintaining a catalog of the location of all satellites in the cislunar region. For the cislunar region, it is very likely that detected satellites will pass through unobservable regions such as exclusion zones, making it imperative to be able to propagate this information over time.
4. ***Communication*** systems include the relay networks and deep space networks that will be used to communicate information across surveillance nodes and to decision-makers. This is necessary for ensuring timely monitoring of systems and maintaining safe cislunar traffic flow.

Our team's primary goal is to develop a flexible model-based framework for analyzing all four links of the "Cislunar Custody Chain." By developing swappable algorithms for each link, we enable a model-based systems engineering approach to optimizing over desired network traits such as percent cislunar volume that is observable as a function of time. The inclusion of all four links at will also enable the investigation of the complementary nature of these various links for knowledge retrieval.

As an example of the complementary nature of the links, consider that having a detailed model of detection capabilities can inform how frequently a cislunar transiting satellite will be detectable by the current distributed sensor constellation under study. This is critical information to the "navigation" team when developing algorithms for tracking the transiting satellite because it informs them of how often they will be receiving measurements versus propagating the uncertain position of the transiting satellite. Furthermore, the "sensors" and "navigation" link optimization can inform the "knowledge" module of how often they will be receiving intelligence on the ground, and what confidence they should place on that intelligence. This integration enables us to provide optimal design solutions for Cislunar SDA while considering the entire "Cislunar Custody Chain" in a holistic and, ultimately, quantitatively rigorous manner.

III. TECHNICAL ANALYSIS

A. REFERENCE MISSION DEVELOPMENT

Our initial research into distributed sensors for cislunar SDA has revealed that (1) the differing capabilities of sensors, (2) the unpredictable orbital dynamics expected in different locations of the cislunar volume, and (3) the varying ranges necessary to detect and track objects leads to a natural segmentation of the ways in which sensor networks should be designed and evaluated. Our systems engineering approach therefore focuses on optimizing networks for two specific Design Reference Missions (DRMs). Breaking the cislunar SDA task into these two different DRMs is based on prior knowledge of the likely trajectories and orbits for targets of interest in these two different zones. These DRMs can be defined in the following manner:

- **DRM 1:** Translunar region, defined as the cone extending from GEO to 450,000 km from Earth
    - Justification: Observation of the translunar region will identify targets on translunar trajectories. In addition to Earth-Moon transfers, this region includes trajectories to the L1, L2 Lagrange points and transfers between them. Targets going directly into a low Lunar orbit (LLO) will pass in the vicinity of either L1 or L2, and the path between the Earth and Moon has a constant geometry in the co-rotating Earth-Moon frame.
- **DRM 2:** Low-Lunar Orbit (LLO), defined as the spheroid with 3,300 km polar and 10,000 km equatorial radii.
    - Justification: Observation of LLO provides situational awareness of objects in the vicinity of the Moon, with a focus on regions stable under perturbations. We assume that spacecraft will target stable orbits by design, and only debris in stable regions pose a long-term risk. [1-3]. To quantify the LLO regions of high interest, we have performed an orbital stability analysis by perturbing frozen orbits. The gravitational anomalies due to the Moon's shape create chaotic patterns in quasi-stable orbits, so the region of interest is bounded by a spheroid with 3,300 km polar and 10,000 km equatorial radii for target missions. Simulated stable orbits for different initial inclinations, subject to only lunar gravity forces, are compiled in Fig. 2 for reference.

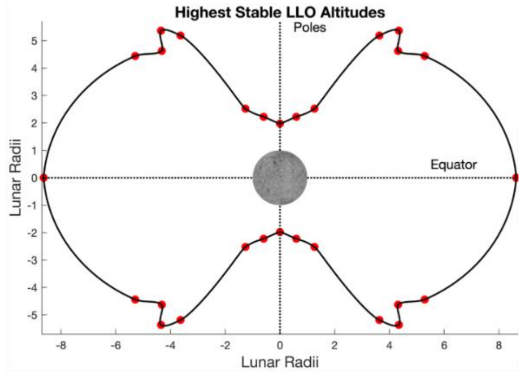


Fig. 2 Summary of stable LLO orbit parameters

The results that are presented in this paper show analysis on the broad translunar region specified in DRM 1, but future results will extend the analysis towards both DRMs. Each of the DRM scenarios will ultimately be analyzed using a rigorous Model-Based Systems Engineering (MBSE) approach. The MBSE model assists in the iterative process of systems design, evolving as requirements and the system change over time. In particular, the MBSE model contains both the requirements of each DRM as well as a description of the system designed to meet those requirements. MBSE offers an object-oriented decomposition of the observer constellation thus enabling rapid exploration of the design space. By linking this decomposition to the requirements of the DRM, the MBSE model enables automated requirements verification as both the system and its requirements evolve. To perform this task efficiently, the analysis tools needed to assess system performance can be integrated into MBSE environment.

An example flowchart of an MBSE model for DRM 1 is shown in Fig. 3. In this flowchart, the network's task is to "Track Objects in Trans- and Cis-Lunar Region." In order to accomplish this task, various requirements can be set for the targeted distributed sensor network. For example, we can set a "Cut-off Magnitude" requirement such that the network can persistently track objects with a cut-off magnitude of less than or equal to 15. One the mission is defined and the requirements are set, the code base can optimize the network based on all user-defined requirements.

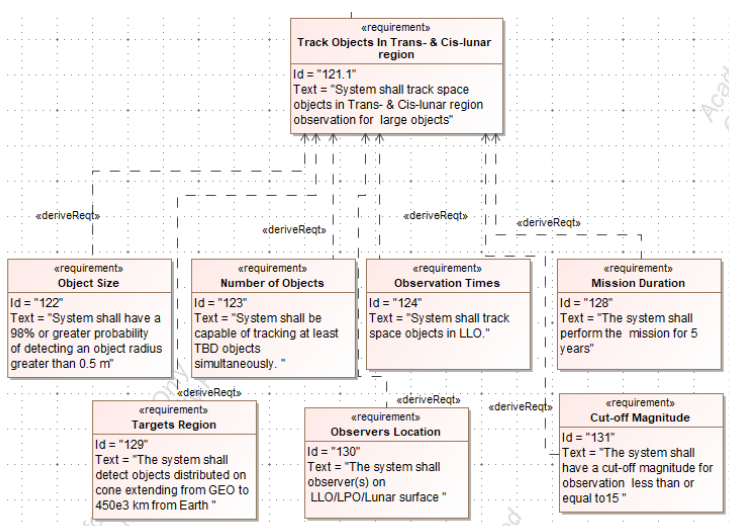


Fig. 3 Example screenshot of MBSE model used to derive functional mission requirements for DRM 1.

Paired with the MBSE model, construction has begun on a multi-disciplinary design, analysis and optimization (MDAO) framework to streamline analysis workflow and create a unified modeling environment. The objective of the MDAO framework is to integrate the various physics based models into a unified framework, allowing design cases to be run quickly and efficiently. This will ultimately enable greater tradespace exploration and optimization for the DRMs of interest. The framework is being built in Python using NASA Glenn's OpenMDAO Python package [28]. To accommodate the variety of analyses being performed and maintain flexibility, the framework uses an object-oriented approach to modularize analysis codes. Each analysis code is modularized using a common base class, in the form of a python wrapper, which creates a standardized interface allowing model components to be rapidly and dynamically reconfigured. Framework components are then responsible for managing modules and the transfer of data between them. The basic layout of this framework is shown in Fig. 4.

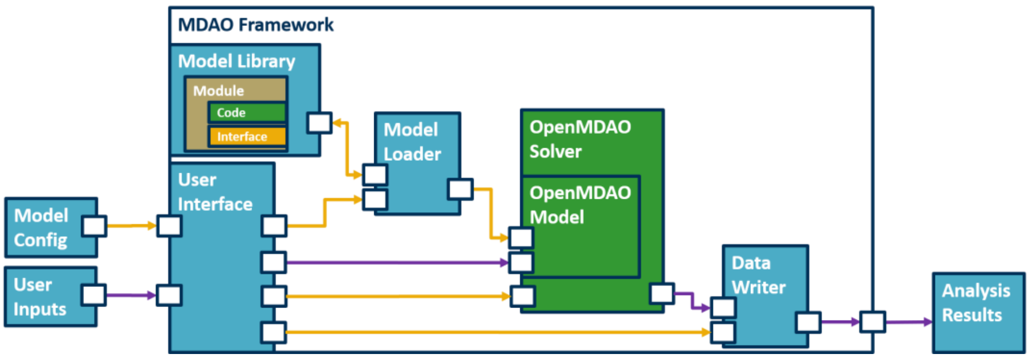


Fig. 4 Diagram of MDAO framework components

B. Design Space Definition and Model Development

As was just discussed, the success of the MBSE and MDAO algorithms for optimizing distributed networks for the DRMs is dependent on having flexible physics models for each link of the "Cislunar Custody Chain." To this end, we have made significant strides towards developing a modeling and simulation baseline for the spacecraft technologies to inform the architecture decisions and tradeoffs, particularly with a focus on the following key technical challenges that span the chain that was shown in Fig. 1.

1. Sensors: Analysis and Optimization for Space-Based SDA Architectures

The central component for analyzing the performance of various links within the "Cislunar Custody Chain" links is our newly developed sensor optimization and analysis tool: the Georgia Tech CisLunar Orbital Surveillance System (GT-CLOSS). GT-CLOSS is a flexible software package for computing EO and radar detection metrics of satellites in the cislunar volume being monitored by observers in space, on the lunar surface, or on Earth's surface. This tool is then used to perform various trade studies for the cislunar SDA architectures as well as assess the technologies needed to achieve the optimal architectures. The system allows the MBSE algorithm to hypertune factors such as observer motion models, telescope sensor quality, and background sky conditions. Each component is object-oriented, and different components can therefore be plugged-and-played across different simulation missions.

For example, one such GT-CLOSS class is the "observer" class for flexibly adding distributed sensors into an observation network. The class allows for positioning a set of observing satellites distributed on Earth's surface, in Earth orbits, or in cislunar orbits. The class automatically generates physics-based sky-brightness models based on where it is looking along the ecliptic plane, allowing for the calculation of realistic Signal-to-Noise Ratio (SNR) metrics. The same observer can have multiple telescopes equipped during an optimization run in order to simulate the detection capabilities of a variety of telescope sizes and etendues within a specific orbit.

While scene factors will ultimately govern how many photons are reflected into the collection mechanisms of the sensors of a cislunar surveillance network, putting optimal sensor hardware into a surveillance network can provide the highest probability of detecting and tracking satellites in the cislunar space. There are two main challenges that will be faced by sensors in any surveillance network. First, the extreme sensor standoff ranges between a sensor and targeted satellite will often mean that there are very few photons for the sensors to collect due to the inverse square law falloff effect. Second, the sensors may frequently be looking at "exclusion zones" which are defined as regions that are near a bright sky background such as the sun or the moon itself. The lunar "exclusion zone" spanning +/-15 degrees from the center of the moon, for example, is often referred to as the "cone of shame" because ground surveillance networks cannot maintain custody in this region. Our technical approach is unique in that it has considered both passive and active sensors that have the potential to overcome these two major scene constraints.

The first consideration that was analyzed using the GT-CLOSS systems was the case of EO sensors in the translunar region outlined in DRM 1. EO sensors are passive systems that rely on reflected sunlight for detection. This becomes an issue for solar-observer geometries in which the targeted object has a high solar phase angle. The concept of solar phase angle was originally shown in the diagram in Fig. *1*. For a high solar phase angle of 180 degrees, the satellite will be directly in between the sun and the observer, meaning that it is shadowed. In order to analyze this effect, a novel metric for the maximum unresolved detection range of an LLO observer was derived using GT-CLOSS. In short, this range metric incorporates factors such as ecliptic Latitude/Longitude dependent sky-background brightness, sensor capabilities, and target reflectivity. An illustration of the concept of unresolved ranging and some results for an LLO observing satellite monitoring a satellite of 1-meter radius are shown in *Fig. 5*. From this figure, it becomes clear that for low solar phase angles (0 to 90 degrees), the targeted satellite reflects sufficient energy toward the observer in order to enable custody out to Lagrange points L1, L4, and L5 by EO telescopes with small aperture diameters. However, as the solar phase angle grows the amount of energy reflected toward the observer shrinks, dropping the detectable range to zero and creating an "exclusion zone."

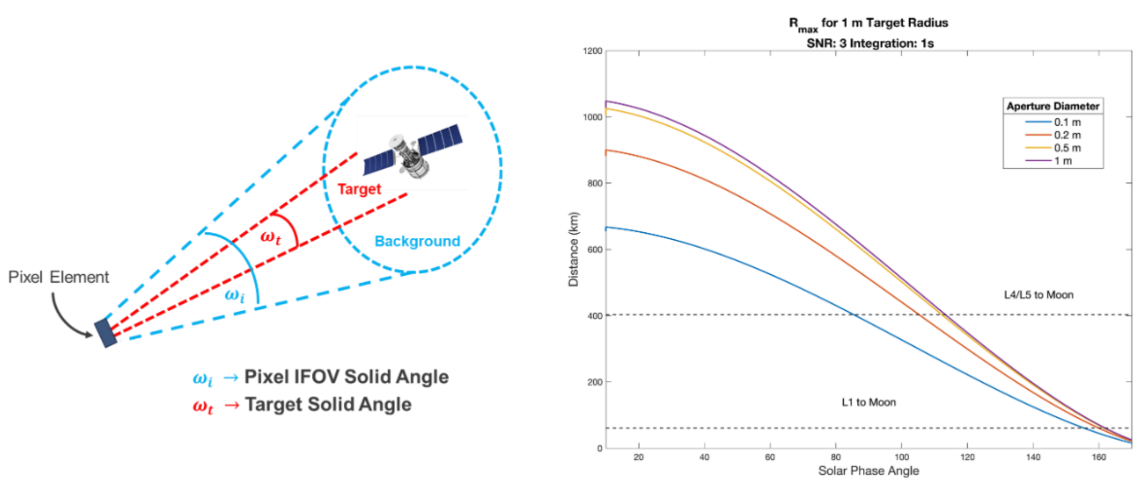
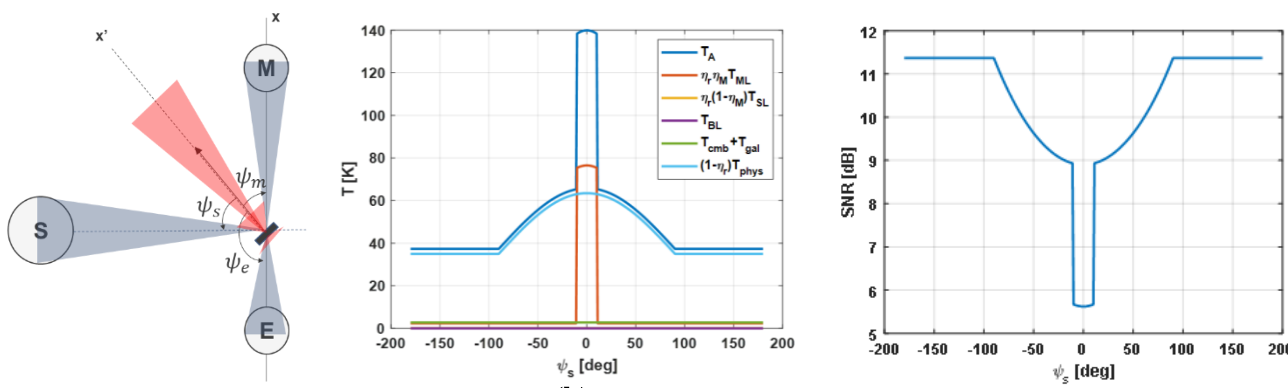


Fig. 5 The concept of an unresolved target being imaged by a pixel element. (Right) The maximum detectable range (R_{max}) of a 1-meter radius target for a Low Lunar Observing satellite with Lagrangian point distances overlaid.

GT-CLOSS also enables the analysis of radar sensor performance in the two DRM locations. Radar systems are active sensors that provide their own energy source rather than relying on reflected energy from the sun for detection. This is an attractive capability for overcoming exclusion zones that are frequently encountered by EO sensors. Rather than being limited by reflected photons, however, radar systems will be limited by the physical temperature of their antenna. The radar system SNR equation shows that as the temperature of the antenna increases, the SNR for a fixed transmitted signal power will shrink. This is problematic for low solar phase angles (i.e. radar antennas facing the sun) because the antenna will become hottest at these orientations. A test case in the GT-CLOSS framework is shown below in Fig. 6 for a space-based radar instance to show the antenna temperature and associated SNR as a function of solar azimuth angle relative to the antenna normal. Fig. 6 (a) shows an orthogonal sun-moon-earth relative arrangement with a sensor located midway between the earth and moon. Fig. 6 (b) and (c) show the antenna temperature contributions and SNR, respectively. It is important to note that even though the SNR is lowest when looking into the solar direction, the SNR is still greater than 0 for distances up to 100 km. While an SNR of >13 dB is preferable for practical purposes, the radar system still provides a potentially viable alternative to the EO sensor's SNR of approximately 0 in this "exclusion zone." The MBSE approach will focus on discovering applications where active systems such as radar can overcome the limitations of passive EO systems. The MBSE approach will also attempt to discover orbital regimes and lunar landing locations that maximize the complementary nature of active and passive sensors.



(a) **(b)** **(c)**

Fig. 6 Orientation test case for a space-based radar in LLO observing targets. (a) shows the sun to earth and moon at apparent angles of 90º relative to the solar direction. (b) shows the change in temperature as a function of solar azimuth angle, ψ_s. (c) shows the SNR of the system as solar azimuth angle.

2. Constellation Maintenance for Distributed Cislunar Sensors

Constellation maintenance in cislunar space is challenging, largely because of the limited availability of GPS and the infeasability of ground-based tracking. For the purpose of discovering the optimal algorithms for autonomous cislunar navigation using our MBSE framework, we have developed models for cislunar localization and navigation that make use of both optical and RF observables. In order to demonstrate the potential of our developed models, a preliminary assessment of navigation performance was conducted using a linear covariance (LinCov) analysis [4,5]. A LinCov analysis provides information on the statistical performance of a navigation system in a single run, as opposed to the thousands of runs typically required for a Monte Carlo. Thus, LinCov is ideal for quick parametric assessment of sensor configuration and mission design parameters.

An open-loop LinCov analysis is similar in structure to running the covariance portion of an Extended Kalman Filter (EKF), but without having to implement the state update portion of the filter. The initial work considered here focuses on just the translational states (position and velocity) of the satellites in the SDA constellation. Future work will introduce bias states (to be modeled as first-order Gauss-Markov processes).

Several measurement combinations were evaluated using the LinCov framework in combination with our simulated distributed satellite trajectories. Evaluating the time-history of covariance along a reference trajectory provides insight into the effectiveness of various measurement methods and how they might be used together. The following measurement options were evaluated for cislunar constellations:

1) Horizon-Based Optical Navigation (OPNAV): Uses the apparent horizon of an ellipsoidal body (e.g., Earth, Moon) in a camera image to estimate the position between the spacecraft and the observed body. This usually only works at large distances when much of the body is visible in an image.
2) Radio Frequency (RF) Ranging: Use the communication system to construct range measurements between a pair of satellites in our constellation. This is achieved by the RF signal time-of-flight.
3) RF Range Rate: Use the communication system to construct range-rate measurements between a pair of satellites in our constellation. This is achieved by observing a Doppler shift.

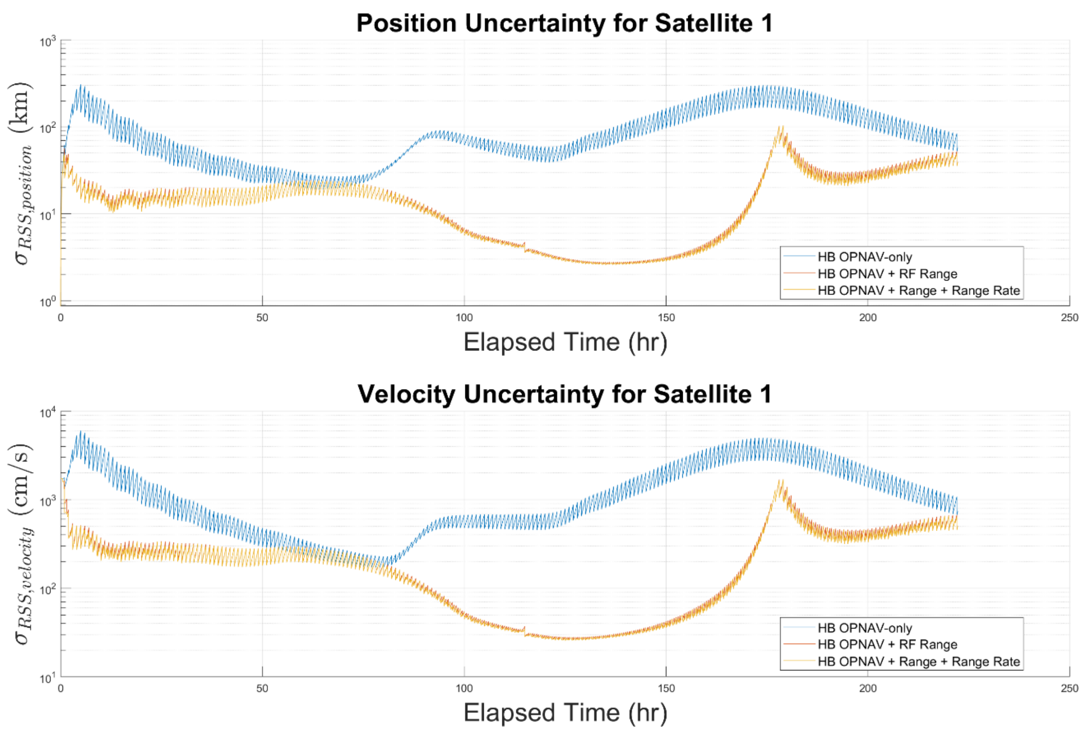


Fig. 7 Position and velocity standard deviation RSS for one satellite.

A sample result is shown in Fig. 7 for one satellite in a 3-satellite constellation. The satellite described here is in a Halo orbit about the Earth-Moon L1 Lagrange point, which is one of the candidate orbits considered for the proposed constellation. OPNAV-only navigation produces errors in the range of 10s to 100s of kilometers, mostly due to the very large distances to the Moon. The incorporation of RF ranging measurements between this spacecraft and one of the others in the constellation provides a substantial improvement, bringing the errors closer to the kilometer level. The further inclusion of range-rate measurements (between the same satellite pair as used to construct the range measurement) provides little additional benefit. This analysis capability is also employed for the proposed constellation in the LLO conditions of DRM 2, which incorporates the terrain relative navigation (TRN) techniques, such as methods using lunar craters [8]. The toolchain developed here allows for a MBSE-based evaluation of any measurement combination by producing an estimate of the navigation performance.

3. Detection and Communication Architectures for In-Space Sensing

Detection and communication architectures are critical for cislunar-orbiting sensing platforms. Without an appropriate communication framework for relaying observations of transiting space objects, the satellites of a distributed constellation are unable to relay information that can be utilized for tasks such as orbit determination. Additionally, the choice of detection algorithms can enable optimization of factors such as where individual sensors should be scanning at a given moment of time and how long it should dwell on a region of sky. In order to enable an MBSE optimization of these factors, we are developing models for the following relevant hardware and software paradigms:

- Algorithms utilized for object detection (match-filters, machine learning, etc.)
- Onboard vs. Ground-based processing of imagery captured in-orbit
- Antenna sizing and its impact on satellite sizing (e.g., deployable CubeSat parabolic antennas [9])
- Necessity of relay satellites or other commercial communication infrastructure for coordinating observations and sky-scanning patterns (e.g., LunarNet [10]).

The trade study results for these decisions will be integrated into the MBSE analysis of both DRMs under consideration. We are currently also analyzing spacecraft bus subsystems (e.g., attitude control/sensor pointing, power, propulsion) for a higher-fidelity mission design of detection and communication components of our distributed sensor systems.

C. PRELIMINARY MISSION ANALYSIS

We performed an analysis on distributed sensor network performance in detection within the Translunar region of DRM 1, This study was carried out in order to determine cislunar orbits that were most promising, and therefore should considered high priority options for the MBSE framework. This subsection shows initial results for the translunar region coverage of distributed cislunar EO sensors simulated using the GT-CLOSS software. The analysis aims at assessing the effectiveness of various satellite orbits for achieving optimal coverage and SDA capabilities along the cislunar highway in between the earth and moon.

In order to examine a critical custody region of DRM 1, a conical region of interest was discretized into a set of grid points fixed within the 3D volume of the rotating earth-moon frame, as shown in Fig. 8. Detection statistics captured as a function of time for each of these points were used to quantify the detection capabilities of the considered networks. The procedure consisted of integrating the position of the sensing platform and computing the apparent magnitude of each target, at each time step. In doing so, the Sun direction vector is updated at each time step, although the Sun's gravitational effect was not accounted for in the motion of the sensing platform. Given the time history of a target's apparent magnitude, this target was considered *visible* if it was observed by the spacecraft sensor with an apparent magnitude above a cut-off value for Γ% of the mission duration. The fraction of *visible* targets over a mission duration is used as a scalar metric to analyze the suitability of a specific orbit. This information can then be used to determine an appropriate observer network and sensor/spacecraft requirements. Parameters of the simulation are summarized in Table 1, and parameters of the telescope are shown in Table 2. The mission start epoch was chosen to coincide with an approximate Sun-Earth-Moon conjunction, where the projection of the Earth-Sun vector onto the Moon's orbital plane has been used. While this facilitates the intuition on the starting angle of observers along certain orbits, the general performance of various orbits remains unaffected by this choice.

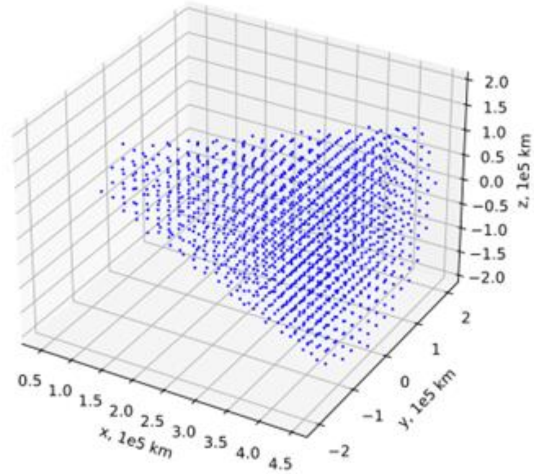


Fig. 8 Example discretization of the translunar region, in Earth-Moon rotating frame.

Table 1. Translunar Region Coverage Simulation Parameters

Parameter	Value
Target diameter, m	2
Target spectral reflectance	0.0
Target diffuse reflectance	0.2
Mission start epoch, UTC	2024 MAR 25 07:12:36.633
Mission duration, day	90
Time-steps, sec	3600

Table 2. Telescope parameters of each sensor of the distributed sensor network.

Parameter	Value
Pixel Pitch (meters)	1.5e-5
Wavelength of Sensor (meters)	6e-7
Diameter of Aperture (meters)	0.1
Integration Time (seconds)	1
Quantum Efficiency (unitless)	0.9
F-number (unitless)	17.6
Dark Current (electrons/second)	15
Readout Noise (electrons)	40
Sky Background Brightness (vmag per square arcseconds)	21
Optical Transmittance (unitless)	1

1. Earth-Orbiting Sensor Performance

The first type of simulated observer locations consisted of Earth-orbits, specifically with the observers in (1) a Geosynchronous Equatorial Orbit (GEO) network of varying longitudinal density and (2) a Highly-Eccentric Orbit (HEO), or specifically, High Orbiter with Profound Eccentricity (HOPE) satellite network. The results for the GEO and Hope networks are shown in Figures Fig***. 9*** and Fig***. 10***, for 6 and 18 evenly azimuthally-separated observers, respectively.

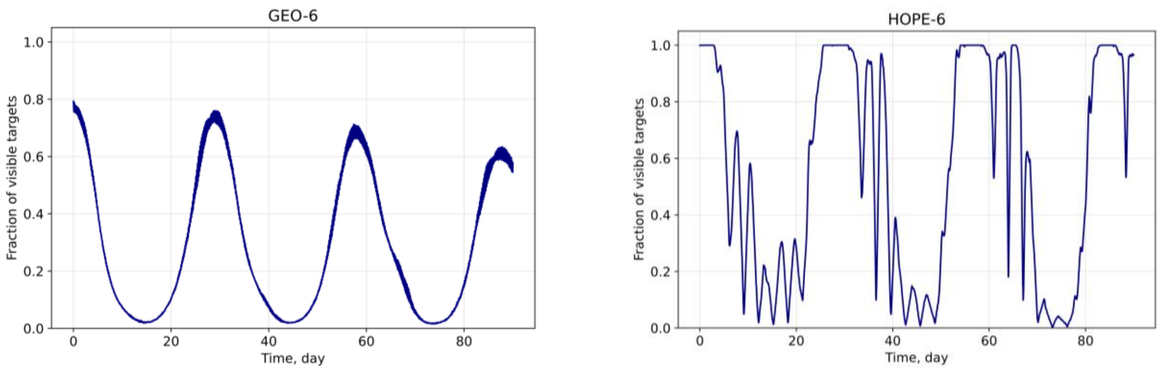


Fig. 9 Fraction of visible targets over time for (a) 6 GEO observers and (b) 6 HEO observers

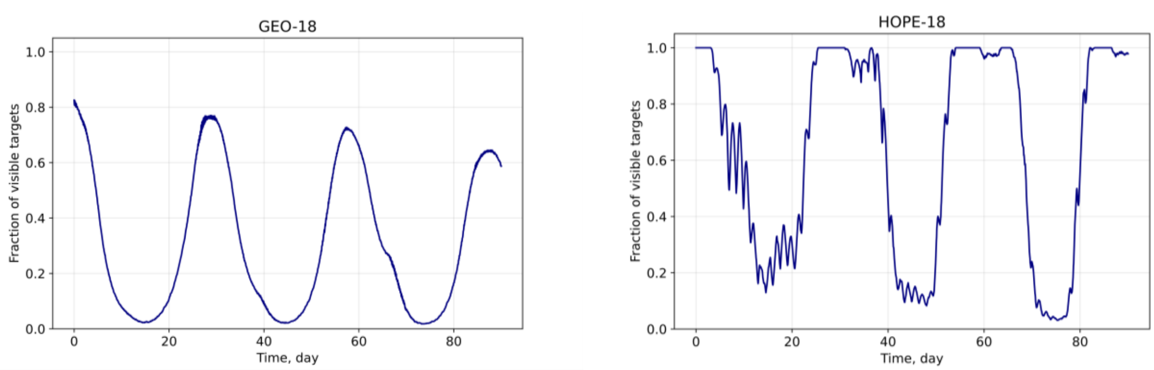


Fig. 10 Fraction of visible targets over time for (a) 18 GEO observers and (b) 18 HEO observers

Both architectures were composed of 6 spacecraft; in the case of the GEO constellation, the spacecraft were placed at equal longitudinal spacing, while for the HOPE constellation, the spacecraft were placed at equal angular spacing in terms of argument of perigee. The pattern of the number of visible targets repeated with a period roughly equaling 30 days, corresponding to the fundamental periodicity of the system. The fluctuation of the peak for the GEO architecture can be attributed to the change of the angle between the equatorial plane and the Moon's orbital plane, which is secular with respect to the 30-day time-frame. There is also an inherent limitation of the geometric diversity provided by the GEO network, limiting the achievable coverage from a GEO constellation even if the number of observers is increased. Indeed, comparing Fig. 9 (a) and Fig. 10 (a), no significant increase in the fraction of visible targets occurs. To increase coverage volume, sensors must instead be added to unique orbits in order to overcome this solar phase angle limitation. In other words, ***there is a saturation of orbital observability that can only be overcome via the diversity provided by an optimally derived distributed sensor network.***

The HOPE regime has been previously theorized to be able to overcome the solar phase angle limitations of GEO sensors [27]. Sensors in HOPE trajectories have high eccentricity and consequently high hangtimes near apogee. The modeled high eccentricity of approximately 4 times GEO altitude provided a view of the ecliptic plane that is highly offset from the GEO belt. The HOPE network used in this work had 6 spacecraft with even spacing in argument of perigee and were phased at even spacing in true anomaly at the initial epoch. This phasing ensures that one sensor is nearly always at apogee, and therefore potentially able to avoid the solar exclusion zone due to its orthogonal offset, always [11]. The results are seen in Fig. 9 (b) for the HOPE network. The high eccentricity certainly helps in achieving a higher coverage volume than the GEO network, however the network still suffers from a periodic performance reduction that is directly correlated to the extreme ranges from the HOPE observer to the targeted cislunar objects. This initial study led us to understand that achieving full cislunar surveillance requires a diverse network that is ***capable of both overcoming solar exclusion zones and having low target-to-sensor distances at all times.***

2. Libration-Point Orbit Sensor Performance

Another potential location for observers are at the vicinity of Earth-Moon Lagrange points. Specifically, certain families of libration point orbits (LPO) have repeating motions in promising locations of the translunar region for the purpose of SDA. Table 4 summarizes the key characteristics of the families of the LPOs considered in our initial study. Of particular interest are LPOs that exhibit a resonance with the Sun-Earth-Moon system; if an observer is placed in such a LPO, its position with respect to the Sun, Earth, and Moon repeats after each resonance period. The advantage of these resonant LPOs has been previously identified by Vendl et al [12], and is used as potentially beneficial observer locations.

Table 3. Characteristics of Candidate Libration Point Orbit Families

Name	Period, day	Approximate location	Planar/Spatial motion	Stability
L1 Lyapunov	11.9 – 30.1	Vicinity of Moon ~ L1	Planar	Medium
L2 Lyapunov	14.8 – 30.0	Vicinity of Moon ~ L2	Planar	Medium
L1 Halo (North/South)	9.03 – 12.1	Vicinity of Moon ~ L1	Spatial	Low - High
L2 Halo (North/South)	12.6 – 14.8	Vicinity of Moon ~ L2	Spatial	Low - High
Distant Retrograde Orbits (DRO)	2.5 – 27.3	Encircles L1 and L2	Planar	High

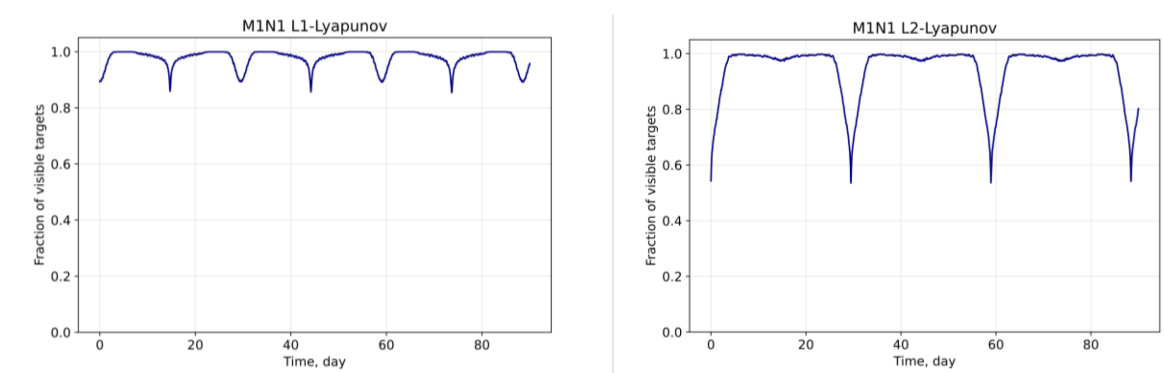


Fig. 11 Fraction of visible targets over time for (a) M1N1-L1-Lyapunov observer and (b) M1N1-L2-Lyapunov observer.

Fig. 11 shows the variation of number of visible targets against time for the M1N1-resonant L1 Lyapunov orbit observer and the M1N1-resonant L2-Lyapunov orbit observer. It is possible that both of these observers are particularly advantageous for achieving high volume coverage of the cislunar region. It is particularly remarkable that these performances are achieved by a single optimally phased observer in both cases, compared to the GEO and HOPE cases previously shown. The higher performance of the L1-Lyapunov observer over the L2-Lyapunov observer follows intuition, since the L1-point is located closer to the center of the translunar region of interest.

To further evaluate the usability of combinations of multiple LPOs, the fraction of *visible* targets over a mission duration, denoted as Γ [12] was introduced as a scalar metric for comparison. Fig. 12 shows the Pareto front of orbital stability against the visibility performance for a representative set of LPOs. It is apparent that L1 halo orbits offer the highest values of Γ, explained by their positioning in the vicinity of L1 combined with their spatial motion. Consideration of the DRO orbital constellation is attractive for their characteristically low stability index, indicating that an observer spacecraft replaced in such orbit would require smaller amounts of station-keeping. While the use of L2-based LPO alone is not likely to be beneficial, its use alongside other observer locations is likely to offer greater coverage. As an example, the use of 1, 2, and 3 observers placed at LPOs has been considered for Translunar SDA. Table 4 shows the observation performance for Translunar SDA. Fig. 13 shows the orbits of the observers for the 3 LPO observer case.

Table 4. Comparison of best architectures for single, two, and three LPO observer(s) for DRM 1

Number of LPO observer	Observer locations	Γ
1	L1 halo Southern	0.75084
2	L1 halo Southern, L2 halo Northern	0.88215
3	L1 halo Southern, L2 halo Northern, DRO	0.90101

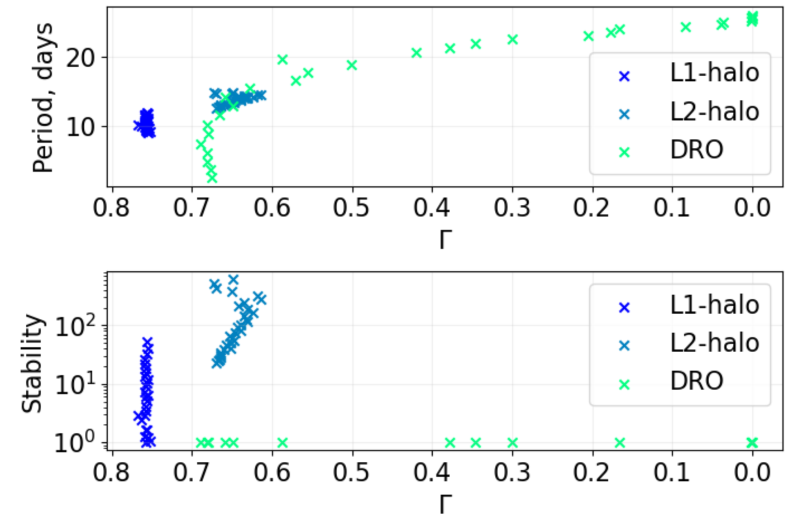


Fig. 12 Stability against Visibility Performance Pareto fronts for families of Libration Point Orbits

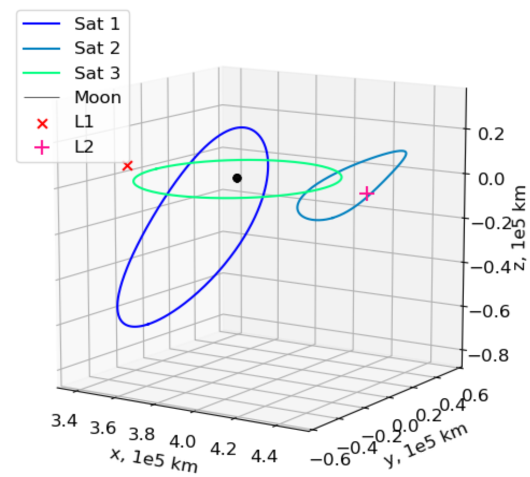
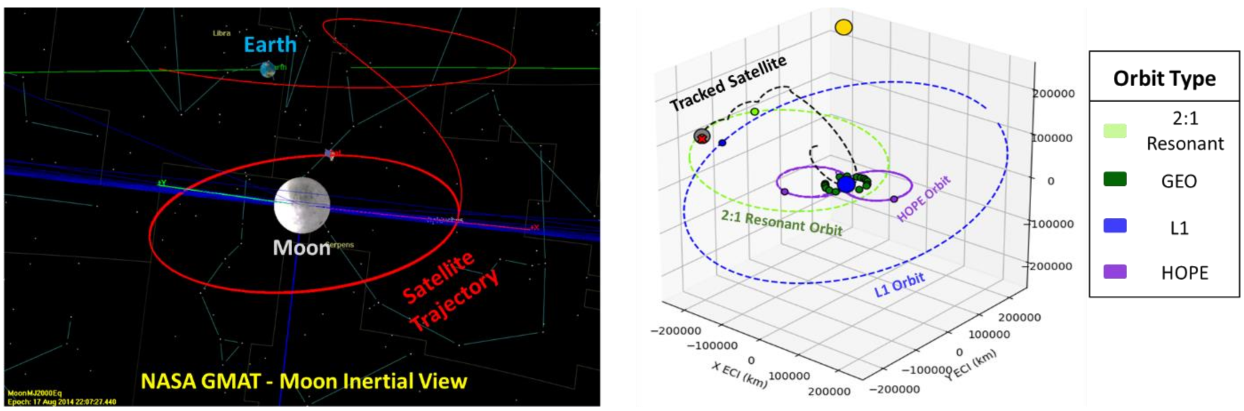


Fig. 13 3-LPO observer orbits, in Earth-Moon rotating frame

3. Constellation Tracking of Target of Interest in Translunar Region

Our simulation framework also allows for modeling of realistic scenarios of cislunar custody maintenance for a target of interest using. The framework specifically allows for the calcultation of a time-history of detection metrics for a diversely-distributed set of sensors in Earth orbits, cislunar space, and on the lunar surface tracking a target as it traverses the cislunar volume. To demonstrate this capability, the mission analysis NASA General Mission Analysis Tool (GMAT) was integrated together with the developed GT-CLOSS software based on its demonstrated capability in the cislunar SDA field [25]. Specifically, we developed a mission in GMAT of a medium-sized satellite performing a translunar insertion over the course of 8 days. At the start of the simulation, the satellite is in near-GEO orbit. It then proceeds to slingshot around the Low Earth Orbit (LEO) region before proceeding to its final Low Lunar Orbit (LLO) about the moon. A view of this mission within a moon-centered inertial frame and an ECI frame is seen in Fig. 14 (a) and (b), respectively.

In order to study our ability to maintain custody of the translunar satellite over the full 8 days, we created a theoretical surveillance network with 5 different sensor types for broad diversity. Figure 14 (b) shows a color-coded representation of the 4 major satellite constellations in the network. There are 24 GEO satellites and 2 HOPE orbiters within each of their sub-networks. In addition, a satellite positioned at the Earth-Moon L1 point and a 2:1 resonant orbiting satellite are considered. This 2:1 resonant orbiter completes 2 revolutions about the earth for every 1 revolution by the moon, dipping into the GEO region before traveling back past the L1 point. This orbit has the advantage of being highly stable over time, while also traversing the entire cislunar volume [13]. The final component of the network is a lunar observer that is positioned directly on the equator of the near-side of the moon.



(a) (b)

***Fig. 14** A Translunar SDA mission from GEO orbit to a lunar orbit in (a) the Moon-centered inertial view and (b) in the Earth-Centered Inertial view.*

GT-CLOSS produced a full-time series of SNR results for each component of the sensor network as seen in Fig. 15 (a). These results show that each sensor in the network typically will go through oscillations in SNR that are influenced by factors such as solar exclusion, proximity to the targeted satellite, and planetary bodies blocking the observer's view of the satellite. It can also be seen that near-earth satellite networks (GEO and HOPE) only have useful SNRs when the satellite is close to the earth (i.e. before July 25). Once the satellite becomes close to the moon, the only viable observation options are the L1 satellite, the 2:1 resonant observer, and the lunar observer.

We took the satellite constellation with the maximum SNR at each observation time and plotted the results in Fig. 15 (b). This provides a time history of the best SNR achievable by our 5 sensor network over the duration of the mission. It is worth noting that each observer type plays a major role in ensuring that observability is achieved over the course of the full 8 days. For example, if the L1 observer was not part of the network, then the translunar satellite would be unobservable for a two-day period from July 24 through July 26 as it begins its ascent from the LEO region to the LLO region. Additionally, if the 2:1 resonant satellite was not a part of the network then the translunar satellite would be unobservable while on the far side of the moon from the period of July 29 through August 1.

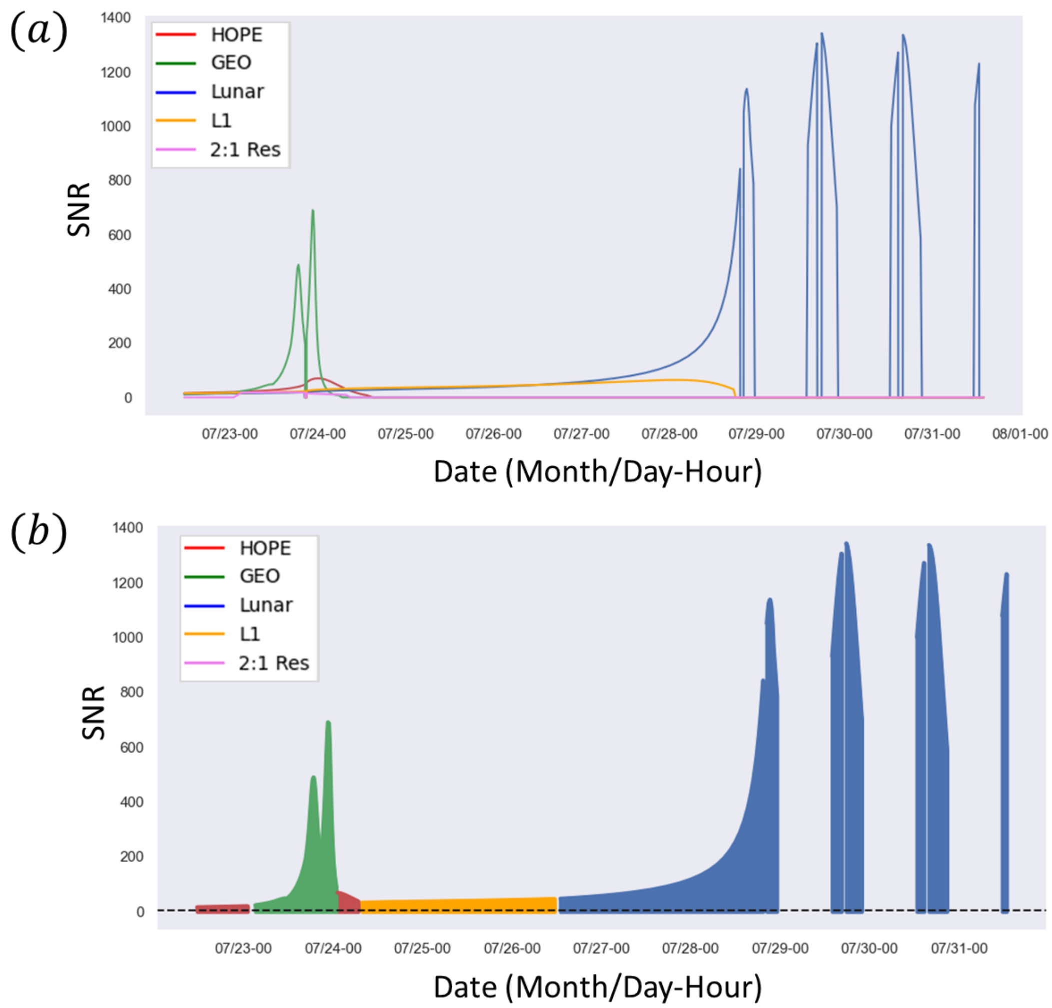


Fig. 15 ***(a) The time history of SNR for each observer type in the sensor network during the Translunar mission. (b) The maximum SNR and the sensor that produced it at each moment in time over the course of the mission.***

Large gaps in observation of a transiting satellite can cause issues with propagation of the position uncertainty of the targeted satellite that can hinder constellation maintenance [13]. In future studies, we will explore methods for minimizing the time in between observations. The above results show that a diverse, distributed constellation is critical for optimal SDA coverage and sensing performance, as opposed to a more conventional single-satellite concept. This finding demonstrates the promising benefit of the proposed distributed cislunar SDA concept. The next phase of our research efforts will expand this capability and provide a more comprehensive and higher-fidelity analysis of cislunar SDA.

D. POLICY ANALYSIS

A novel contribution of our team is the incorporation of policy analyses into our constellation design. Our current work has focused on tasks such as (1) identifying the key stakeholders and (2) determining the larger international and domestic policy and political issues related to cislunar Space Domain Awareness. This effort is a prerequisite to any more in-depth analysis that must be done to ensure safe and collaborative cislunar traffic management [14, 15].

With respect to major international debates, we found that organizations in the United States and elsewhere around the world are still identifying the key missions and requirements that need to be met by cislunar SDA. Initial statements by NASA and Space Force officials suggest that there will be both safety and security requirements for a cislunar SDA system [16]. As cis-lunar activity ramps up, tracking activity in this region will ensure that no accidental collisions or interference occur. While cislunar space is much less densely populated than Earth's orbit, there has already been an example of a potential collision between two Lunar missions [17]. Additionally, the United States has expressed an interest in detecting and tracking a broad array of objects to determine whether they may pose a threat to U.S. operations [18]. These factors will be ingested as parameters into our MBSE framework where applicable.

Many of the international political issues that may affect cislunar SDA have not yet generated significant debate on the international stage. However, an examination of challenges that have arisen with respect to SDA in Earth's orbit provides some insight into these issues. For example, with respect to SDA in Earth's orbit, the United States military runs the most advanced surveillance system in the world and conducts conjunction analyses for all objects larger than ten centimeters. The United States freely provides these conjunction warnings to all satellite operators globally. In recent years, several other nations, as well as commercial entities, have developed some SDA capabilities. The United States has made steps to engage international partners and commercial entities. There have also been efforts to transition some SDA data-sharing missions to a civil agency [19].

Projecting to the cislunar environment, it is worth asking whether a cislunar SDA capability would be developed by the military, by a civil organization (like NASA or the Department of Commerce), or through a partnership between the two. Given that the Space Force has expressed significant interest in this mission, it is likely that the U.S. military will be involved [20]. However, civil, commercial, and international missions to the Moon are likely to make up the bulk of cislunar traffic, so it would be prudent to develop an organizational structure that allows close engagement with these entities from the beginning [21]. Our analysis will focus on developing answers on the potential benefits in cislunar SDA capabilities that could result from such partnerships.

IV. CONCLUSION

This paper outlines the methodology and current outputs of a Georgia Tech (GT) and Georgia Tech Research Institute (GTRI) collaboration to optimize the design of distributed small-satellite cislunar surveillance networks. At the time of writing, we have integrated astrodynamics, sensor modeling, and navigation algorithms into one framework that can be fed into Model Based Systems Engineering (MBSE) tools to optimize network design as a function of tunable network capabilities. We have also identified a few representative cases for two separate Design Reference Missions (DRMs) that were chosen based on the differences in expected satellite behaviors as a function of gravitational influences: the translunar case and the Low Lunar Orbit case.

In the next phase of the project, we will integrate the first-order analysis of detection data processing and communication into the optimization tools and present a complete preliminary analysis of each DRM. The design space will be explored to show the Pareto front of the metrics including coverage, sensing performance (SNR), orbit stability, and navigation cost. This analysis will lead to a small number of mission designs to be analyzed with higher fidelity based on their demonstrated promise for persistent and comprehensive cislunar surveillance. In addition, we will complete the development of the first version of GT-CLOSS software which can be used for technology assessment analysis. Finally, the needed key technologies to achieve the proposed concepts will be mapped to the existing GT/GTRI's expertise, and a first-order technology roadmap that leads to the potential flight project will be delivered.

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