QuantumNet: A scalable cislunar space domain awareness constellation

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ABSTRACT

The expected uptick in missions to the Moon over the next decade will drive demand for data related to tracking, monitoring, and coordinating the behavior of actors in cislunar space. Given the vastness of cislunar space, no single spacecraft can provide the coverage required. Here we present a subset of the capabilities of a tool developed for architecting a cislunar space domain awareness (SDA) constellation called QuantumNet, enabling optimization across sensor capability, orbit design, and asset distribution in cislunar space. An optical sensor throughput model was developed in MATLAB using first-principles physics that simulates photons reflecting from a resident space object (RSO) with specified physical geometry at a given range and solar phase angle, and reports signal-to-noise ratio (SNR) across the detector. This model is then solved for the maximum range at which a threshold signal-to-noise ratio (SNR) value could be achieved as a function of solar phase angle, resulting in an instantaneous field of regard over all possible viewing angles for a given sensor configuration. By simulating the geometric placement of these sensor configurations in cislunar space using satellite position states generated in Ansys Government Initiatives (AGI) Satellite Tool Kit (STK) over one lunar period, a general constellation coverage model is constructed that allows volume coverage metrics to be optimized as a function of visible sensor configuration, satellite orbit selection, and number of satellites within each orbit. The constellation coverage model is embedded within Ansys ModelCenter, and a genetic algorithm is employed to optimize designs across multiple observation metrics. Feasible designs, as well as Pareto-optimal designs, are shown for two possible target coverage volumes.

1. INTRODUCTION

The expected increase in missions to the Moon over the next decade will drive demand for space domain awareness (SDA) data related to tracking, monitoring, and coordinating the behavior of debris and actors in cislunar space, the area beyond geostationary orbit between the Earth and the Moon. The vastness of cislunar space requires exploration of new SDA architectures to provide sufficient levels of coverage. Existing ground-based and Earth-orbiting telescopes that have been used for SDA in orbits below the geostationary belt cannot provide the level of coverage necessary to detect and track all objects—cooperative and non-cooperative—in the cislunar environment [1]. A geometrically diverse constellation of spacecraft, distributed throughout the cislunar volume and equipped with carefully chosen SDA sensors is required to provide adequate coverage on timescales to enable strategic and tactical responses.

The unstable orbital dynamics inherent to the cislunar volume, and the libration points that exist as a result, provide many unique quasi-periodic orbit families for use in a cislunar SDA constellation, each exhibiting varying levels of stability, temporal relationships to sensor exclusion zones, and geometric diversity within the cislunar volume. SDA optical sensor design parameters like maximum detection range, point spread function, and instantaneous field of view (iFOV) are traded and must be optimized to meet constellation requirements. Optical sensor design, when combined with satellite placement, reveals a rich trade space with varying solutions depending on performance metric priority.

Other work toward cislunar SDA constellation design, namely [2], [3], and [4], emphasize the importance of strategic decision making in both optical sensor design and satellite placement, employing various methods to uncover optimal constellation design architectures for performance parameters such as target volume coverage, visual magnitude or signal-to-noise ratio (SNR) detection thresholds, and overall constellation cost. To this end, Quantum Space is developing an optical sensor and constellation design tool, as a subset of a larger model encompassing end-to-end space mission design, to evaluate candidate constellation architectures and enable strategic engineering design decisions that inform customer requirements evaluation. Quantum Space intends to maximize usefulness to cislunar stakeholders by using this tool to determine which design factors are most important in cislunar SDA constellation design and leverage that knowledge to optimize constellation buildout plans for our future QuantumNet SDA constellation. The next sections will detail the methodology behind this tool and show example designs within the trade space for two target coverage volumes to demonstrate initial tool capabilities.

2. METHODOLOGY

The technical scope of this work encompasses the development of a detailed optical sensor throughput model that is then incorporated into an SDA constellation coverage model, enabling sensor design and constellation asset placement to be traded to maximize constellation performance.

2.1 Optical Sensor Throughput Model

To effectively size an optical sensor for cislunar SDA, a high-fidelity photon-to-detector optical throughput model is needed to inform optics design and enable accurate component acquisition. A first-principles physics radiometric model has been developed that takes optical design, detector parameters, and RSO geometry as inputs and outputs signal-to-noise ratio (SNR) across the detector.

The model first calculates the spectral irradiance reflected by the target given an assumed albedo value.

$$E_{RSO,\lambda} = E * \alpha \tag{1}$$

where E is the solar spectral irradiance and α is the target's albedo. The spectral irradiance is then adjusted for the target incident solar phase angle ϕ with the following equation:

$$E_{RSO,\lambda,\phi} = E_{RSO,\lambda} \frac{2}{3\pi}(sin(\phi) + (\pi - \phi)cos(\phi)) \tag{2}$$

This irradiance value is then converted into a radiance value by assuming a Lambertian target:

$$L_{RSO,\lambda,\phi} = \frac{E_{RSO,\lambda,\phi}}{\pi} \tag{3}$$

Finally, the photon flux at the sensor accounting for RSO distance, $\gamma_{RSO,\lambda,\phi,R}$ is calculated as

$$\gamma_{RSO,\lambda,\phi,R} = \frac{L_{RSO,\lambda,\phi}}{\lambda hc} \frac{\pi(\frac{d}{2})^2}{R^2} \tag{4}$$

where R is the RSO range, λ is the wavelength, h is the Planck constant, c is the speed of light, and d is the RSO diameter.

The number of photons collected by the optic each second can be determined by multiplying the spectral photon flux by the aperture area, optical efficiency, and sensor bandpass:

$$\gamma = \gamma_{RSO,\lambda,\phi,R}\eta\pi(\frac{d_a}{2})^2\delta\lambda \tag{5}$$

where d_a is the diameter of the optic aperture, η is the optical transmission efficiency, and $\delta\lambda$ is the sensor bandpass. Total signal electrons collected in a single image are then estimated using sensor quantum efficiency and image integration time:

$$e^- = \gamma\eta_{QE}IT \tag{6}$$

where η_{QE} is the quantum efficiency and IT is the image integration time. Total system noise is a root-sum-squared combination of background noise, shot noise, dark noise, electrical system noise, and quantization noise:

$$N_{RSS} = \sqrt{N_{bg}^2 + N_{shot}^2 + N_{dark}^2 + N_{elec}^2 + N_{quant}^2} \tag{7}$$

Assuming the RSO is being tracked over successive images, the total image SNR is determined by dividing the number of signal electrons measured by the total noise calculated, and then multiplying by the square root of the number of images being stacked:

$$SNR = \frac{e^-}{N_{RSS}}\sqrt{n_{images}} \tag{8}$$

This model, in conjunction with simulated optical point spread functions, will establish an SNR threshold for RSO detectability that can be used to evaluate optical sensor designs for SDA applications. The main model inputs and their descriptions are summarized in Table 1.

Table 1: Main inputs to the SNR throughput model, with units and descriptions of each.

Parameter	Units	Description
Aperture Diameter	m	Diameter of telescope opening
Primary F#	N/A	Ratio of focal length to aperture diameter
Pixel Size	m	Side length of each pixel (assumed square)
Integration Time	s	Exposure time for a single image
Detector Temperature	C	Temperature of focal plane array
Solar KOZ	deg	Solar KOZ half-angle, determined by baffle length

2.2 MATLAB Constellation Coverage Model

To effectively leverage the EOIR sensor model for constellation design, a time-based constellation simulation model was developed in MATLAB. This takes as input satellite orbital states, RSO geometry parameters, and sensor configurations, couples them with the EOIR sensor model mentioned previously, and outputs various constellation performance metrics for a chosen target coverage volume. The model is composed of three modules that generate target coverage volumes, determine sensor instantaneous detection volumes as a function of time, and generate coverage zone observation metrics to inform constellation performance.

2.2.1 Constellation Orbit Modeling

Many candidate orbit families exist that can be leveraged for cislunar constellation design [5]. A small subset of the possible orbit trade space is explored in this work by limiting possible satellite orbits to just three options, one from each of three distinct orbit families: a 30,000 km Z-amplitude EML-1 Halo orbit, a 30,000 km Z-amplitude EML-2 Halo orbit, and a large Distant Retrograde Orbit (DRO). These orbits are shown in Fig. 1. These orbits were propagated in the full ephemeris model for one Lunar orbit period in STK's Astrogator, and orbital state time histories saved for use within the MATLAB constellation coverage model. These orbits were selected for this work due to their combined geometric diversity and ability to provide supplemental coverage on the Lunar near- and far-side in the event of solar exclusion. Stationkeeping maneuvers were included in STK to maintain orbits for the entire lunar orbit period where necessary, but stationkeeping costs are not considered in this work. In the case of multiple satellites in a single orbit, the model phases each satellite equally throughout the orbit based on the orbit's period. The full cislunar SDA constellation design tool will explore other orbits, such as high altitude Earth-centered orbits, Lunar resonant orbits, and other libration point orbits, as well as their associated orbital insertion and stationkeeping costs, to evaluate their potential for cislunar SDA constellation use.

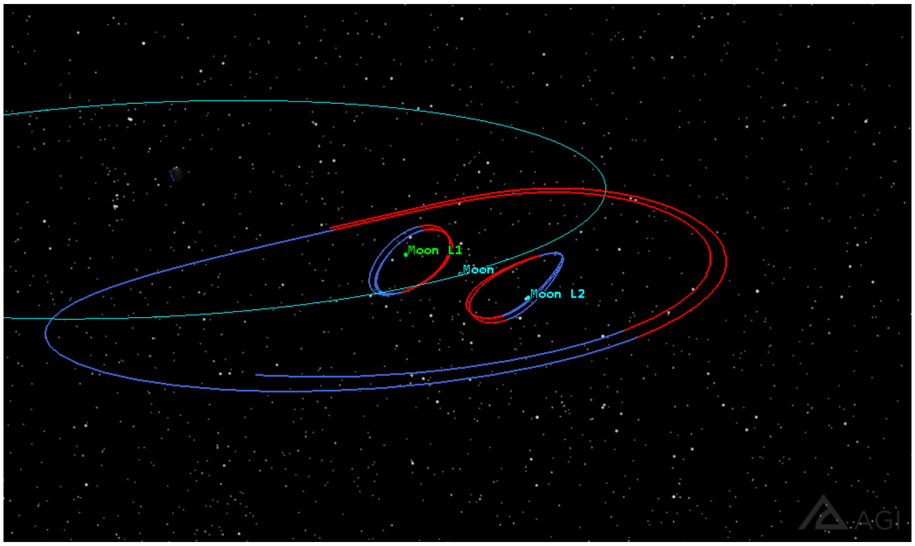

Fig. 1: 30,000 km EML-1 Halo, 30,000 km EML-2 Halo, and large DRO used as possible orbits for the scope of this work. Orbits are shown propagated for one lunar orbit period in the full ephemeris model within STK, represented in the Moon-centered Earth-Moon rotating frame.

2.2.2 Target Coverage Volumes

To geometrically evaluate constellation performance, a discrete target coverage volume is needed. The first module constructs user-specified geometric volumes encompassing strategic areas of interest for space domain awareness, discretizes them into points, and employs them as target coverage volumes for constellation performance assessment. Two example target volumes are evaluated in this work, one encompassing the 200,000 km sphere immediately surrounding the Moon, and the other encompassing the cislunar corridor extending between the Earth and the Moon in which ground-based assets are blinded at local solar noon. These two volumes are shown in Fig. 2.

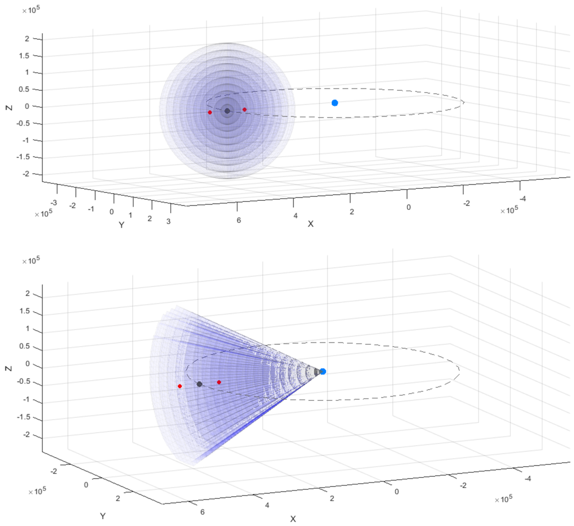

Fig. 2: Two example coverage volumes assessed in this work. Top: The 200,000 km cislunar sphere surrounding the Moon. Bottom: the ”cone of shame” extending between the Earth and Moon wherein ground-based assets can be blinded by solar exclusion zones. The grey and blue spheres represent the Moon and Earth, respectively, and the red dots represent EML-1 and EML-2.

2.2.3 Sensor Instantaneous Detection Volume

While the optical sensor throughput model discussed in Section 2.1 determines sensor SNR as a function of RSO geometry, RSO range, and phase angle, the inverse problem needs to be solved in order to leverage this model in a constellation design context. The inverse problem seeks to find the RSO geometry, RSO range, and solar phase angle necessary to meet a user prescribed detector SNR threshold. That is, for a given sensor configuration:

$$SensorModel(Geometry, Range, PhaseAngle) = SNR_{threshold} \tag{9}$$

This is an under constrained problem that has many solutions. To constrain the problem, an assumption is made for RSO geometry, and Sun, Earth, Moon, and satellite states are propagated in the full ephemeris model to generate realistic solar phase angles. The result is an equation with RSO range being the only unknown needed to determine detector SNR response for a given sensor configuration:

$$SensorModel(Range) = SNR_{threshold} \tag{10}$$

By rearranging this equation, the maximum RSO range to meet a given SNR threshold can be solved for a given sensor configuration, RSO geometry, and solar phase angle:

$$SensorModel(Range) - SNR_{threshold} = 0 \tag{11}$$

In MATLAB, the maximum RSO range is solved for using the function *fmincon* with a minimum SNR threshold of 6. This threshold value will be iterated through future RSO detection analysis using vehicle pointing performance and simulated imagery. To construct a full instantaneous detection volume for each sensor configuration, a sphere centered on the satellite at a given time instant is discretized into points equally in azimuth and elevation. Each point on the sphere, having its own azimuth and elevation, functions as a possible look direction at a given time instant, with each having a unique solar phase angle depending on the relative solar geometry at that time instant. By repeatedly solving Equation (11) using the solar phase angle corresponding to each point on the sphere, a cardioid instantaneous detection volume is formed, with larger ranges at smaller phase angles and shorter ranges at larger phase angles. An example of an instantaneous detection volume is shown in Fig. 3.

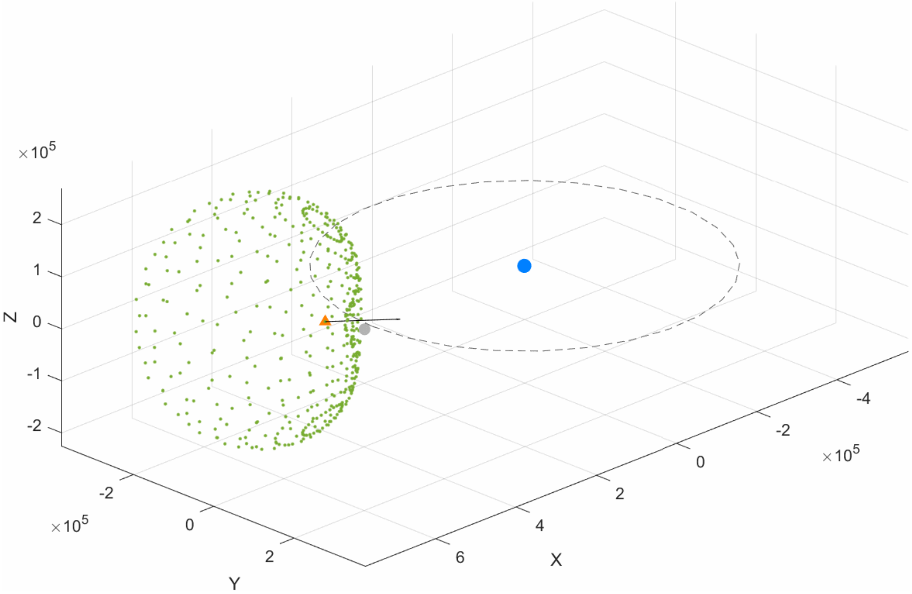

Fig. 3: Example of instantaneous detection volume with a satellite (orange triangle) orbiting at EML-2. The grey and blue spheres represent the Moon and Earth, respectively. The black vector points toward the Sun.

2.2.4 Coverage Zone Observation Performance

Optical sensor and constellation performance metrics are evaluated through a time-based simulation. For a given sensor design and constellation configuration, each sensor's instantaneous coverage volume is determined at each time step using satellite and planetary state histories propagated in STK. At each time instant the discrete target volume points that are within a sensor's instantaneous detection volume are flagged as observable, giving an instantaneous observable volume. Fig. 4 shows an example of an instantaneous observable volume for a single satellite in EML-2.

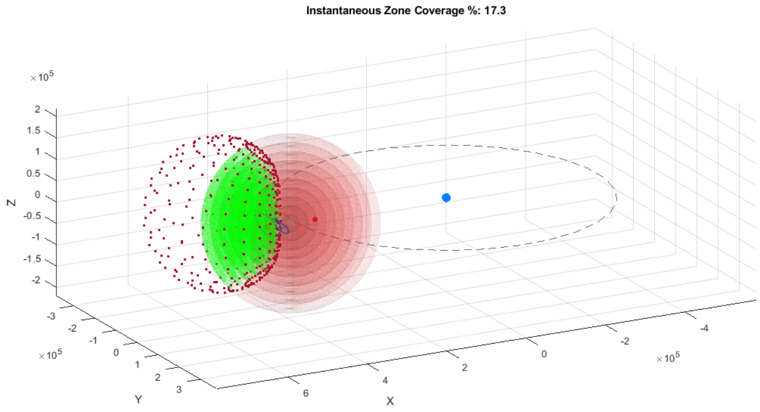

Fig. 4: Example of target volume observability for a single satellite orbiting at EML-2. The green portion is observable by the satellite's instantaneous detection volume, and the red portion is not.

Each satellite's observable volumes are then combined to give an instantaneous observable volume for the constellation as a whole. This process is repeated for each time step in the simulation span. Once the simulation is complete, the following metrics are derived from the time history of the constellation's observable volume:

1. **Mean Observation Percentage:** the constellation-wide observability as a percentage of the total coverage volume, averaged across all time steps.
2. **Maximum Observation Gap:** the maximum amount of time across all points that a single point in the target volume goes without being observed by any sensor in the constellation.
3. **Time to Maximum Observability:** the amount of time it takes for all potentially observable points to be observed at least once. Note that the set of potentially observable points may not span the entire target volume for a given constellation configuration.
4. **All-sky Scan Time:** the amount of time it would take for a given constellation configuration to cooperatively image an arbitrary 4π volume. Requires assumptions to be made for satellite slew and settle times.

3. EXAMPLE SIMULATION RESULTS

The model discussed previously enables exploration of a rich trade space consisting of constellation asset placement and optical sensor parameters. Examples of optimal constellation configurations within the trade space are generated for the example target coverage volumes shown previously by wrapping the constellation model within Ansys ModelCenter.

3.1 ModelCenter Configuration

A MATLAB wrapper script was written to interface ModelCenter with the MATLAB coverage model. ModelCenter calls this script which handles parsing design variable inputs, running the model, and passing outputs back to ModelCenter. The Optimization Tool within ModelCenter is used to generate model inputs (given upper and lower bounds on input values) and leverages various candidate optimization algorithms to optimize those inputs for a set objectives based on model outputs. For this study a small number of discrete values were defined for each input variable to reduce the size of the trade space and encourage faster convergence due to long model runtimes. The possible discrete input variable values are shown in Table 2.

Table 2: ModelCenter design variables and their possible values. Discrete values for design variables were prescribed to reduce the size of the possible trade space and expedite convergence due to long model runtimes.

Design Variable	**Units**	**Possible Values**
Aperture Diameter	m	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8
Primary F#	N/A	1.5, 3, 6, 12
Pixel Size	m	6E-06, 12E-06
Integration Time	s	1, 10
Detector Temperature	C	0, 20
Solar KOZ	deg	30, 50
# EML-1 Sats	N/A	1, 3, 5, 7, 10
# EML-2 Sats	N/A	1, 3, 5, 7, 10
# DRO Sats	N/A	1, 3, 5, 7, 10

Additionally, select optical sensor and constellation model input values were assumed to allow unique solutions to be generated for this study, detailed in Table 3.

Table 3: Assumptions made for various optical throughput and constellation models

Parameter	**Units**	**Value**	**Description**
RSO Diameter	m	1.5	RSO geometry parameter required to solve for maximum observation distance at a given SNR threshold using the optical throughput model.
RSO Albedo	N/A	0.2	RSO material parameter required to solve for maximum observation distance at a given SNR threshold using the optical throughput model.
Satellite Slew & Settle Time	s	22	Time needed to slew and settle to a new imaging position on an arbitrary 4π sphere. Used with sensor iFOV to estimate All-Sky Scan Time.

For this study the Darwin genetic algorithm included in ModelCenter was employed to generate an example set of optimal constellation designs. The performance metrics from Section 2.2.4, along with an additional metric capturing the total number of satellites in the constellation, are optimized over the above input variables with the objectives in stated in Table 4.

Table 4: Objectives for each model output specified for the Darwin genetic algorithm within ModelCenter.

Metric	**Objective**
Mean Observation Percentage	Maximize
Maximum Observation Gap	Minimize
Time to Max Observation	Minimize
All-Sky Scan Time	Minimize
Number of Satellites	Minimize

The multiple objectives specified result in a Pareto front of optimal solutions. The next two sections will show example Pareto-optimal designs for both target volumes assessed in this study.

3.2 Moon-Centered Sphere Coverage Results

Figs. 5 and 6 show feasible design points, along with the Pareto-optimal set, for the Moon-centered volume shown in Fig. 2. Since the coverage volume in question is spherical, feasible designs have been constrained to be those with a value less than 1 day for the All-Sky Scan Time objective.

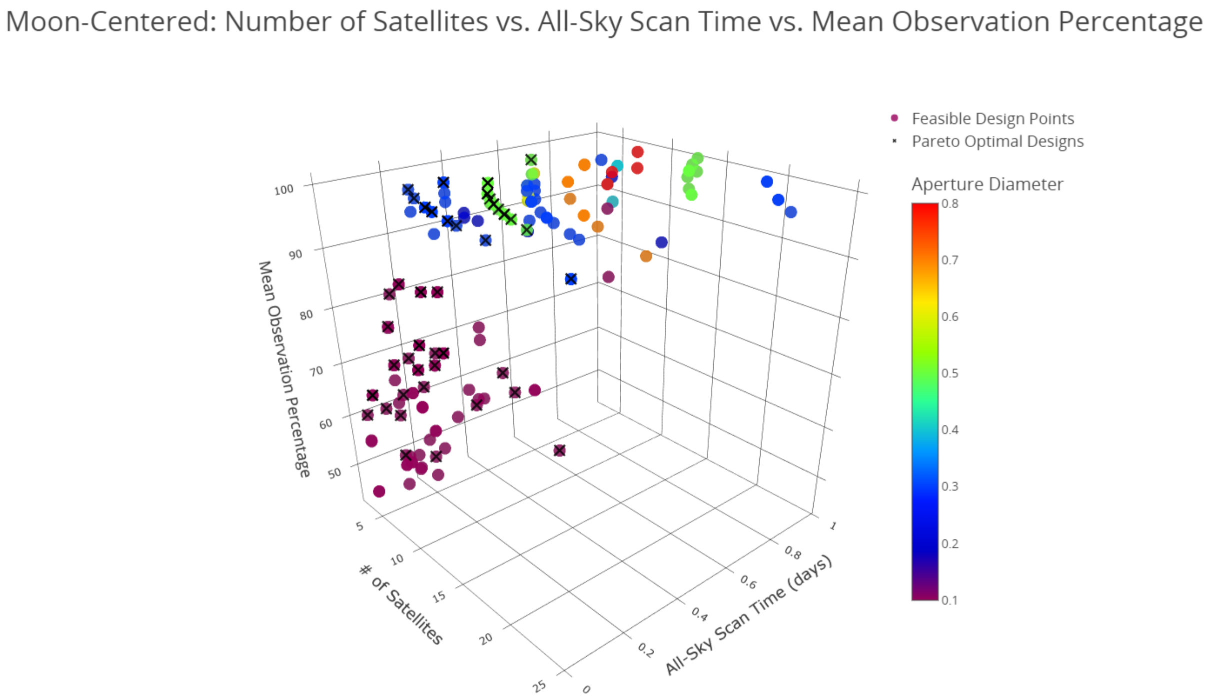

Fig. 5: Feasible design points for three of the five objective performance metrics: Number of Satellites, All-Sky Scan Time, and Mean Observation Percentage. Points are colored based on the Aperture Diameter value. The Pareto-optimal set for all five objectives is denoted by a black X on the corresponding points.

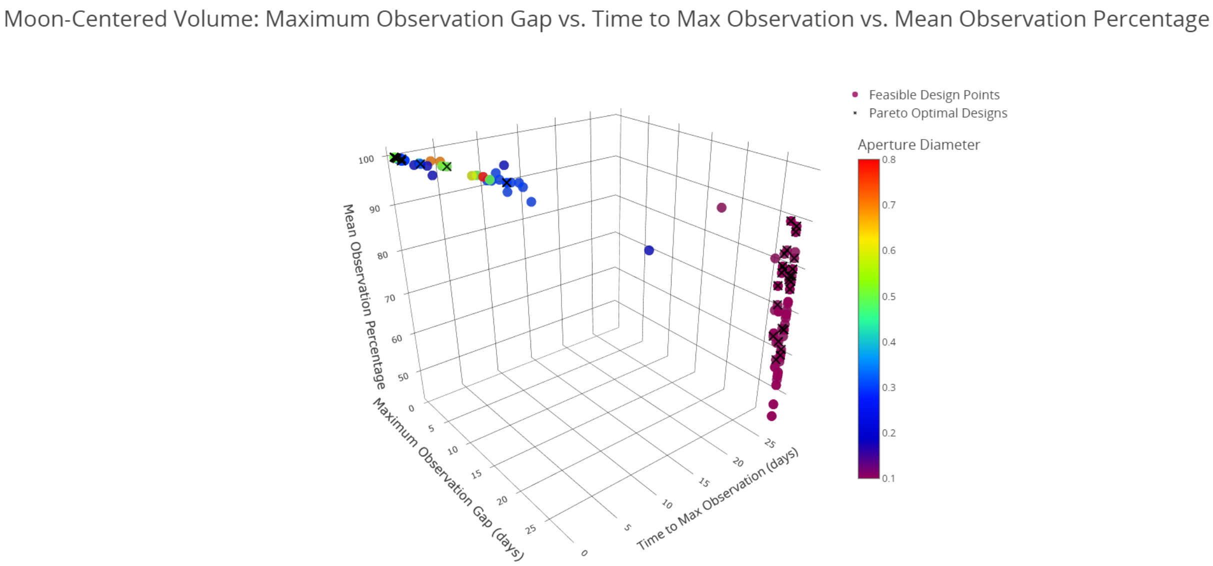

Fig. 6: Feasible design points for three of the five objective performance metrics: Maximum Observation Gap, Time to Max Observation, and Mean Observation Percentage. Points are colored based on the Aperture Diameter value. The Pareto-optimal set for all five objectives is denoted by a black X on the corresponding points.

Pareto-optimal designs with maximal and near-maximal volume coverage exist for a wide range of aperture diameters and constellation sizes. 99.9% volume coverage can be attained with a constellation of only 5 satellites using 0.3 meter aperture sensors, at the expense of larger values for Maximum Observation Gap and Time to Max Observation. 100% coverage can be attained, along with no observation gaps and <0.5 day All-Sky Scan Time and Time to Max Observation, with a larger 0.5 meter aperture and 9 satellites.

By looking at narrower slices of the design space, namely a single objective against one or more design variables, objective-specific insights are revealed. Fig. 7 shows Pareto-optimal values for Mean Observation Percentage plotted against Aperture Diameter. Coverage values >90% can be achieved with 13 satellites carrying sensors with 0.1 meter apertures, or by only 3 satellites carrying sensors with larger 0.3 meter apertures. Table 5 shows design values and performance metrics corresponding to a Pareto-optimal design that achieves >95% coverage with only 3 satellites.

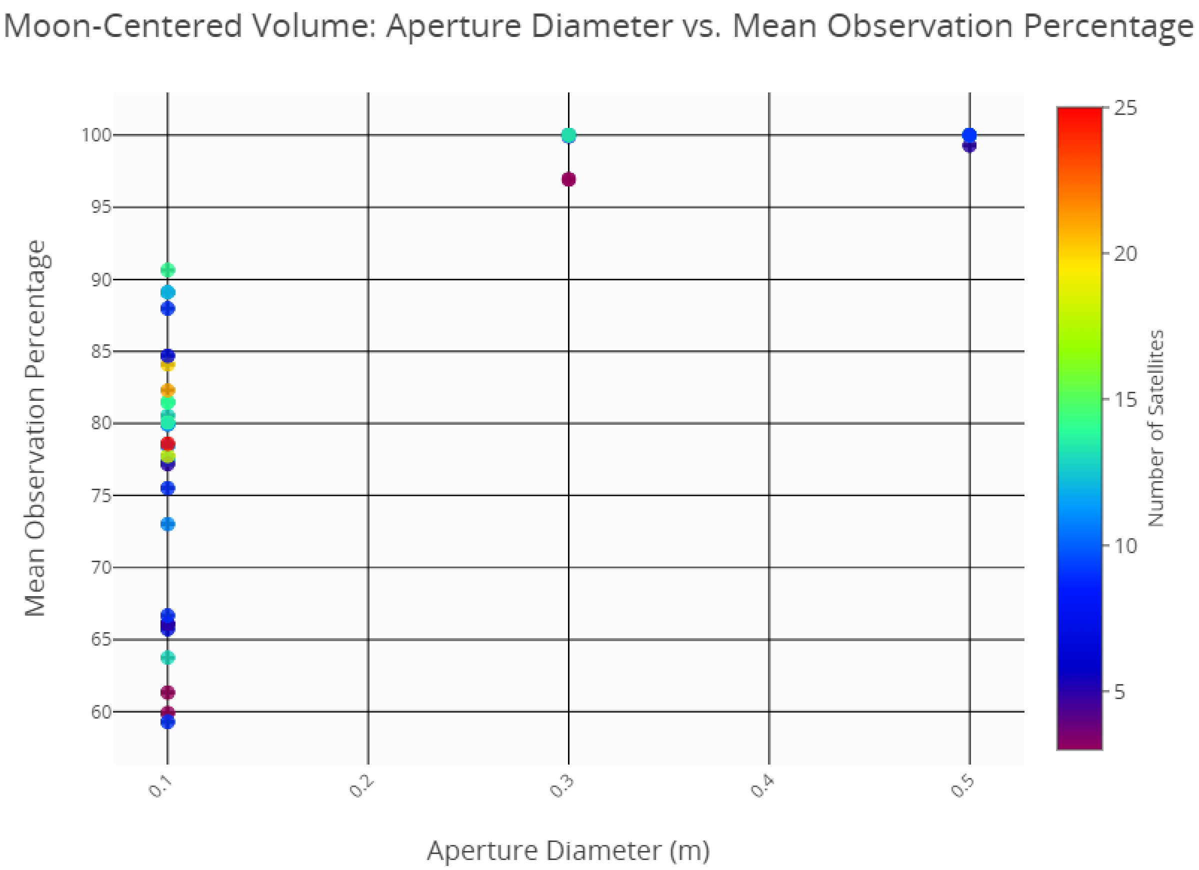

Fig. 7: Pareto-optimal design points plotted with a focus on the Mean Observation Percentage objective, with Aperture Diameter on the X axis, Mean Observation Percentage on the Y axis, and each point shaded based on Number of Satellites.

Table 5: Example Pareto-optimal design achieving >95% Moon-centered volume coverage with only 3 satellites.

Parameter	**Units**	**Value**
Aperture Diameter	m	0.3
Primary F#	N/A	1.5
Pixel Size	m	12E-06
Integration Time	s	10
Detector Temperature	C	0
Solar KOZ	deg	30
# EML-1 Sats	N/A	1
# EML-2 Sats	N/A	1
# DRO Sats	N/A	1
Mean Observation Percentage	N/A	96.9%
Maximum Observation Gap	days	9.67
Time to Max Observation	days	7.00
All-Sky Scan Time	days	0.38

3.3 Cislunar Corridor Coverage Results

Fig. 8 shows all design points evaluated, along with the Pareto-optimal set, for observation of the Earth-Moon corridor shown in Fig. 2. Since the target volume in question is not spherical, the All-Sky Scan Time objective was not applicable and was not considered during the optimization process for this target volume. Additionally, the large detection ranges inherent to detecting near-Earth points from near-Moon locations imparts a large sensitivity to solar phase angle for this particular simulation. Certain points in the target volume are not revisited by the constellation until more optimal solar phase angles are revisited, meaning the value for Max Observation Gap is equivalent to the simulation duration of one lunar period for every design evaluated. Therefore, this objective's values are excluded from any results.

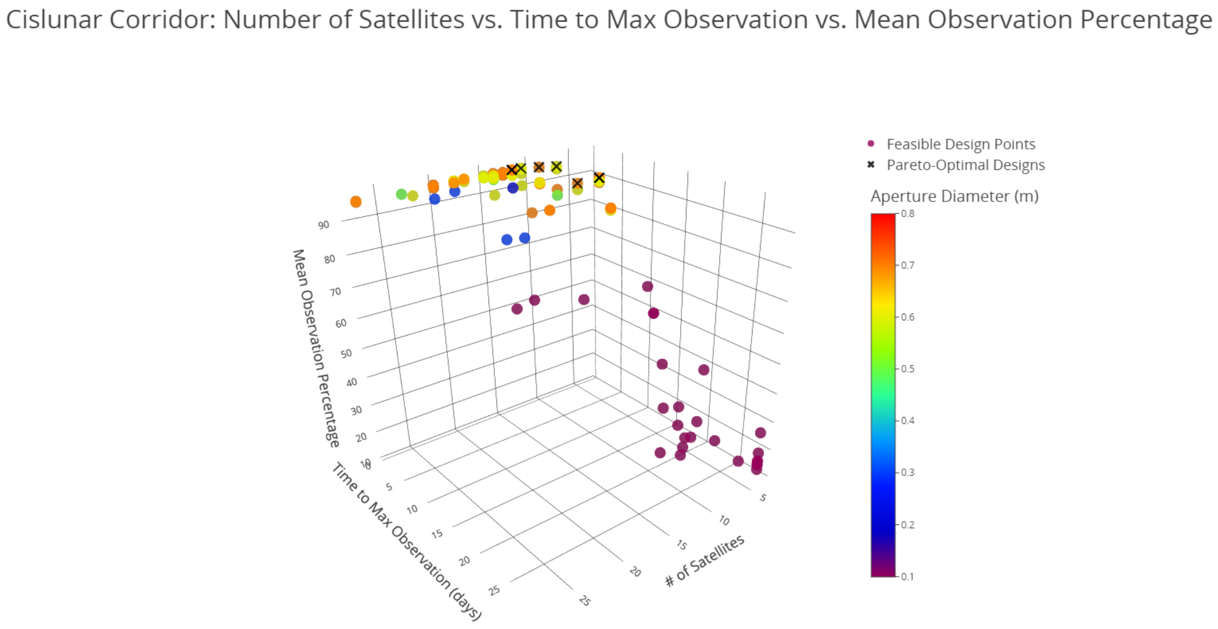

Fig. 8: Feasible design points for three of the four objective performance metrics: Time to Max Observation, Number of Satellites, and Mean Observation Percentage. Points are colored based on the Aperture Diameter value. The Pareto-optimal set for all four objectives is denoted by a black X on the corresponding points.

Fig. 9 shows Aperture Diameter plotted against Mean Observation Percentage for the Earth-Moon corridor. Designs with >90% Mean Observation Percentage for this target volume almost exclusively employ large 0.6 - 0.8 m aperture diameters, to cover the vast range between the Moon and the Earth. These large sensors still require a moderate number of satellites, with most designs having >90% coverage including 7 or more in the constellation. An example design point fitting this description is shown in Table 6.

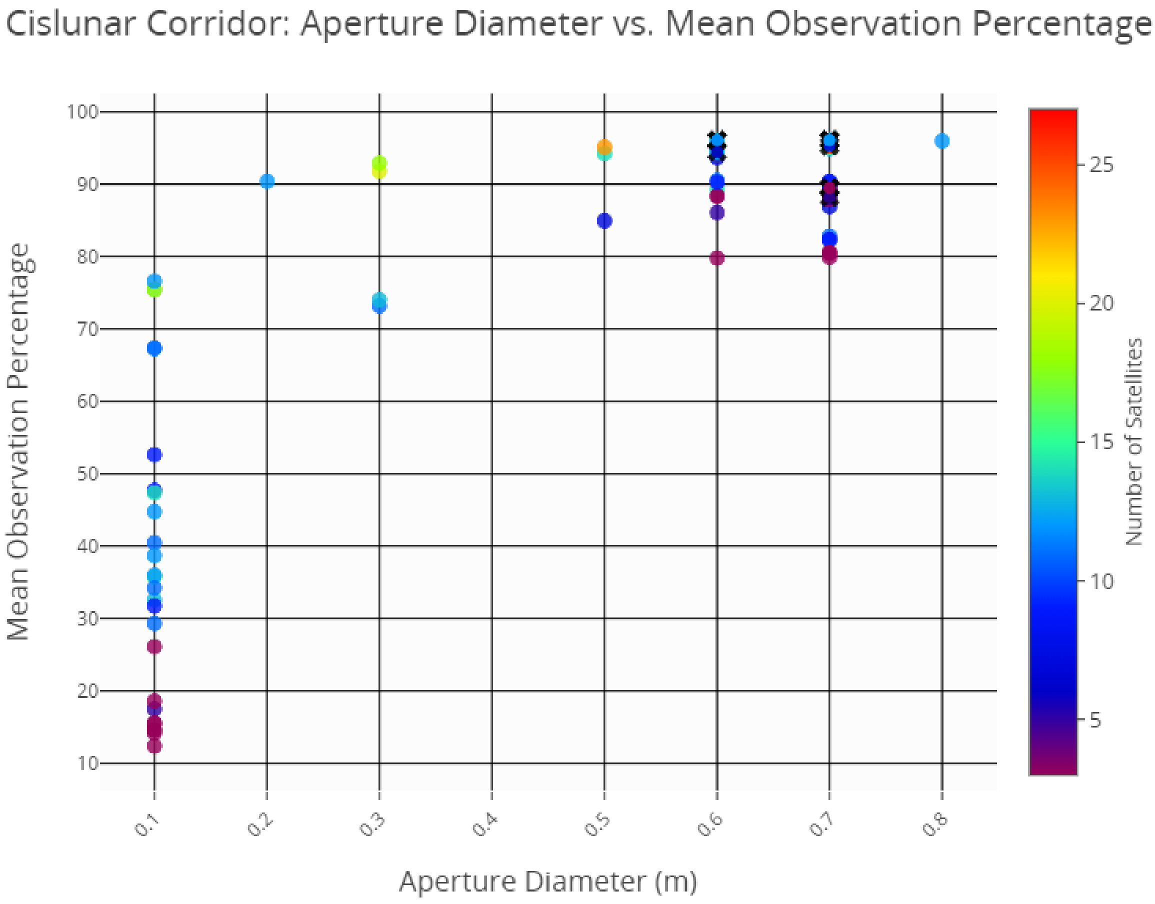

Fig. 9: Feasible design points plotted with a focus on the Mean Observation Percentage objective, with Aperture Diameter on the X axis, Mean Observation Percentage on the Y axis, and each point shaded based on Number of Satellites. Pareto-optimal designs are denoted with black X marks.

Table 6: Example Pareto-optimal design achieving 95% Earth-Moon Corridor volume coverage with 7 satellites.

Parameter	**Units**	**Value**
Aperture Diameter	m	0.7
Primary F#	N/A	6
Pixel Size	m	6E-06
Integration Time	s	1
Detector Temperature	C	20
Solar KOZ	deg	30
# EML-1 Sats	N/A	1
# EML-2 Sats	N/A	1
# DRO Sats	N/A	5
Mean Observation Percentage	N/A	95.0%
Time to Max Observation	days	0.33

Aperture diameters from 0.3 - 0.5 m, similar to those optimal for the Moon-centered volume, can still achieve coverage values above 90% assuming 15+ satellites are included in the constellation. Based on the results for both target volumes assuming strictly cislunar asset placement, 5 satellites carrying short-to-medium aperture diameter and short focal length sensors combined with 5-7 satellites carrying large aperture diameter and medium-to-large focal length sensors could actively cover the Moon-centered volume with rapid 4π scan times while also tracking RSOs within the Earth-Moon corridor. These assets would still suffer from reduced detection range toward the Earth when the Sun appears behind the Earth, meaning further increases in Earth-Moon corridor observation would require utilizing assets closer to the Earth, such as existing ground-based sensors or by placing assets in the geostationary belt. The ground-based/geostationary and cislunar assets would provide complementary coverage during periods of either group's reduced effectiveness due to sub-optimal solar phase angles.

4. CONCLUSION

As more spacecraft are launched with destinations in cislunar space, the need for cislunar SDA grows rapidly. Persistent coverage of the large cislunar volume requires multiple dedicated spacecraft with strategically chosen sensor suites. Quantum Space is dedicated to developing best practices for cislunar SDA mission design that enable rapid and actionable intelligence within the cislunar volume and beyond. The content of this paper focuses on a first-principles optical sensor and constellation design tool for cislunar coverage optimization. Given the multi-objective nature of this optimization problem, a set of Pareto-optimal solutions exists that enables constellation designers to prioritize constellation performance parameters that suit their unique mission needs. This tool is a subset of a larger model that Quantum Space is developing which includes modules for propulsion, communication, pointing control, and power systems design, resulting in a holistic space mission design model used for maximizing constellation performance capabilities while balancing mass and cost constraints.

REFERENCES

[1] *Memorandum of Understanding Between The National Aeronautics And Space Administration and The United States Space Force*, 2020. [Online]. Available: `https://www.nasa.gov/sites/default/files/atoms/files/nasa_ussf_mou_21_sep_20.pdf` (visited on 12/07/2022).

[2] A. C. Snow, "Multi-objective cubesat constellation optimization for space situational awareness," *Atlanta, Georgia: Georgia Institute of Technology*, 2015.

[3] M. Klonowski, M. J. Holzinger, and N. O. Fahrner, "Optimal cislunar architecture design using monte carlo tree search methods," *The Journal of the Astronautical Sciences*, vol. 70, no. 3, p. 17, 2023.

[4] N. O. Fahrner, J. Correa, and J. Wysack, "Capacity-based cislunar space domain awareness architecture optimization," Sep. 2022.

[5] M. J. Holzinger, C. C. Chow, and P. Garretson, "A Primer on Cislunar Space," en, Air Force Research Laboratory, Tech. Rep., 2021, p. 23. [Online]. Available: `https://www.afrl.af.mil/Portals/90/Documents/RV/A%20Primer%20on%20Cislunar%20Space_Dist%20A_PA2021-1271.pdf?ver=vs6e0sE4PuJ51QC-15DEfg%3d%3d`.