Contrasting Architectures for Cislunar SDA and STM

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ABSTRACT

Discussions of Space Domain Awareness (SDA) and Space Traffic Management (STM) often get muddled in terms of the objectives that they are trying to meet. Though the two missions have significant overlap in requirements, they do have differences that will drive different architectures to support cislunar space. Chief amongst these differences are the surveillance volume and revisit rate to search the volume. This paper will present architectures for SDA and STM that reflect the differences in requirements space between these two missions. Various cislunar orbit families will be evaluated to determine their viability for deep-space volume search, and their applicability to the different mission focuses. Surveillance volumes will be defined for both mission areas and candidate architectures will be examined.

1. INTRODUCTION

As traffic increases in the Earth-Moon system, a space-based surveillance capability will be required to maintain safe operations in those regions, while maintaining the more populated near-Earth region. The Space Domain Awareness (SDA) mission is a crucial step in the advancement of surveillance capabilities because its focus on threat protection results in focused deployment of assets to provide an Indications & Warning (I&W) capability to crucial areas of space; namely, GEO and below. Space Traffic Management (STM) has the responsibility of catalog maintenance, which requires searching a larger volume of space and hence more observing assets to fulfill that mission.

Search volumes for cislunar STM are often defined as spherical shells extending from GEO altitude to some multiple of GEO altitude; i.e., the 4π XGEO volume. This multiplier can extend the outer radius to near Earth-Moon L2 at 10 XGEO, with some definitions extending even further [5]. The result are volumes that range from 1000 (10 XGEO) to 2000 ($\sim$13 XGEO) times larger than the typical volume used for Earth-orbiting objects defined as a spherical shell extending from a 300 km LEO orbit out to GEO. With a focus on threat detection of GEO and below and activity around the Moon, smaller SDA volumes have been proposed with tighter requirements on search time. An example volume is composed of a 3.4 XGEO spherical shell and a corridor volume that extends to L2 [6]. This volume is roughly 50 times larger than the LEO to GEO volume.

This paper will present architectures for SDA and STM that reflect the differences in requirements space between these two missions. Surveillance volumes will be defined for both mission areas. The focus will be on space-based sensors that utilize visual sensors designed for the vast ranges of cislunar space. We will trade families of periodic cislunar orbits using metrics of orbit stability and access to the cislunar surveillance volume. Best performing architectures will be those that have high coverage using capacity analysis. Architecture design will utilize optimal scan plans that allow the observing sensors to work in collaboration [2].

2. ARCHITECTURE CONSIDERATIONS

This section will define the SDA and STM missions and describe how the cislunar application differs from the LEO-GEO mission. We will then motivate the choice of search volumes for the two missions. Then discuss cislunar orbits and their potential to provide candidate orbits for the deep-space surveillance applications.

2.1 Overview

The primary goal of Space Domain Awareness is to provide I&W capability for designated Areas of Responsibility (AOR). A cislunar SDA mission will be responsible for protecting GEO and below and the high-value assets (HVA) that reside in that regime. New and known objects need to be detected, tracked, and identified with sufficient warning time for responsive action in a threat scenario. This necessitates short revisit times, on the order of hours, so the SDA search volume must be defined to account for this.

The Space Traffic Management mission shares some of these responsibilities with SDA. Rather than guarding against potential threats, its main objective is the cataloging of objects with routine state updates to allow for traffic management, collision avoidance, and to maintain an AOR for sustainable use [2]. Revisit rates may be chosen such that reliable state vector information can be maintained and close approach encounters can be predicted several days in advance. The SDA mission must account for change detection (specifically unwarned spacecraft maneuvers), which necessitates that the revisit rate be on the order of hours. This requires the mission to discover new objects that might come from outside the cislunar surveillance volume or are released from a parent object. Maneuvers from known objects that puts them on a collision trajectory must be tracked and reacted to in a timely manner.

There are a variety of missions that will benefit from a space-based surveillance capability in cislunar space. This will become increasingly more important over the next decade as space traffic increases in the vicinity of the Moon and the Earth-Moon corridor, though spacecraft that can afford to add long transfer times to their mission profile will inhabit areas outside the corridor along their flight path. The following provides an overview of mission types and thoughts on mission parameters such as orbits and flight times that are weighing factors in their need for support from SDA or STM missions.

Human space flight

- Flight time: Earth-Moon transfer < 5 days
- Origin: Earth
- Destination: cislunar stable orbit, Lunar orbit, Lunar surface
- Trajectory objective: transfer time for astronauts, return to Earth

Science

- Flight time: mission dependent
- Origin: Earth / Lunar surface for sample return mission
- Destination: stable Lagrange orbit, Lunar orbit

Cislunar infrastructure (PNT, comm relay, refueling, etc.)

- Flight time: mission dependent
- Origin: Earth / Lunar surface for sample return mission
- Destination: stable Lagrange orbit, Lunar orbit

Threat to space HVAs

- Flight time: short (<5 days)
- Origin: cislunar Lagrange orbit
- Destination: intersect Earth orbit

2.2 Cislunar Volume Definitions

2.2.1 SDA

An SDA volume can be defined by a required warning time for GEO High-Value Assets (HVAs) from direct descent ASATs and a threat trajectory timeline. A trip wire search volume must be sufficiently large to allow for an object to be detected while allowing adequate time to provide warning to potential targets residing in GEO. Thus, a SDA search volume can be defined by plausible threat trajectory timelines to the LEO-GEO regime. Figure 1 provides Delta Velocity (DV) costs associated with trajectories for GEO intercept trajectories from several originating cislunar orbits for up to 6.5 day transfer times. Based on fuel load for a 'typical' satellite we use a two-day transfer to establish the threat volume.

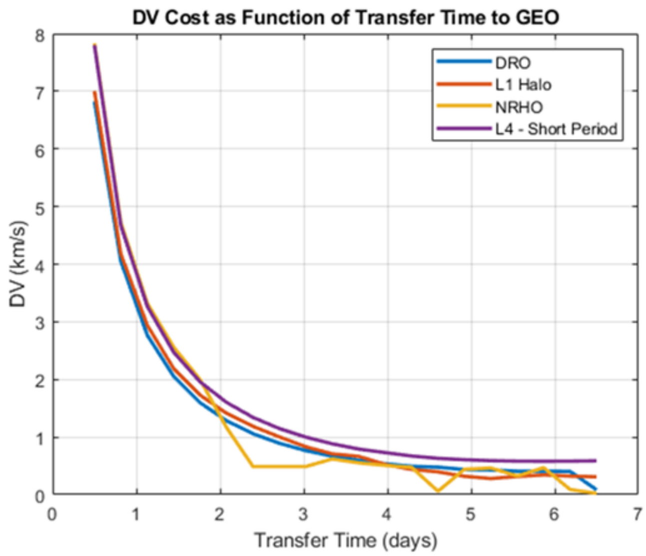

Fig. 1: DV cost as a function of transfer time from various cislunar orbit to GEO.

For a six-hour warning time for a satellite in GEO, a Resident Space Object (RSO) on a two-day return trajectory is 2.7 GEO radii away. A volume based only on the altitude of the six-hour warning time is insufficient. Take the case of a RSO that is just outside a 2.7 XGEO diameter volume at the start of the search period. That RSO could transit nearly to GEO altitude before it is observed during the next search period. Therefore, a 4 XGEO volume is proposed to provide a sufficient trip wire for objects to be detected and allow for the necessary warning time for further action. This concept is shown in Figure 2.

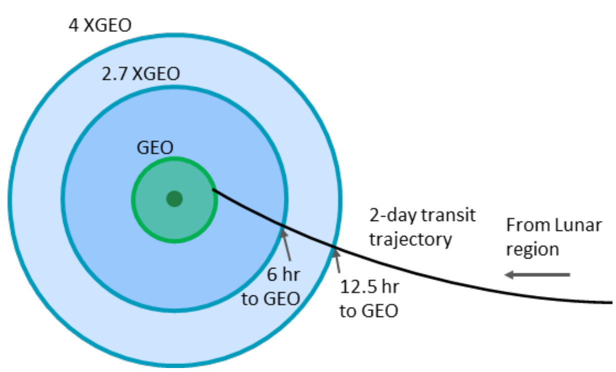

Fig. 2: Cislunar volume definition for Space Domain Awareness surveillance.

2.2.2 STM

Given the focus of the STM mission, a different approach is used to determine the search volume. This volume should consider not only threats, but also other cislunar mission orbits such as infrastructure satellites, science, as well as supporting the collision avoidance mission. Priority in the volume selection are coverage of the Earth-Moon transit corridor, Earth orbits beyond GEO, Lunar orbits, and most of the periodic cislunar orbits. For this work a 10 XGEO hollow sphere is chosen that extends down to GEO radius. Figures 3 - 6 show the 10 XGEO volume in relation to example orbits from several major families of cislunar orbits. All orbits shown are stable and are more likely to be chosen by operational spacecraft (Section 2.3 will provide more detail on orbit stability). Not shown are Earth-centered orbits which include circular XGEO orbits of various radii and Resonant Planer Orbits (RPO) that are all contained within the 10 XGEO volume.

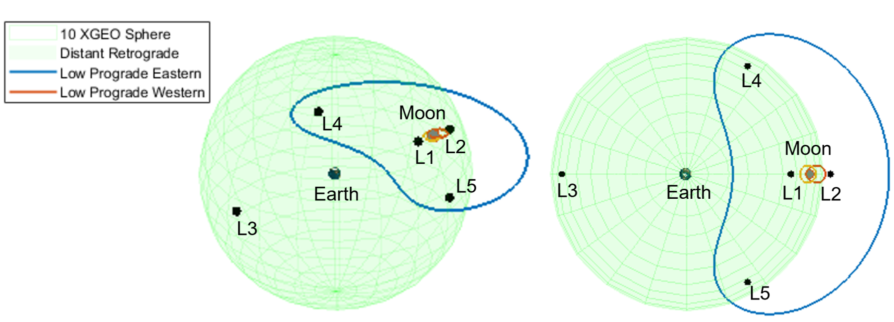

Fig. 3: STM 10 XGEO volume with Lunar orbits. 3D view (left) and view orthogonal to Earth-Moon plane (right). Of the Lunar orbit families, only the Distant Retrograde Orbit (DRO) extends outside the volume.

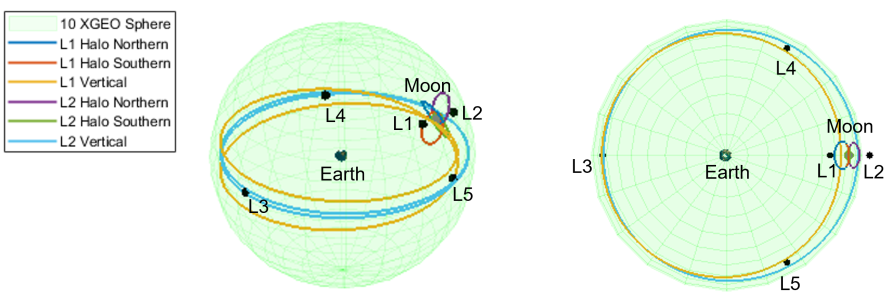

Fig. 4: STM 10 XGEO volume with L1 and L2 Lagrange family orbits. 3D view (left) and view orthogonal to Earth-Moon plane (right). The stable Halo orbits are closer to the Moon than the L1 or L2 point and are therefore largely contained within the volume.

Several orbit families do have trajectories that pass outside the 10 XGEO volume. Most notably the Distant Retrograde Orbits (DRO) can pass well beyond the outer radius. We maintain the the 10 XGEO volume is a reasonable choice as a starting point for the STM mission. Our goal in this work is to show contrasts in architectures for SDA and STM, rather than make a statement on a definitive STM volume.

Of the five Lagrange points only L2 is outside of this volume, but many of the orbits about L2 will be seen for most of their orbital periods, In addition, [7] shows that trajectories on an Earth-return trajectory from L2 will pass through a pinch point at L1 and therefore, will be detected within a 10 XGEO volume.

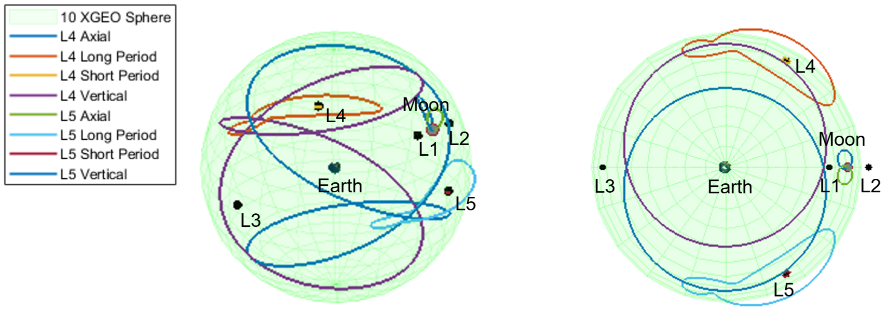

Fig. 5: STM 10 XGEO volume with L4 and L5 Lagrange orbits. 3D view (left) and view orthogonal to Earth-Moon plane (right). The extent of the L4 and L5 Vertical orbits relative to the Earth-Moon plane illustrate why a spherical volume is required to enclose their trajectories.

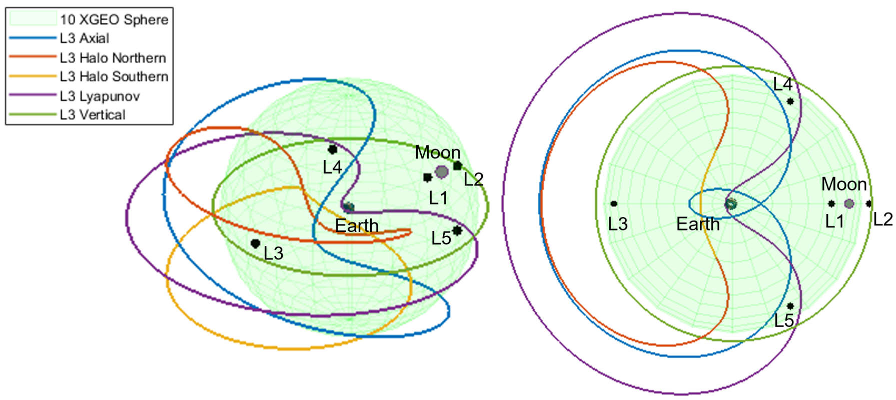

Fig. 6: STM 10 XGEO volume with L3 Lagrange family orbits. 3D view (left) and view orthogonal to Earth-Moon plane (right). Several orbits from the L3 periodic orbit family do extend beyond the volume.

2.3 Orbits

Families of cislunar orbits exist due to the gravity potential in the two primary body Earth-Moon system. The gravitational potential of the Earth-Moon system allows orbits to reside in the vicinity of the Earth, Moon, and each of the five Lagrange points. About each of these points periodic orbits exist that allow objects to occupy many different portions of cislunar space and can provide different viewing geometries for observing architectures.

For this paper, orbits from the JPL Three-Body Periodic Orbits database [4] were utilized for analysis. This data is available via a website that contains thousands of orbits, developed with Circular Restricted Three-Body Problem (CRTBP) dynamics, for the Earth-Moon system, as well as other two primary body systems within the solar system, such as Sun-Earth. While the extent of these various orbit families traverse much of cislunar space, many of the orbits are unstable, so they will not remain periodic for multiple periods with a finite stationkeep budget. This makes them infeasible for long-term missions. A multiple-shooting method is a common technique to form long-term stable orbits when propagated with high-fidelity dynamics. The required stationkeeping budget to maintain a periodic orbit can also be obtained via this technique. That analysis is outside the scope of this paper, so we will utilize the stability index as a proxy metric for determining practical operational orbits. The lower bound of the stability index is 1.0, indicating a stable orbit. Orbits become more unstable as the stability increases. Tables 1, 2, and 3 provide the stability index for Lagrange, Moon-centered, and Resonant Planar Orbits (RPO), respectively. XGEO orbits are quite stable from 1 - 4 XGEO radius, since the dynamics are dominated by the Earth's gravity and the Moon remains a third-order perturbing force.

Orbit Family	L1	L2	L3	L4	L5
Halo N/S	1.00 - 1180.41	1.00 - 606.11	1.00 - 1.38	—	—
Lyapunov	53.67 - 1337.71	49.60 - 726.78	1.00 - 1.67	—	—
Vertical	1.42 - 263.73	1.00 - 241.80	1.00 - 1.60	1.00 - 1.005	1.00 - 1.005
Axial	201.31 - 254.24	127.89 - 167.67	1.05 - 1.16	1.00 - 1.005	1.00 - 1.005
Short Period	—	—	—	All 1.00	All 1.00
Long Period	—	—	—	1.00 - 61.99	1.00 - 61.99

Table 1: Stability index data for Lagrange family of orbits.

Orbit Family	Stability Index
Butterfly N/S	1.00 - 211.18
Dragonfly N/S	209.03 - 287.46
Direct Retrograde Orbit (DRO)	1.00 - 1.0002
Direct Posigrade Orbit (DPO)	1.00 - 2656.25
Low Prograde Orbit (LPO) E/W	1.00 - 51.39 (E) 1.00 - 32.52 (W)

Table 2: Stability index data for Moon-centered family of orbits.

Orbit Family	Stability Index
RPO 1:1	1.00 - 1.0002
RPO 1:2	1.00 - 74.16
RPO 1:3	1.00 - 417.43
RPO 1:4	1.00 - 5.11
RPO 2:1	1.00 - 1.00003
RPO 2:3	2.08 - 95.96
RPO 3:1	1.37 - 8.49
RPO 3:2	1.00 - 33.83
RPO 3:4	1.00 - 168.85
RPO 4:1	1.00 - 1.006
RPO 4:3	1.00 - 16.36

Table 3: Stability index data for Resonant Planar Orbits.

Here we limit the candidate orbits for a cislunar surveillance architecture to those with stability < 2.0. From the available orbit families that meet our stability criteria, we find the observability of a sample architecture to determine which families are best suited to each mission. Observability is defined as line-of-sight access for a sensor's range capability subject to solar phase angle and celestial body keep-out zones. For each orbit family, the orbit with the best observability is provided in Table 4 for a 4 XGEO volume and Table 5 for a 10 XGEO volume.

Candidate observer orbits will be chosen from the top performing orbits for each surveillance volume. Orbits from this list can be varied in number and permuted to find high coverage while minimizing the total number of observing spacecraft.

Orbit Family	Observability Percentage
3 XGEO	97.3
4 XGEO	93.2
RPO 4:1	86.4
5 XGEO	82.0
RPO 3:2	76.2
RPO 3:1	69.8

Table 4: Observability for various orbit families against a 4 XGEO volume. Architecture composed of three mv 20 sensors.

Orbit Family	Observability Percentage
RPO 3:2	52.2
4 XGEO	47.9
RPO 3:1	47.1
5 XGEO	46.8
3 XGEO	46.3
RPO 4:1	44.6
Vertical L5	35.6
Vertical L3	34.4

Table 5: Observability for various orbit families against a 10 XGEO volume. Architecture composed of three mv 20 sensors.

3. ARCHITECTURE DEVELOPMENT PROCESS

Utilizing the orbits discussed in Section 2.3, we leveraged the process established in [6] to develop surveillance architectures. This process allows for the rapid analysis of thousands of orbits using observability analysis to develop candidate orbits for full architectures. These results are then refined using the performance of the architecture within a collaborative sensor tasking schedule. An overview of the process is shown in Figure 7.

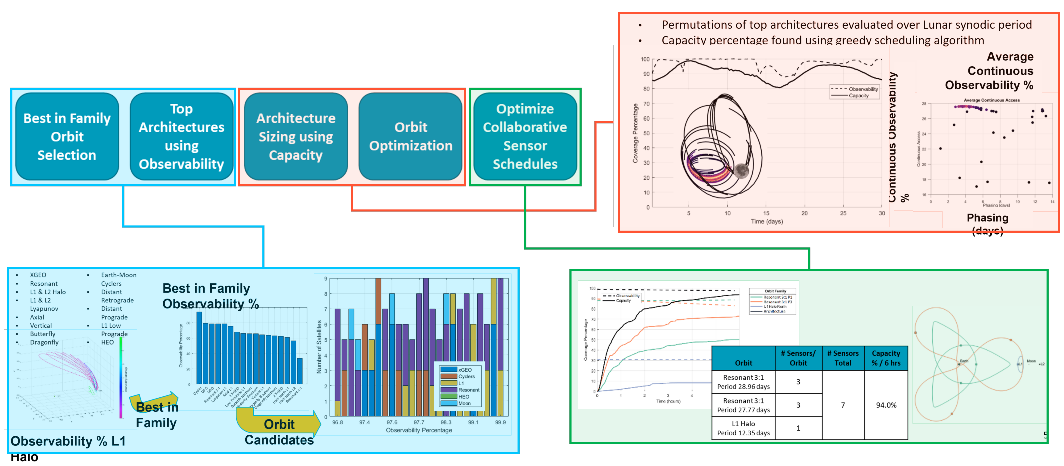

Fig. 7: Overview of the architecture development process.

Initial orbit viability for a volume search is performed using observability analysis. This is evaluated at multiple evenly distributed times over a lunar synodic period with the mean of these results allowing for all Sun angles to be taken into account in the coverage evaluation. Permutations of top candidate, or 'best in family,' orbits are evaluated to determine favorable architectures for coverage of the designated surveillance volume.

To assess the true capability of an architecture the performance of the payload must be taken into consideration. This is done with capacity analysis that takes into account the field of view (FOV) of the sensor and the agility of the payload. The next step of the architecture development process uses capacity analysis within a scheduling optimization algorithm that provides optimal coverage results for a constellation of sensors working collaboratively. We chose to use a greedy algorithm in this analysis because the speed of this algorithm allows for analysis over a synodic period. The software developed for [6] also employs a genetic algorithm (GA) to improve upon the coverage results calculated via the greedy algorithm. The GA was not used in this work due to the much longer runtimes compared to greedy, because were are interested in contrasting SDA and STM architectures, both in architecture size, and the orbits best orbits to used for the surveillance architectures.

4. SDA AND STM ARCHITECTURES

In this section we will provide SDA and STM architectures and contrast their attributes. Multiple architectures are available for the 4 XGEO SDA volume, whereas it was challenging to find architectures with high coverage of the 10 XGEO STM volume. A visual sensor with mv 20 sensitivity was used in this analysis. The volumes are composed of equally-spaced targets modeled as 1 m diameter Lambertion spheres with 20% reflectivity. As stated previously, the range capability of the sensor takes into account the solar phase angle.

4.1 SDA Architectures

The orbits that provided good observability of the SDA volume are Earth centered with symmetry about the Earth-Moon line. We analyzed each family independently using equal phasing of observers over the orbits as the initial configuration of each architecture. We varied the number of satellites until a result of near 90% average capacity was obtained. The average was calculated as the cumulative coverage over each six-hour revisit period.

Architecture	Number of Sensors	Capacity Percentage
RPO 4:1	6	90.2
RPO 3:1	6	89.6
4 XGEO	9	89.9
3 XGEO	9	88.0
RPO 3:2	6	61.3

Table 6: Top SDA architectures to cover a 4 XGEO volume. Capacity percentage is the average of results for each six-hour search time over the Moon's synodic period.

Table 6 provides results for several architectures providing coverage of the 4 XGEO SDA volume with a six-hour revisit time. The 4:1 and 3:1 RPO orbits perform well due to the variation in altitude during their period, as opposed to circular XGEO orbits that maintain a constant altitude. This is exhibited in Figure 8 which shows the best-performing architecture comprised of six satellites in RPO 4:1 orbits.

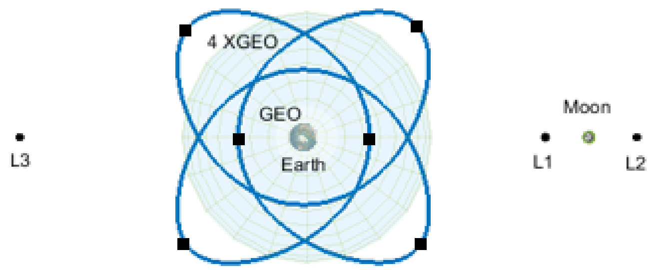

Fig. 8: Architecture for SDA mission comprised of six satellites in RPO 4:1 orbits.

4.2 STM Architectures

Given the vastness of the 10 XGEO STM volume many more sensors will be needed to search the volume. In addition, the orbits suitable for this volume come from different cislunar families than those favorable for SDA architectures. The Vertical orbit families for L3, L4, and L5 proved to be favorable due to their extension into regions orthogonal to the Earth-Moon plane and the RPO families were also well-suited to contribute to STM architectures. Table 7 provides sample STM architectures. The top result contains 72 total satellites comprised of RPO 3:2 and Vertical L3, L4, and L5 orbits with observers distributed equally across the three orbits. With 72 satellites, greater than 90% capacity can be achieved. Various other results are shown, including architectures that contain only Vertical orbits. Deploying a constellation of double digit satellites to perform cislunar STM will be a challenge. Efficient ways of monitoring the high-traffic areas of cislunar space must be a part of a future architecture [7].

Architecture	Number of Sensors	Capacity Percentage
RPO 3:2 (18) Vertical L3 (18) Vertical L4 (18) Vertical L5 (18)	72	92.0
RPO 3:2 (24) Vertical L4 (24) Vertical L5 (24)	72	90.3
Vertical L3 (24) Vertical L4 (24) Vertical L5 (24)	72	84.2
RPO 3:2 (18) Vertical L4 (18) Vertical L5 (18)	54	79.3
Vertical L3 (18) Vertical L4 (18) Vertical L5 (18)	54	77.4

Table 7: Sample STM architectures to cover a 10 XGEO volume with a revisit time of 12 hours. Capacity percentage is the average of results for each 12-hour search time over the Moon's synodic period.

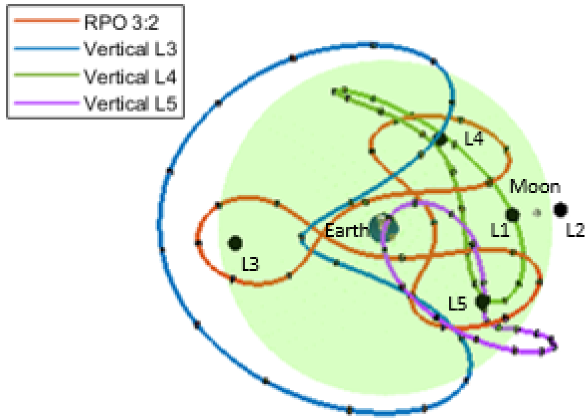

Fig. 9: Architecture for STM mission comprised of 72 satellites in RPO 3:2 and Vertical L3, L4, and L5 orbits.

Figure 9 shows the 72 satellite STM architecture. The RPO 3:2 remains in the Earth-Moon plane, while the Vertical orbits extend far above and below that plane, in particular the Vertical L3 orbit.

We evaluated the effect of the 12-hour revisit time on the capacity results to determine if a CONOPS with up to a 24-hour revisit time would result in better coverage. Figure 10 shows a typical result of this analysis. For this example with 48 satellites, the capacity increase from 12 to 24 hours was less than 5%. This highlights the fact that the difficulty in achieving a high percentage of coverage is the size of the volume, rather than the choice of the revisit rate.

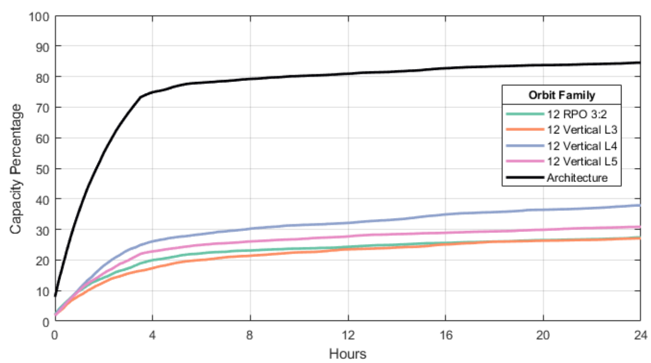

Fig. 10: Cumulative distribution of capacity percentage for a single 24 hour search time. A modest increase in coverage is seen from 12 to 24 hours. Contributions from orbit families are shown with the combined capacity of the complete architecture.

5. CONCLUSIONS

As cislunar space becomes more important for commercial and government stakeholders, a space surveillance presence will be necessary and must be comprised of the correct components for the job. The SDA and STM missions are similar, but the search volumes and observing architectures to satisfy them are different. We have shown architectures that can provide coverage of a 4 XGEO SDA volume. This trip wire volume will allow from 6 - 12 hours of warning time for objects in GEO and below from threat objects on direct descent ASAT trajectories. A six-satellite constellation of visual sensors with mv 20 capability in 4:1 or 3:1 RPOs can provide 90% coverage for this SDA mission. The 3:1 RPO is a proven orbit demonstrated by the IBEX mission [1] that has maintained a stable orbit for years with a minimal stationkeep budget.

Employing a future cislunar STM architecture will be more challenging. The 10 XGEO STM volume evaluated in this work is 15.5 times larger than the SDA volume and 999 times larger than the LEO-GEO volume. With a 12 hour warning time it may require 72 satellite observers to provide adequate coverage. Several of the orbits that comprise the STM architectures are untested in operations and could motivate the need for demonstration missions to test orbit stability and stationkeep strategies before deploying expensive surveillance spacecraft. Similar to the CAPSTONE [3] spacecraft in its pathfinder mission to test the feasibility of the Near Rectilinear Halo Orbit (NRHO) for NASA Gateway.

Future work will investigate how architectures can be developed for complimentary SDA and STM missions. This will allow for distinct portions of a surveillance volume to have different revisit rate requirements. A complete architecture can be optimized for efficient use of surveillance resources. We will also investigate other sensing phenominologies, such as infrared (IR), which may provide improved coverage over visual sensors because IR sensors are not subject to the same solar phase angle (SPA) constraint that can limit visual sensors.

6. REFERENCES

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