ON ORBIT SENSING OF OBJECTS BEYOND GEO

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The increasing number of missions planned beyond the GEO belt is necessitating the development of Space Domain Awareness for the cislunar region. It is foundational to identify objects, track their motion, and respond to potential issues such as conjunctions. An evaluation of different constellations is conducted to sense objects beyond GEO extending within the cislunar region. Analysis of each constellation's performance provides insight for improving Space Domain Awareness of higher altitudes.

INTRODUCTION

The number of objects on orbit has continued to grow at an increasing rate with more countries developing space capabilities and commercial space endeavors; this has also included an increase in the number of countries attempting missions to the moon. Space Domain Awareness (SDA) is defined by Holzinger and Jah as "the actionable knowledge required to predict, avoid, deter, operate through, recover from, and/or attribute cause to the loss and/or degradation of space capabilities and services."[1] SDA is functional to the ability to operate in space and, as the domain become more congested, it is critical to be able to sense objects accurately at higher altitudes. Impacts of a spacecraft with orbital debris or micro-meteors can cause significant damage. Small explosions or spacecraft collisions on orbit result in additional debris that must be tracked to avoid future mishaps.

Geostationary orbit (GEO) is at 35,786 km altitude (42,164 km semi-major axis). Approximately 35 percent of satellites on orbit are currently in GEO. To minimize long term orbital debris, satellites in lower orbits are designed burn up upon reentry in the atmosphere at the end of their life.[2] Objects in orbits above 1000km have a lifetime on orbit of thousands of years. Objects above 2500 km, including GEO have lifetime that can be much longer.[3] Additionally, reentry of GEO satellites is not feasible due to the fuel cost that would be required. A GEO disposal belt is currently used as the graveyard orbit. This supersynchronous orbit is at GEO + 300km (42464 km semi-major axis).

In 2018 there were 1273 GEO resident space objects.[4] four percent of GEO objects 1 cm and larger are contained in the public space object catalog.[5] Collisions with space objects larger than 1 cm can cause catastrophic damage, however tracking objects smaller than 10 cm from earth is

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challenging.[3] An altitude increase of 2000 km above GEO has been proposed for the future to reduce the long term-term risk of collision among GEO satellites and debris from defunct spacecraft explosion fragmentation.[6]

The potential to position satellites in orbits beyond geosynchronous has gained significant interest in recent years. "Cis-Lunar" is Latin for "on this side of the moon" and refers to orbits well beyond the Geosynchronous regime. High altitude orbits are of interest as they offer potential parking location from which to reconstitute lower constellations.[?] There has been a look toward cislunar orbits and the potential uses of such orbits as lunar missions of various types have progressed. Cislunar missions include those to orbit the moon as well as near the Lagrange points where the combined gravitational pull of the earth and moon provide balanced forces, allowing an object to be in periodic orbits about "fixed" points in space, when viewed in the rotating reference frame.

The US plans to return to the moon include the lunar gateway which will be positioned in a southern halo orbit utilizing the stability of near rectilinear orbits around the co-linear Lagrange points. China has three satellites at the L2 Lagrange point and is working with Russian for future lunar missions.[?,?,?,?] Commercial companies have also started planning missions to the moon.

Based on the interest in cislunar it is critical to be able to sense objects throughout cislunar space. Object identification and tracking in the near earth environment is will understood and there is a robust architecture to perform the mission. Sensing of objects using the current terrestrial Space Situational Awareness architecture has been shown to face significant challenges based on the distances to the objects of interest and the limited visibility due to the scenario geometry.[?] Cislunar Periodic Orbits have been analyzed for space object detection, identifying retrograde orbits with a resonance to the moon's period as having characteristics beneficial to observing in cislunar space.[?] The three body problem is a chaotic system and no closed form solution exists. Analysis of a variety of cislunar sensing constellations is valuable to understand the trade space for potential future missions. This research formulates multiple scenarios for space vehicles at various locations within cislunar space including orbits at Lagrange Points. These are analyzed to determine which sensor orbits provide the best visibility for objects of interest.

BACKGROUND

Keplarian and Three-Body Problem Orbital Dynamics. In this work, there are two orbital regimes that are being simulated, which have very different dynamics driving them. The first contains Earth centered orbits, which generally follow perturbed Keplerian orbits; it is assumed that the center of the Earth is an inertial origin. These include the GEO orbits, the GEO disposal belt (both current and proposed), as well as orbits at multiples of the GEO altitude (e.g. 3×GEO). The equations of motion for these orbits are generally expressed as:

$$\ddot{\vec{r}} = -\frac{\mu_\oplus}{\|\vec{r}\|^3}\vec{r} + \vec{a}_d \tag{1}$$

where $\vec{r} = [x,\ y,\ z]^t$ is the position ($x,\ y,\ z$ measured from the center of the Earth), $\mu_\oplus$ is the gravitational parameter of the Earth, and $\vec{a}_d$ represents all disturbing accelerations. For GEO and beyond the disturbing accelerations commonly include the gravitational attraction of the sun and moon, and the solar radiation pressure on the satellite. Additional disturbances can be included if higher accuracy models are required.

The second set of mechanics are those that govern motion in the cislunar regime. It is common to approximate the motion in this regime using the Circular Restricted Three-Body Problem (CR3BP) formulation. In the CR3BP, it is assumed that the Earth and moon move in circular orbits about the system barycenter under their mutual gravitational attraction, while the object of interest is allowed to move freely in three dimensions. This leads to the following equations of motion:

$$\begin{aligned}
\ddot{x} &= 2\,\dot{y} + x - \left(\frac{(1-\mu)(x+\mu)}{\rho_{\oplus}^{3}} + \frac{(\mu)(x+\mu-1)}{\rho_{☽}^{3}}\right) \\
\ddot{y} &= -2\,\dot{x} + \left(1 - \frac{(1-\mu)}{\rho_{\oplus}^{3}} - \frac{(\mu)}{\rho_{☽}^{3}}\right) y \\
\ddot{z} &= -\left(\frac{(1-\mu)}{\rho_{\oplus}^{3}} + \frac{(\mu)}{\rho_{☽}^{3}}\right) z
\end{aligned} \tag{2}$$

where $x,\ y,\ z$ are rotating coordinates measured from the Earth-Moon (EM) barycenter, μ is the mass parameter of the EM system, and $\rho_{\oplus}$ and $\rho_{☽}$ are the distances from the Earth and moon to the satellite, respectively.

Conversion of the motion for one system into the other is complex. For this work, the authors use Systems Tool Kit (STK) to model all of the orbits. Objects in cislunar are modelled using STK astrogator and then propagated in a common simulation with the Earth centered orbits.

Detection Signal to Noise. The ability of an optical sensor to detect an object in space depends on the amount of light the object reflects based on the Phase angle (between sun, object, and observer), the shape of the object, material composition, and the brightness of the sky. The irradiance is the reflection of the sun's light back towards the observer. Often a Lambertian Sphere assumption used to simplify the vehicle geometry considerations. The Signal to noise ration for detection is given by equation 3.

$$SNR = \frac{S}{\sqrt{S+N}'} \tag{3}$$

Where S is the signal of interest and N is the background noise. For standard optical sensors the detection threshold is set to approximately 2.5.[?]

METHODOLOGY

This work evaluates two potential SDA problems: a) sensing objects in at altitutes beyond the GEO belt and b) sensing objects in cislunar space. The first problem models the observers and the debris to be observed in the Earth centered system (Eq. 1). The second models the observers in the Earth centered system, while placing the resident space objects to be observed in the cislunar regime.

To evaluate a notional constellation STK is used to model objects at approximately 8 times GEO which is approximately the limit for the Earth gravity as the primary force allowing for Keplarian dynamics. The gravitational parameter for satellites bound by Earth is $3.986x10^5$ orbital period of an object at a specific semimajor axis (a) is given by:[7]

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{4}$$

The semimajor axis, and its change over time, can be found from the mechanics represented in Eq. 1. The orbital periods for the initial set or orbits evaluated for sensing constellations are shown in Table. (**??**)

The synodic period of Moon is approximately 29.5 days. This is the time it takes the Earth-Moon system to complete one revolution of the Sun. A vast variety of families of orbits within cislunar space can be developed that are closed around the Lagrange points or maintain a resonance within the CR3BP formulation.

The SDA constellation considered for observing the beyond GEO has an altitude which places it above GEO but below the disposal belt to avoid having to maneuver in a region with a high resident space object (RSO) population. The SDA constellations are shown in Fig. **??**.

The SDA constellations are considered with spacecraft in orbits at higher altitudes above GEO disposal for observing objects at $8\times$ GEO and near L_1 and L_2.

The phase angles for the sensing constellation vehicles relative to the sun and resident space objects of interest will change over time resulting in periods of time without visibility for certain sensor object combinations.

There is a growing need for SDA of objects (large and small) in the cislunar regime. For this problem, the authors assume an optical sensor field of view in the 3-5 degree range will be employed. Optical sensors can refine the state (position and velocity) of an object of interest to high accuracy based on angular measurements. This will be important when conjunctions are forecast or re-positioning maneuvers are being monitored. The range, line of site, and relative attitude are used to identify vehicle status. The vehicle image can be processed, photometric data can be evaluated to characterize an objects status (i.e. operational, recently damaged, etc).[8] The image processing for optical is complex and must be done off line resulting in additional time to provide results.

The research evaluates optical sensor SDA constellations for observing resident space objects beyond GEO at altitudes of eight times GEO. The higher altitude resident space objects will be increasingly affected by three body effects. With the interest in cislunar missions, higher altitudes need to be considered.[9] The model contains 20 objects near 8 times GEO to represent very high altitude debris or a vehicle at a point along the their transit trajectory moving through the greater cislunar space.

The SDA constellations considered are located above GEO, twice GEO, and four times GEO with parameters as shown in Table 1. The sensors on all of the vehicles are orientated radially away from earth to maximize the sensing of objects within cislunar space. The higher altitude constellations require additional spacecraft to maintain coverage however a parametric study was not conducted to maintain identical coverage levels or maintain constant arc spacing. Figure Fig. 1 depicts the scenario to sense an object near $8\times$ GEO. This is representative of a potential mid trajectory object location for a spacecraft in cislunar or trapped debris.

The same set of constellations from Table. 1 are used to sense an object in orbit around the colinear Lagrange points L1 and L2. Each of the SDA satellites has two sensors with 5 degree Field of View which are configured to track L1 and L2 respectively. These scenarios are represented in Fig. 2.

The duration of access and range for a sensor to the object of interest is used as an initial assessment for capability of detection. Object visibility based on meeting the signal to noise threshold gives greater fidelity to the capabilities of a sensing constellation at various locations. A combination of different types of orbits in a sensing constellation will provide the ability to sense greater area of cislunar space due to the variety of orbits and vast distances possible.

Table 1. Constellation Parameters for Space Domain Awareness

Constellation	SemiMajor Axis (km)	Period (hh:mm:ss)	Number of Satellites
GEO Stationary	42,164	24:00:00	N/A (reference)
GEO plus	42,414	24:08:51.45	4
2× GEO	84,328	67:41:47.29	6
4× GEO	168,656	191:28:28.2	12
8× GEO	337,312	541:34:18.48	24

RESULTS

STK analysis was completed for sensing of resident space objects near 8× GEO, and in orbit around L1 and L2. For each scenario STK access reports and Azimuth Elevation Range reports are generated and the global statistics are evaluated for each satellite.

For sensing of objects the mean range from sensors to objects is reduced by placing a constellation near GEO, so resolution of small objects (< 10 cm) will be better than sensing from ground sensors. Varying the number of observers in the constellation will provide various geometries for observing the objects, which would be expected to increase the number of observation opportunities.

Evaluation of resident space objects at a very high altitude near 8 time GEO are considered representing debris or a point along a cislunar trajectory that would be challenging for terrestrial or near earth orbiting sensors to identify and track due to the distance and geometry. Each satellite in the constellation at a given altitude has comparable performance. For these scenarios as the SDA constellation altitude increases the mean range to the object of interest decreases and the duration of access increases as detailed in table 2. These factors will allow higher altitude sensing constellations to perform better overall for a space domain awareness mission. Ensuring a smooth hand off between satellites to maintain custody of objects on non traditional orbits will be necessary. The number of satellites required for the many times GEO constellations may be challenging to implement.

The final set of scenarios compared the capability of SDA constellations at high altitudes orbits beyond GEO to sense objects orbiting at L1 and L2. The results from the access and azimuth, elevation, range reports are shown in table 3 and 4. The results are similar to the scenario sensing objects near eight times GEO in that as the constellation altitude increases the access duration is longer and the minimum range decreases, however based on the size of the orbits the maximum range also increases. The trends are the same for both the L1 and L2 objects. This is intuitive because a smaller percentage of the constellations orbit is obstructed by the earth for sensing.

Locating SDA sensors farther into cislunar space will allow for better sensing of objects especially smaller debris without requiring unrealistically large sensors. It also holds that the capability of sensors on a constellation of very high altitude beyond GEO satellites has better visibility for objects located in orbits around the Lagrange. Placing vehicles in orbit at the Lagrange points will likely provide good visibility in the cislunar region while requiring fewer vehicles to cover the vicinity near the moon. Constellation cost and potential for dual use satellites may be significant for design

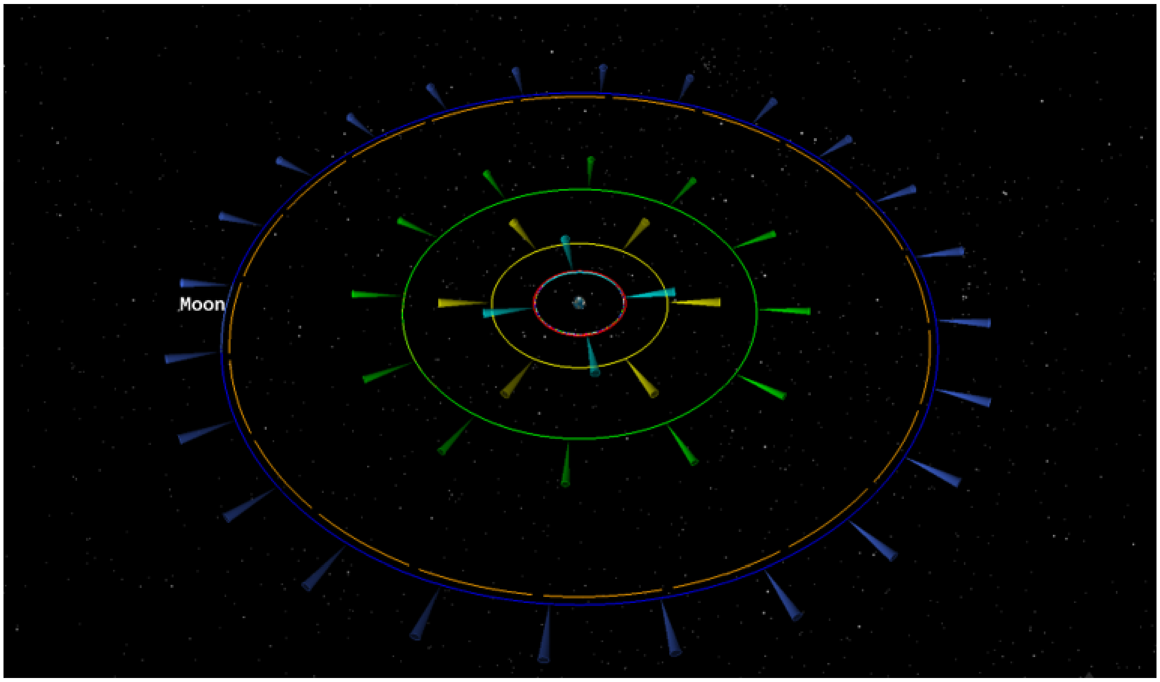

Figure 1. SDA Constellations for sensing cislunar debris near 8× GEO

Table 2. High cislunar debris near 8× GEO Access Summary for different sensing orbits

8× GEO	GEO+	2× GEO	4× GEO
Min Duration Max Duration	32 min 23 hr 21 min	2 hr 42 min 24 hr	6 hr 10 min 24 hr
Elevation Min Elevation Max Elevation Mean	-81.4 deg 90 deg -0.4 deg	-85.7 deg 90 deg -5.439 deg	-87.8 deg 90 deg -14.1 deg
Range Min Range Max Range Mean	287586 km 371870 km 329173 km	245672 km 414025 km 331129 km	161344 km 498474 km 340923 km

trades but were beyond this research.[10]

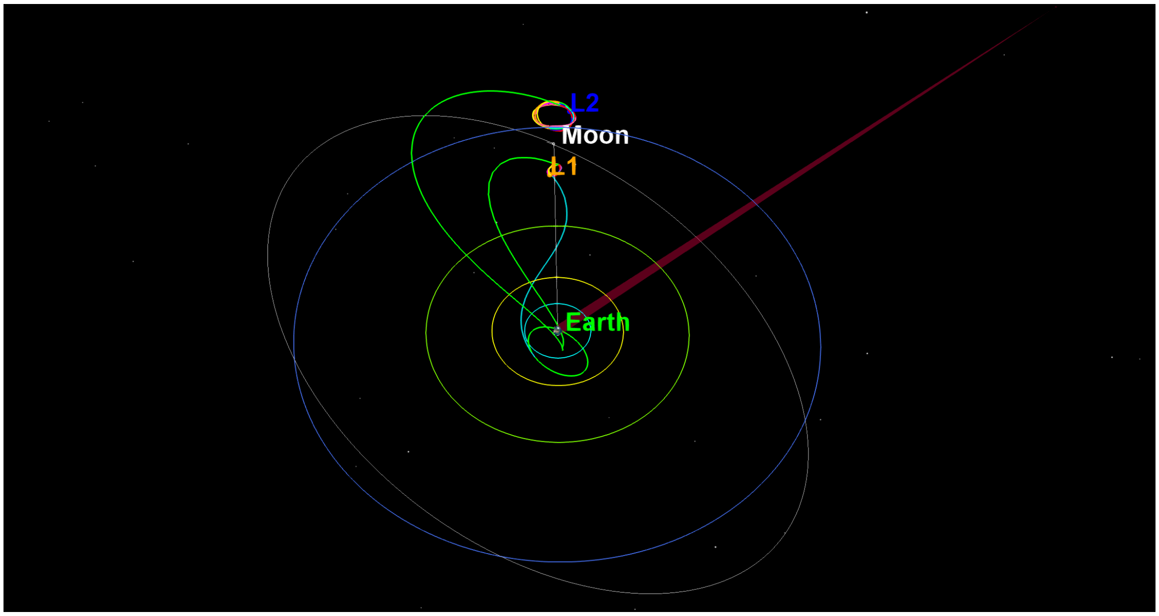

Figure 2. SDA Constellations for cislunar sensing objects at L1 and L2

Table 3. L1 Access Summary for different sensing orbits

L1	GEO+	2× GEO	4× GEO	8× GEO
Min Duration (sec) Max Duration (sec)	84913.75 1077104.36	13914.80 75313.54	Full scenario Full scenario	Full scenario Full scenario
Elevation Min (deg) Elevation Max (deg)	-81.37 89.809	22.9 88.69	-72.548 58.582	-85.43 deg -55.83 deg
Range Min (km) Range Max (km)	263800.82 385451.25	224348.64 260000	209781.40 509881.12	52999.25 673011.72

Table 4. L2 Access Summary for different sensing orbits

L2	GEO+	2× GEO	4× GEO	8× GEO
Min Duration (sec) Max Duration (sec)	85036.022 1079442.594	91778.718 169945.21	1677087.11 Full scenario	Full scenario Full scenario
Elevation Min (deg) Elevation Max (deg)	-81.376 89.436	-28.88 89.20	-87.84 86.41	-85.43 -11.15
Range Min (km) Range Max (km)	377524.08 520722.61	339273.30 450000	260423.64 643375.88	92721.34 801515.99

CONCLUSION

With the ever-increasing number of missions on orbit, continued developments in Space Domain Awareness are critical to ensure safe operation for all spacecraft at GEO and beyond. This research evaluates on-orbit sensing constellations to provide for SDA beyond GEO within cislunar space. Higher altitude satellites are shown to have better coverage beyond the GEO and within cislunar space. The scenarios considered sensing of objects in very high altitude orbit near 8 times GEO, and around the L1 and L2 points. The SDA constellations considered increasing altitude primarily affecting the access duration and range to objects of interest. Overall increasing the altitude of SDA constellations for beyond GEO missions will improve their detection capability by reducing the observation distance.

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