Geosynchronous Patrol Orbits for Optimized GEO Space Domain Awareness

Matt Schierholtz, Tom Kubancik, Kyle Charles, Islam Hussein, Erin Griggs
Trusted Space, Inc.

Blair Thompson
United States Air Force Academy

Elvis Silva
Blue Canyon Technologies, LLC

ABSTRACT

Using inclined, eccentric geosynchronous (GEO) orbits allows monitoring of a single target or longer-term full in-plane coverage of multiple targets in the GEO belt. This is due to the eccentricity-produced motion of such an orbit relative to objects that are stationary with respect to earth's longitude. Previously, "Geosynchronous Patrol Orbit for Space Situational Awareness (SSA)" by Thompson (2017) analyzed two classes of patrol orbits: (1) an asynchronous or drifting orbit that visits all longitudes, and (2) a patrol orbit that will focus on space domain awareness (SDA) around a resident space object (RSO). A delta-v budget was developed for station-keeping, maneuvering, plane changing, and orbit insertion. This paper adds a delta-v analysis for switching between orbit classes over a year. Different concepts of operations (CONOPS) are explored, such as optimized pointing, ground site considerations, and careful phasing of patrol orbits. Using a newly developed tool for modeling constellations of patrol satellites and RSOs, we find that the number of satellites and pointing strategies are the most effective variables for increasing detection of RSOs.

1. INTRODUCTION AND PREVIOUS WORK

Previous work on "Geosynchronous Patrol Orbit for Space Situational Awareness" applied eccentricity to a geosynchronous orbit, which "produces both longitudinal and radial motion when viewed in Earth-fixed coordinates" [1]. This is the foundation of the Patrol Satellite family of orbits, so called because the orbits appear to "fly around" a fixed region of the geo belt. In that paper, a basic patrol orbit is explored for its applicability to a Space Domain Awareness (SDA) mission, showing the diversity of measurement geometry a patrol orbit can provide for a number of Resident Space Objects (RSOs). The Keplerian (classical orbital) elements that define a patrol orbit were characterized. Additionally, a delta-v analysis was performed for each stage of the patrol orbit's life: orbit insertion, station keeping (the delta-v required to overcome the effects of perturbations), and end of-life disposal. The general properties of geosynchronous orbits may be found in Soop [2].

We describe and demonstrate a tool to create the orbital elements for such orbital phasing in a Modeling and Simulation environment. We discuss the considerations necessary when designing CONOPS optimized to meet complex mission objectives. We explore two, three, four, six, and eight-satellite constellations for their respective performance at different combinations of phasing and longitude at different times of the year.

Pointing for different desired lighting conditions can be applied to gain continuous custody of an object with low or zero associated delta-v cost. This is especially true if a well-matched payload is chosen for this mission. The considered payload is visible band in nature, as the visible band is best suited to SDA missions. Multiple pointing Concepts of Operations (CONOPS) were modeled to evaluate performance against mission objectives. The pointing strategies analyzed include 1) solar opposition pointing, which optimizes for the best possible lighting conditions, 2) fixed-nadir-offset pointing, which is closer to a typical pointing CONOPS for GEO Space Domain Awareness missions, and (3) a four-pi-steradian scan, which sweeps the full sky, modeled as a sphere of Fibonacci points, over a set period of time. We analyze whether these CONOPS are adequate to monitor the modeled RSO or incoming threats.

This paper will, for the first time, also explore the effects of phasing for patrol orbits. Phasing the patrol and drift orbit classes in predetermined ways is shown to provide more complete coverage of RSO and threat orbits with high diversity of measurement geometries. When employing phased patrol orbits in conjunction with ground sites, a command center may attain more complete custody of an RSO.

We conduct a ground site analysis to determine the rarity of coinciding ground site blackouts and patrol orbit blackouts, as well as the frequency of excellent viewing conditions from ground coinciding with an earth exclusion from the patrol satellite. This capability would augment a GEO SDA regime.

2. INTRODUCTION TO ASYNCHRONOUS DRIFT ORBIT

A useful variation of the patrol orbit class is the Asynchronous, or Drift, Orbit. By increasing or decreasing the Semi-Major Axis (SMA) Keplerian parameter, a desired drift rate per day may be achieved. Starting with Kepler's Third Law, the orbital period is related to the SMA by the following equation [3]:

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{1}$$

where T is the orbital period, a is the SMA, and μ is the Earth's gravitational parameter.

To find the period that corresponds to a desired degrees longitude per day rate, set orbital mean motion n using the following relation:

$$n = \sqrt{\mu/a^3} = \omega_\oplus + \Delta\lambda\frac{\pi}{15\,552\,000} \tag{2}$$

where $\pi/15\,552\,000$ is the conversion from degrees longitude per day to radians per second. Rearranging to find SMA for the desired period:

$$a = \left[\frac{\mu}{\left(\omega_\oplus + \Delta\lambda\frac{\pi}{15\,552\,000}\right)^2}\right]^{1/3} \tag{3}$$

where a is the semi-major axis, μ is the Earth's gravitational parameter, $\omega_\oplus$ is the Earth's rotation rate, and $\Delta\lambda$ is the desired drift rate in degrees longitude per day. For the purposes of this paper, only increased SMA was considered, not decreased. This means the $\Delta\lambda$ parameter is always negative, and the orbit will drift westward with respect to the Earth. This drift orbit may also be referred to as a super-geo orbit, as it is marginally above the geo belt.

The chosen drift rate for these studies is fixed at $-5°$ of longitude per day, which corresponds to an SMA of 42,558 km, 394 km above the geo belt with its SMA of 42,164 km. Drifting at $5°$ of longitude per day, a satellite in this orbit will "tour" the whole of the geo belt in 72 days, about 2.5 months. Over the course of the month-long time periods in these trade studies, the satellites in drift orbits will travel through about half of the geo belt.

By changing SMA and holding all other Keplerian elements constant, a satellite in such a drift orbit can switch to a synchronous orbit around a fixed point in the geo belt. Performing maneuvers to drift between fixed patrol orbits around the geo belt may be an important part of a mission. It is useful to note that the time to traverse the geo belt to a desired longitude may be shortened by increasing the drift rate, however this would come at the cost more fuel for larger maneuvers. A sample schedule and Δv budget for these maneuvers can be seen in §8.

3. POINTING CONSIDERATIONS

Perhaps the best and least costly way (in terms of Δv) to gain knowledge of adversaries is to make assumptions about where they are most likely to be. With this in mind, three different pointing strategies specific to geo belt scenarios were developed and simulated in a series of trials. These trials assessed the ability of each pointing strategy to detect threats in the geo belt via optical imaging. The strategies are as follows:

1. FourPiScanning: This strategy is a continuous scan of a Fibonacci sphere of points at a fixed rate. It makes no assumptions about where a threat may be. This makes it a useful baseline, as the performance will not likely drop below the threshold established by this semi-random sky scan. This randomness is noticeable in the results, as FourPiScanning consistently performs worse than the other pointing strategies.

2. OffNadir: This strategy is a geo belt in-plane scan with a fixed offset from nadir. For these studies a 75° offset was chosen. OffNadir attempts to improve performance by choosing the look direction to be either forward or backward in velocity direction at each time step, based on which lighting conditions are most favorable.

3. SolarOpposition: This strategy points the Field of View (FOV) opposite to the spacecraft-to-sun vector at all times. It represents the absolute best lighting conditions at a given time. Its underlying assumption is that the satellite, sun, and target lie in the same plane at least some of the time.

The baseline constellation for these trials consisted of 6 patrol satellites spaced evenly around the geo belt. There were 4 geo belt targets, also evenly spaced. Each trial was one month, centered in time around the solstices and equinoxes, with satellites and targets at 0° of inclination. Both asynchronous and fixed patrol orbits were simulated. The results for these trials are as follows.

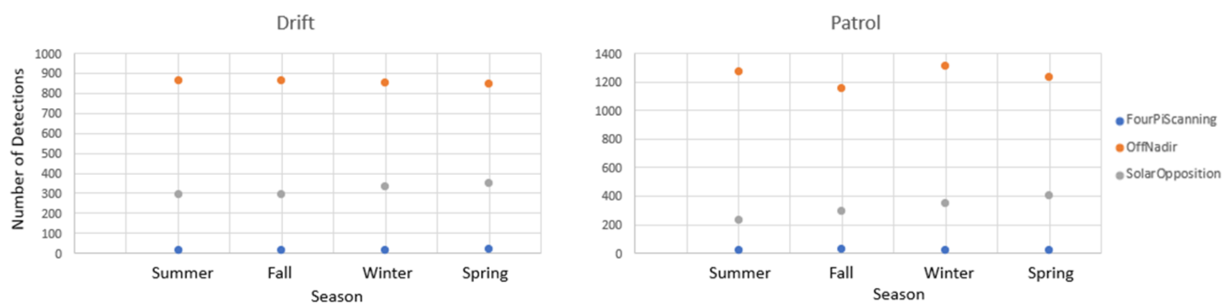

Fig. 1: Comparison of the absolute number of detections for the Asynchronous Patrol Orbit (left) and the Fixed Patrol Orbit (right).

As seen in Fig. 1, the absolute number of detections over the course of a month for the FourPiScanning strategy is low, regardless of the season or orbit type. It is however nonzero, meaning that this constellation can still detect threats that are new and unknown with this strategy. During the month, the FourPiScanning strategy detects the targets a total of about 20 times, and it detects all the targets in the simulation, regardless of challenging geometries.

Perhaps more interesting is the performance of the OffNadir and SolarOpposition scanning strategies. The number of detections by SolarOpposition is in the low hundreds during each month, which means that near-optimal lighting conditions occur. It should be noted that if a target falls within the FOV of an observer using this strategy and is not in an exclusion zone, it will almost always result in a detection due to the excellent lighting conditions. SolarOpposition is also mostly unaffected by the type of patrol orbit, so if targets are expected to be nearly in-plane with the patrol satellite and sun it can be a viable strategy.

The OffNadir strategy returns the most detections in every trial with the parameters used in this study. It returns fewer detections when using the Asynchronous orbit type, due to the fact that the satellites will have periods of time where they are farther away from the targets in the course of their drifting. This effect is seen when employing the other two pointing strategies as well, but since the number of detections is significantly lower, the effect is also much smaller.

Another takeaway from these results is that time of year can affect performance of patrol satellites used to monitor RSOs in the geo belt. Any constellation design must perform simulations at various times of year to fully understand its limitations.

4. MULTI-ASSET PHASING OPTIONS

Another way to improve imaging conditions is to add another asset to an area where greater coverage is desired. To this end, placing a second satellite in the same orbit at a different "phase angle" is explored. This requires changing both the Right Ascension of the Ascending Node (RAAN) and True Anomaly (TA) of the orbits. The correct RAAN depends on the TA and eccentricity (ECC) parameters. With correct application of the relations, 2 satellites orbiting at 180° apart in the same patrol orbit is achievable, as is 3 satellites evenly spaced at 120°.

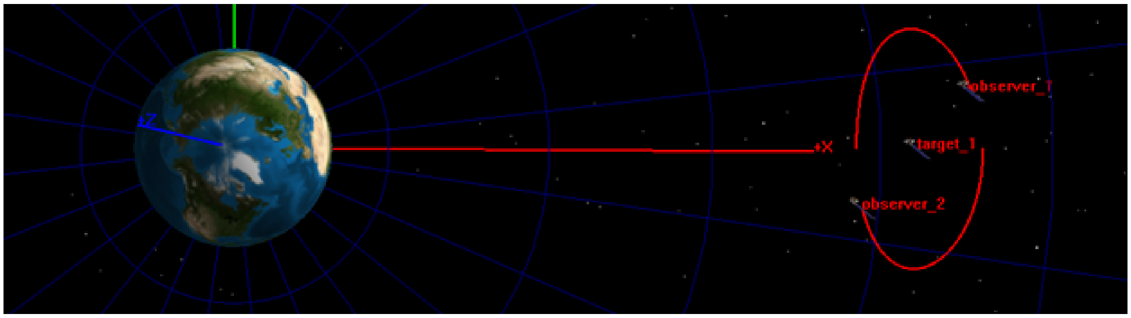

Fig. 2: Two opposing satellites in the same fixed patrol orbit around a target, separated by 180°.

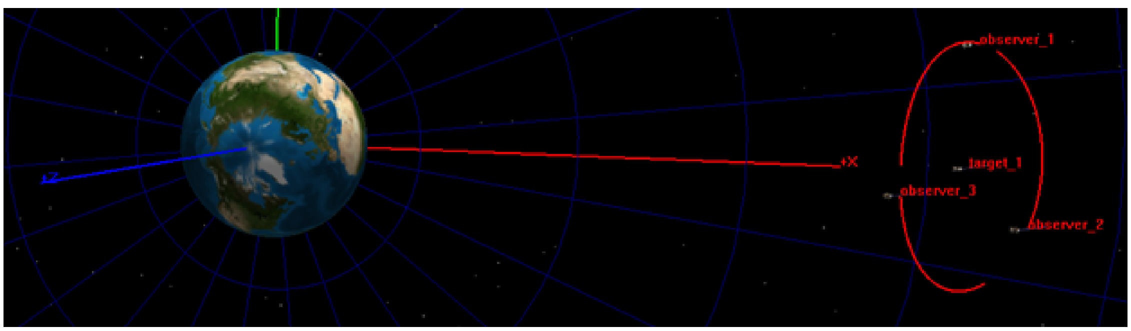

Fig. 3: Three evenly spaced satellites in the same fixed patrol orbit around a target, separated by 120°.

Conducting simulations with the parameters and pointing strategies described in §3 yielded the following results:

First, Fig. 4 shows results for the baseline configuration of a single satellite in a fixed patrol orbit around a target. No detections occurred with the FourPiScanning strategy. OffNadir and SolarOpposition both yielded some detections.

Next, Fig. 5 shows results for two opposing satellites in orbit around a single target. This configuration yields detections in just Summer and Winter for FourPiScanning, and a significant number of detections for the OffNadir and SolarOpposition strategies - approximately double the number of detections of the baseline.

Finally, Fig. 6 shows results for three phased Patrol Satellites in orbit around a single target. The OffNadir strategy continues to increase linearly with the number of satellites, but SolarOpposition sees approximately the same results as for the opposing satellites case. FourPiScanning now has at least one detection in every season.

As expected, the results show an advantage to adding more satellites in patrol orbits around the same object.

Increasing from two patrol satellites to three gives marginal improvements. For the FourPiScanning pointing strategy, the number increase is very small, and not significant. For the OffNadir strategy, the improvement in adding a third patrol satellite is more pronounced, jumping from approximately 80 detections per simulation to 120. The SolarOppositon strategy, however, does not see significant improvement when a third satellite is added. This suggests that without further assumptions or knowledge of the target position, 120 detections is approaching the best possible performance, regardless of the number of additional satellites. This claim remains to be studied.

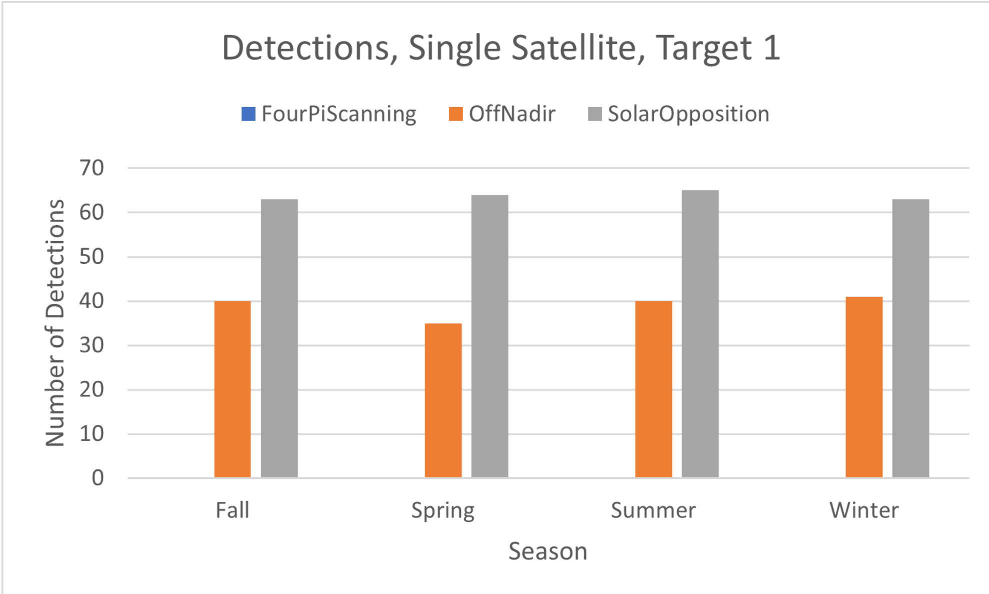

Fig. 4: Number of detections for a single satellite in patrol orbit around a single target.

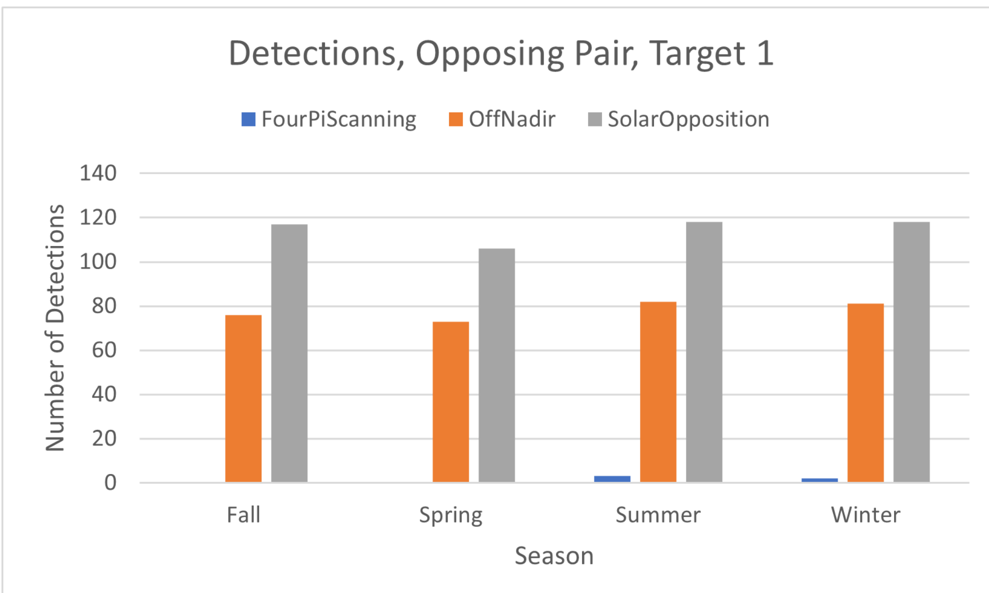

Fig. 5: Number of detections for an opposing pair of patrol satellites at 180 degrees phasing.

Uneven spacing (90° or 45° for two satellites, etc.), could potentially also increase measurement diversity and therefore success of detections, but that is outside the scope of this paper.

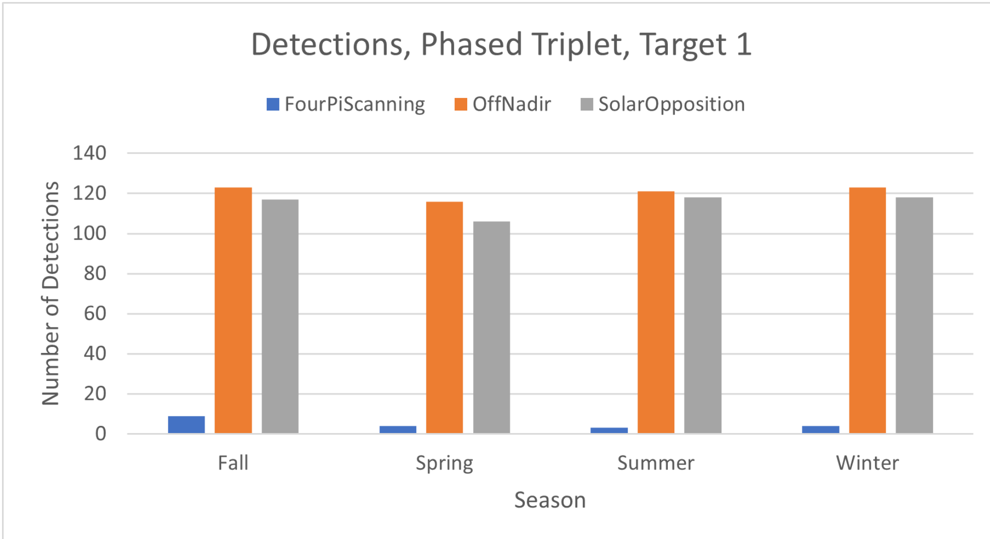

Fig. 6: Number of detections for a phased triplet of patrol satellites in orbit around a target, 120 degrees apart.

5. GROUND SITE COMPARISON AND GROUND SITES AS COMPLEMENT

New and growing observation constellations often incorporate a ground site component. In this section two ground site trials are conducted. The purpose of the first is to compare ground-based observation capability with space-based patrol satellite capability, and to motivate a space-based constellation. The second establishes how ground sites can still be useful as a complement to the space-based assets.

For the comparison portion, two simulations were set up. The first used four ground sites, chosen at points around the world to give constant access to the chosen targets. The second spaced six fixed patrol satellites evenly around the geo belt. Both simulation setups use four target spacecraft, evenly spaced around the geo belt. The ground stations and target layout are seen in Fig. 7.

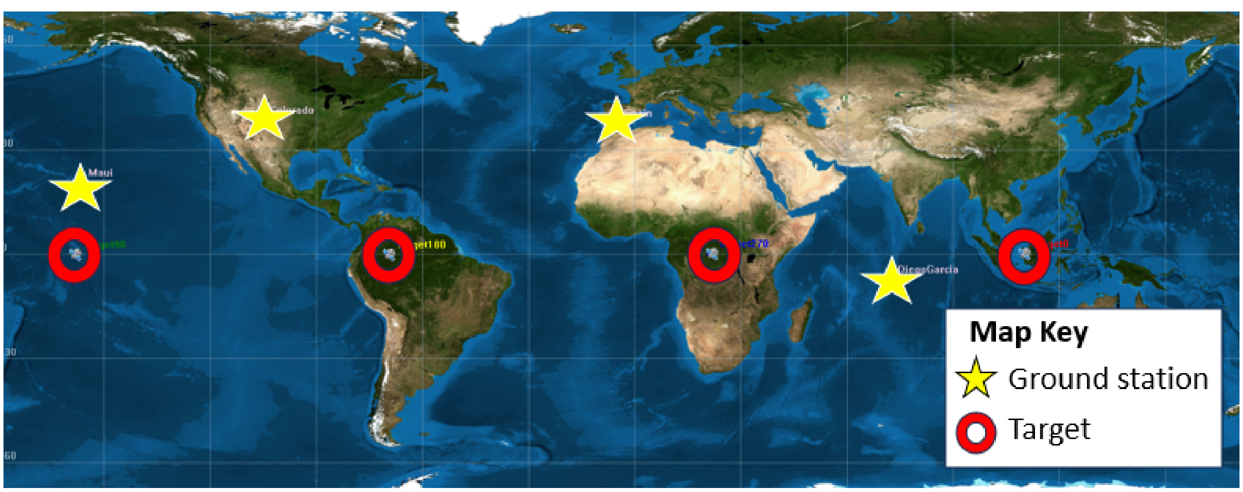

Fig. 7: Position of ground stations and targets for comparison simulation.

Assuming perfect knowledge of the targets' positions, those trials produced the following results:

It is seen in these results that the ground-site only solution does not provide adequate coverage of the target, especially when compared to the 6-ball, completed constellation. The ground sides provide a single detecting observer for a

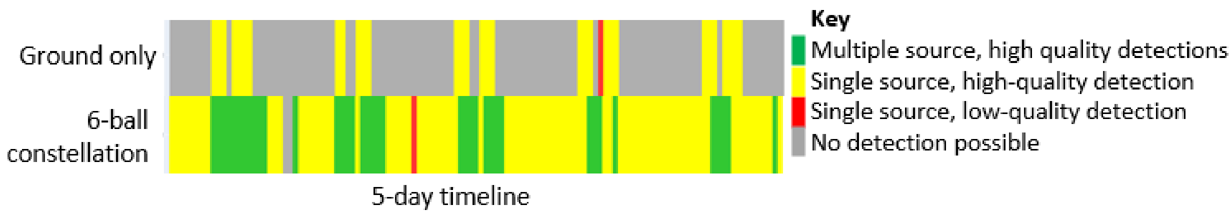

Fig. 8: Results of ground-sites-only trial (top) and 6-ball constellation (bottom). Results are for a representative target with perfect positional knowledge over a period of 5 days.

few hours during the day for the target in question, while the 6-ball constellation provides nearly continuous detections, with periods of multi-observer high-quality detections. This difference in performance is the motivation for a constellation of space-based observers.

However, incorporating ground site capability into a growing constellation is a useful interim strategy. The last trial for this section used the following configuration, combining two ground sites and two fixed patrol satellites, as seen below (Fig. 9).

Fig. 9: Position of ground stations, patrol satellites, and targets for ground complement trial.

The results for this combined study are as follows:

Fig. 10: Results for one target in the combined ground and space-based asset trial.

The results show that it is possible to hand off the ability to detect a target from satellite to ground station at different times of day. The authors are confident that given careful selection of the ground sites and patrol satellite positions, this configuration type can provide near-constant possibility of detection around RSOs of interest.

6. INCLINATION STUDY

Varying inclination yields greater diversity of measurement geometry. Depending on the exact geometries involved, this can increase the likelihood of detection.

For this section, all trials use an 8-ball, evenly-spaced constellation to increase detection, and 24 threats spaced evenly around the geo belt to explore as many geometries as possible. These trials were conducted with observing assets at $0°$, $1°$, $2°$, $5°$, $8°$, and $10°$ of inclination.

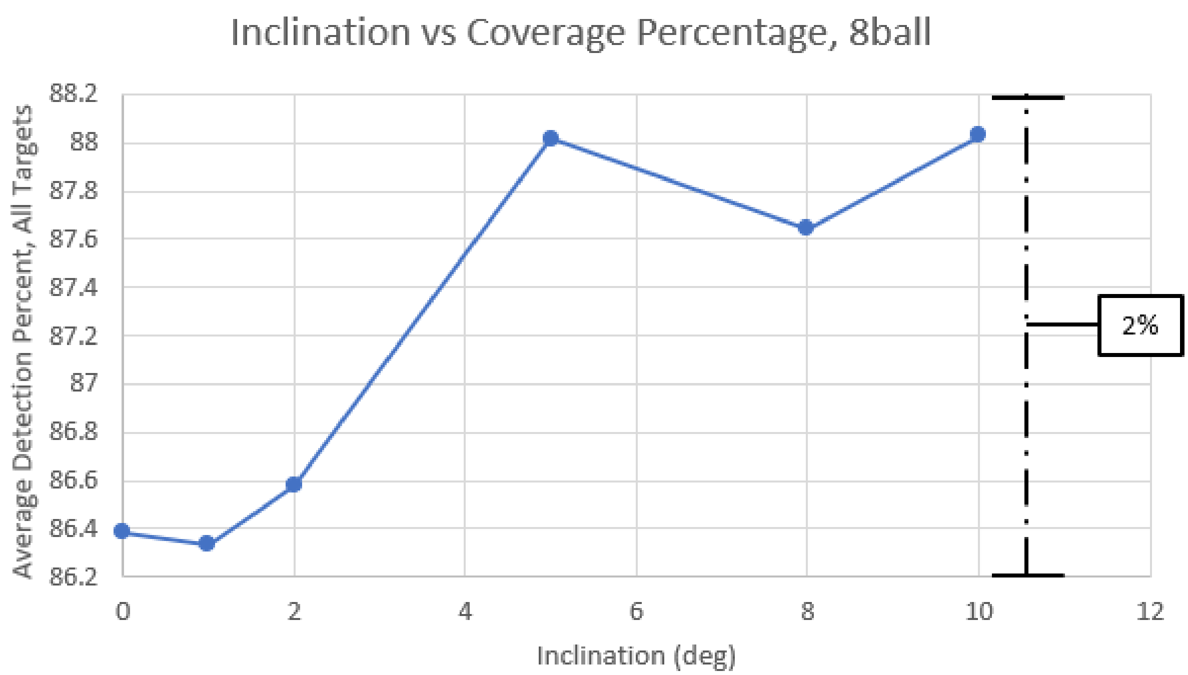

Fig. 11: Results for inclination study. Constellation of 8 evenly-spaced fixed patrol satellites. Inclination varied per x-axis.

Results of the inclination study are shown in Fig. 11. They show an increase with inclination in the average amount of time a target spent being detected by at least one Patrol Satellite over the course of the simulation. The total amount of that increase is 2%.

Higher inclinations are of course possible, but the data show a potential asymptote in performance for higher inclinations, and as our targets are all in the geo belt, allowing observers to spend more time farther away from the targets will only decrease possible detection time. The other drawback with higher inclinations is the high required delta-v associated with inclination changes. To assess how much delta-v an inclination change requires, the minimum amount of delta-v is calculated, assuming that the inclination change can be done from a circular orbit. This assumption allows the following equation to be applied [4]:

$$\Delta v = 2 \sin\left(\frac{\Delta i}{2}\right) \tag{4}$$

The Δv then required for one degree of inclination change is 53 m/s.

If the plane change must be performed from an orbit with eccentricity, as is the case of all patrol orbits, then the following equation applies [4]:

$$\Delta v = \frac{2 \sin\left(\frac{\Delta i}{2}\right)(1 + e \cos(f))na}{\sqrt{1-e^2}\cos(\omega + f)} \tag{5}$$

where f is the True Anomaly, n is the Mean Motion, and ω is the Argument of Perigee. The required Δv for the eccentricity of patrol orbits in this paper is a minimum of 75 m/s.

Increasing inclination yielded some performance gain. When considered in conjunction with the Δv cost to achieve performance-enhancing inclinations, increased inclination may not be the best way to achieve observation-angle diversity.

7. NUMBER OF ASSETS

The number of assets required to achieve a high baseline coverage of the GEO belt is explored. Much of a constellation's performance is determined by the capability of the sensor, so the sensor is assumed to be the same for every asset in the constellation for this portion of the study. Assets are equally spaced at $0°$ of inclination within the geo belt. 24 targets are evenly spaced within the geo belt. These trials assume perfect knowledge of target positions at all times, and are not limited by scheduling constraints. If a target can be detected, it is.

Fig. 12 shows detection type as a percentage of total time on a per-target basis, organized by number of assets.

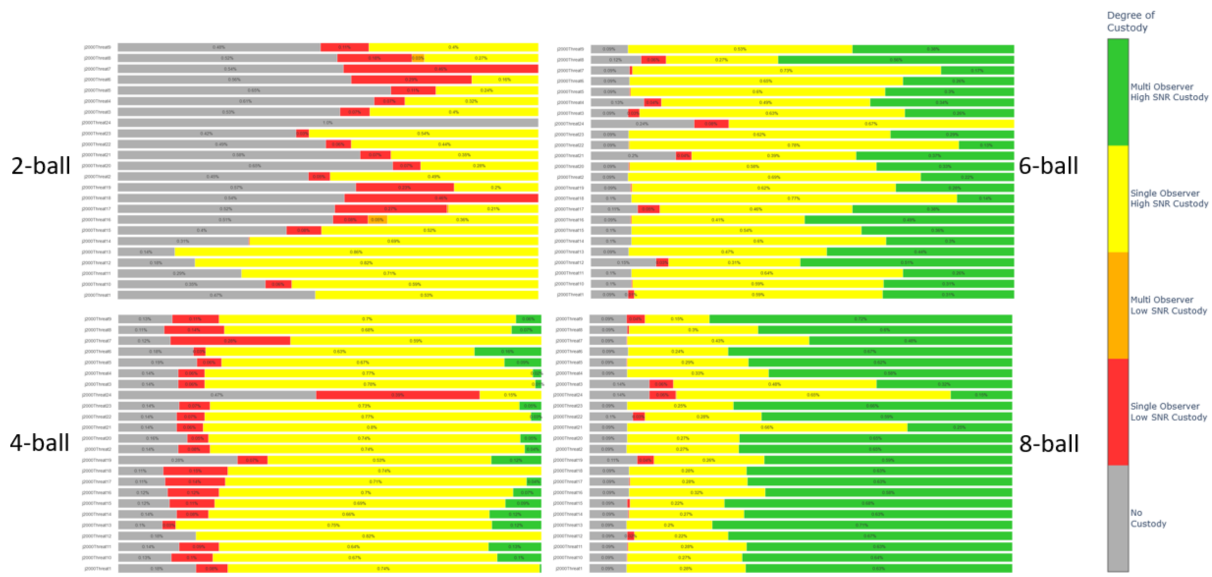

Fig. 12: Plot of the effect of evenly-spaced patrol sat assets along the GEO belt. Upper left: 2 assets at $180°$ separation. Lower left: 4 assets at $90°$ separation. Upper right: 6 assets at $60°$ separation. Lower right: 8 assets at $45°$ separation.

As expected, this plot clearly shows a large increase in the quality of detections and number of assets with high quality detections of targets with increasing number of satellites. The major assumption of this chart is perfect knowledge of target positions. With this, it can be seen that even targets with very challenging geometries (for example the 7th target in each plot, which is the least-detected object in the 4-ball case) can be detected a majority of the time with just 4 satellites in patrol orbits.

When this simulation runs with only asynchronous patrol orbits, the results show similar increases in performance for additional observing assets.

The purpose of this section is not just to state that adding more satellites increases detections, which should be obvious, but to show that the mod-sim tool used in these studies can be used to rapidly evaluate a wide variety of patrol-orbit based configurations. The total setup and run time to produce the plots in Fig. 12 was less than 8 hours.

8. DELTA-V ANALYSIS FOR "SORTIES"

This section deals with the ability of patrol satellites to maneuver between fixed and asynchronous orbits. A "sortie" is defined as cycling from fixed to asynchronous and back to a fixed patrol orbit.

The delta-v required to switch between the asynchronous orbit and the fixed patrol orbit is the delta-v for raising (from fixed to asynchronous) and lowering (from asynchronous to fixed) the SMA. The delta-v can be found by

$$\Delta v = v_2 + v_1 \tag{6}$$

Where v_1 and v_2 can be calculated by using the vis-viva equation [3, 5]

$$v = \sqrt{\mu \left(\frac{2}{r} - \frac{1}{a} \right)} \tag{7}$$

as the basis for a Hohmann transfer [6, 3]

$$\begin{aligned} v_1 &= \sqrt{\frac{\mu}{r_1}} \left(\sqrt{\frac{2r_2}{r_1 + r_2}} - 1 \right) \\ v_2 &= \sqrt{\frac{\mu}{r_2}} \left(1 - \sqrt{\frac{2r_1}{r_1 + r_2}} \right) \end{aligned} \tag{8}$$

where μ is the gravitational parameter of earth, r_1 is the distance of the spacecraft from the earth's center of gravity at apogee for the initial orbit, r_2 is the distance of the spacecraft from earth's center of gravity at perigee for the target orbit, and a is SMA. Using ellipse geometry, r can be expressed in terms of SMA, Eccentricity, and True Anomaly, all of which are known for both orbit types.

$$r = \frac{a(1 - e^2)}{1 + e \cos(\theta)} \tag{9}$$

where θ is the true anomaly (TA). Setting θ to $0°$ gives the distance at perigee (r_2), while setting θ to $180°$ gives the distance at apogee (r_1).

Combining these equations, it is seen that the delta-v for changing between these two orbit types is about $13.6m/s$. To plan "sortie" operations over the course of a year, when switching between these orbits every 3 months, multiply that value by 4 to get $54.5m/s$ for the example year of sorties.

Maneuver	Month of Year	Longitudinal Location	Δv (m/s)
Transfer from asynch to fixed	February	30° East	13.6
Transfer to asynch	June	30° East	13.6
Transfer to fixed	July	150° West	13.6
Transfer to asynch	December	150° West	13.6
		Total Δv	54.4

Table 1: A sample schedule and Δv requirements chart for moving between Fixed and Asynchronous Patrol Orbits over the course of a year. This schedule "tours" half the geo belt in that time, with 6-month stays at 2 different longitudes.

With the typical drift rate of $5°$ longitude westward per day, the sample schedule in Table 1 shows a drift of $180°$ longitude around the geo belt, which occurs in 36 days.

9. CONCLUSIONS

Assets in Geosynchronous Patrol Orbits maybe used in a variety of ways to execute a Space Domain Awareness mission. The case for having space-based assets in the GEO belt is strong, as many of the assets in that domain are extremely high value. Optimization of such missions is essential for the continued assured operation of such assets. In this paper the authors explored a number of configurations for a GEO-based patrol constellation, and identified ways to optimize such a constellation. More assets, no or low inclination, "sorties" to move assets around the GEO belt, monitoring of RSOs by multiple patrol sats, and a ground-segment complement are the ways identified to improve coverage within the GEO belt.

10. FUTURE WORK

This trade study was performed for a limited number of variables. The authors recommend the following continuations:

1. Simulations that integrate "sorties" into a constellation simulation.
2. Simulations of different incoming threat trajectories.
3. Performance of a range of sensors.
4. Simulations of unevenly-spaced phased assets (Spaced at $90°$, $45°$, etc. in TA)

Disclaimer

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the United States Air Force, United States Space Force, Department of Defense, or the U.S. Government.

References

[1] Thompson B, Kelecy T, Kubancik T, Flora T, Chylla M, Rose D, "Geosynchronous Patrol Orbit for Space Situational Awareness," *Advanced Maui Optical and Space Surveillance Conference (AMOS)*, 2017. https://amostech.com/TechnicalPapers/2017/Poster/Kelecy.pdf

[2] Soop EM, *Handbook of Geostationary Orbits*, Springer-Science+Business Media, Dordrecht, Netherlands, 1994.

[3] Vallado DA, *Fundamentals of Astrodynamics with Applications*, 5th ed., Microcosm Press, Hawthorne, California, 2022.

[4] Braeunig, RA, *"Basics of Space Flight: Orbital Mechanics,"* archived from the original on 2012-02-04. Retrieved 2023-07-31. http://www.braeunig.us/space/basics.htm

[5] Logsdon T, *Orbital Mechanics: Theory and Applications*, John Wiley & Sons, New York, 1998. ISBN 978-0-471-14636-0

[6] Hohmann W, *The Attainability of Heavenly Bodies*, Technical Translation F-44, National Aeronautics and Space Administration, Washington, 1964. https://archive.org/details/nasa_techdoc_19980230631