A Constellation of Sensors Optimized for Maneuver Tracking

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INTRODUCTION

Lockheed Martin Space has been studying architectural solutions that could better address maneuvering objects at geosynchronous earth orbit (GEO) and provide timely observations following those maneuvers in GEO. Space Domain Awareness (SDA) has always been a challenge and, recently, there has been a lot of concern about what proliferation will do to this challenge. In a June 2019 article written for SpaceNews, LeoLabs founder and CEO Daniel Ceperley said "There's a lot more maneuvering going on. Keeping track of those maneuvers and feeding those into collision prediction services has been a challenge in the past." [1]. Although Ceperley is referencing low earth orbit (LEO) in this article, the applicability exists for all orbits as satellites and launches become more affordable and accessible. The result being that space is becoming more congested as more and more entities are launching satellites into all orbits.

The size of CubeSats, in particular, makes it difficult to track and even more difficult to predict where they are going to be when they change position or come close to another satellite. When you add debris created from launches, decommissioned satellites not in the graveyard orbit, and expected on-orbit collisions, the result only adds to the increasing need to keep an accurate catalogue of objects and events and update that catalogue quickly as the situation changes. Fig. 1 highlights all the cataloged items in space whether it be a satellite (red), rocket body (blue), or debris (grey) that are trackable.

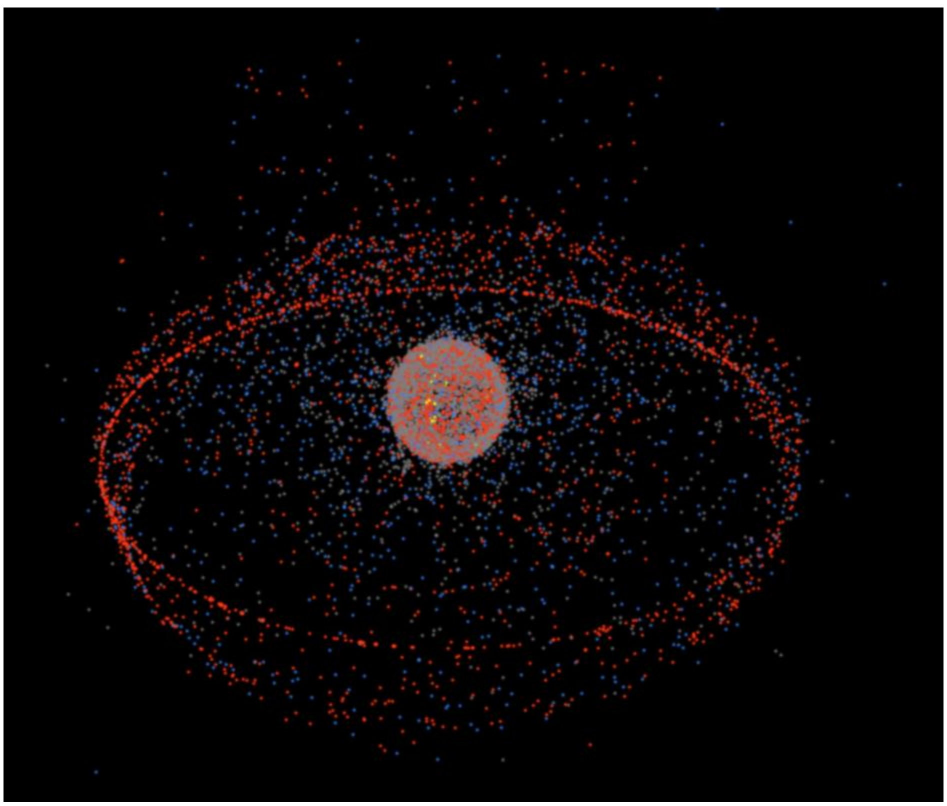

Fig. 1. Screenshot of James Yoder's "Stuff in Space" website [2]

As proliferated LEO constellations have become more common in the recent years with large constellations like OneWeb and Starlink, it is important to look ahead and focus on how large constellations in other orbits, like GEO, will affect SDA. It is only a matter of time before proliferation hits GEO. This will exponentially increase the number of objects at GEO as well as maneuvering objects at GEO. It is imperative to look at different architectures that can help determine what sensors could be used to effectively track these movements. Traditionally ground-based telescopes are used for these observations as well as a few space based systems; however, numerous space-based sensors in-situ to the environment such as GEO, could provide more accurate and timely data output. Ground based optical sensors also, generally, have solar exclusion zones and have trouble tracking when the sun is overhead. This can lead to gaps in coverage of the important objects in GEO. Ground based optical systems have a higher sensitivity and their locations are very well known, which helps reduce the orbit error. A balance of accuracy and minimized gap periods between observations is necessary to quickly predict collisions. Looking at various sensor parameters can help understand what characteristics space-based sensors should invest in. For example, larger fields of view will help with area coverage but will reduce sensitivity and have larger solar keep out zones. Also, the number of satellites can have a large effect performance of the architecture but comes with an increased cost. Using this high-level background information on various sensors, Lockheed Martin developed various scenarios in Matlab and Systems Tool Kit (STK) to analyze space-based sensors along with other key factors that would most effectively reduce the coverage gap within the GEO belt. The purpose of the study is to develop high level conclusions about basing orbits, sensor parameters, hosting options, among others. The conclusions will inform more detailed trades that need to be performed that balance space and ground sensors as well as data management and fusion.

ARCHITECTURAL STUDY/ METHODOLOGY

For this study, the focus was on what space-based sensors and constellation designs provide the most value in terms of coverage and observation gap periods. Varying parameters such as altitude above GEO, sensor characteristics, and field of view among others will provide insights into interdependencies and diminishing returns. There are too many variables to truly optimize a GEO based system without performing a complex systems of systems trade study, but this study was the high-level start to this more detailed analysis. Table 1 highlights the five space-based sensors that were applied to this study. These are representative sensor parameters and not based on any specific sensor to understand the performance variability. These sensors were applied to various orbits and constellation sizes and analyzed to determine coverage and observation gap periods. For this analysis, it was assumed that the sensor was pointed along the velocity vector and staring. No slew profile was included. Several sensor offsets were used to understand the sensitivity to canting the sensor field of view as the altitude above GEO was increased.

Table 1 – Representative Sensor Parameters Studied

	Field of View (degrees)	**Detection Range (km)**	**Solar Exclusion (degrees)**
Sensor #1	5	30,000	15
Sensor #2	15	10,000	30
Sensor #3	30	5,000	60
Sensor #4	60	3,000	90
Sensor #5	180	1,000	180

Analysis Methodology

The analysis for this particular study required the use of a simulation software – in this case, STK (Systems Tool Kit, courtesy of AGI). To automate the process of creating constellations and extracting access data, an STK scenario was paired with a MATLAB script, wherein specific integration code was used to allow the two programs to interact. Several scripts were used to test the varying parameters: Each had an identical base but was lightly modified to fit the needs of each individual study. Once the script was run for a set of constellations and the required access metrics were calculated, the raw data was exported to a .xlsx file to be filtered, plotted, and analyzed in Microsoft Excel.

To begin, an orbit epoch and desired analysis period were outlined in the scenario properties. Most of the constellations tested were analyzed for one full day, with an epoch in mid-August 2020. Secondly, there needed to be a field of resident space objects (RSO) in the scenario to be cross-checked with each hypothetical constellation. A two-line element (TLE) catalog of GEO objects from space-track.org was acquired as a bulk download and imported into STK, constrained to objects of up to 15º inclination for this study. Fig. 2 shows a single scenario in STK with the sensor field of view and the catalogue of GEO objects.

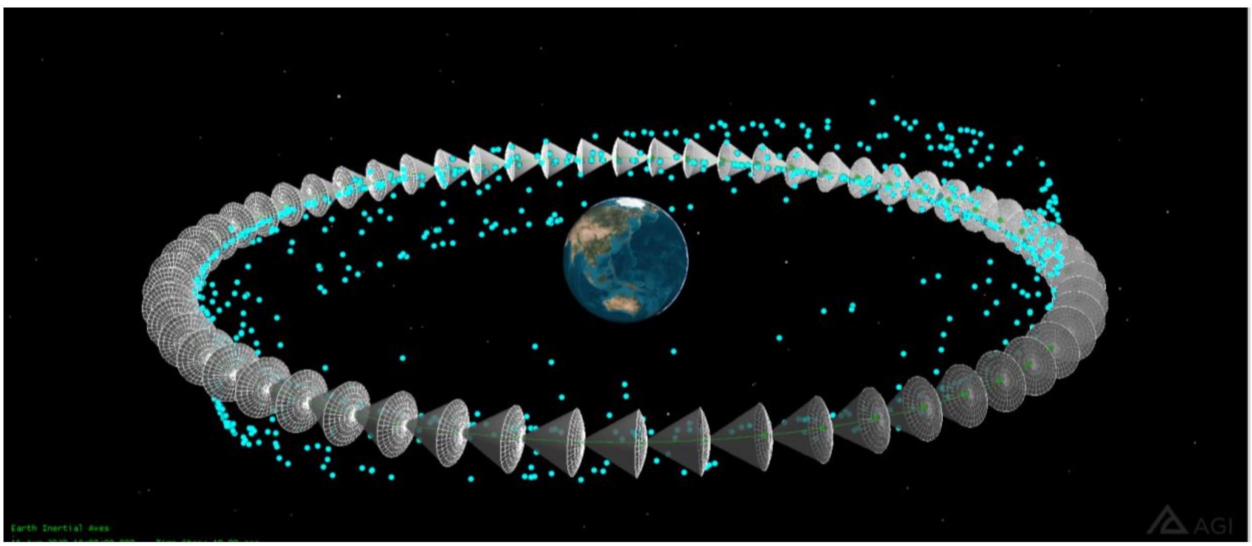

Fig. 2. Representative STK scenario used in the analysis

Access Metrics and Gap Analysis

Following the construction of the constellation, the MATLAB script begins to investigate the access data for each RSO. All satellites are pulled from STK and are classified by constellation object or RSO by a specific naming convention applied in the creation of the structure. For each RSO, the script adds the satellite to the chain object as the second access parameter following the constellation of sensors, and computes access. It proceeds to access relevant data providers in STK to pull information about the quantity and duration of all accesses into MATLAB. This data is then used to calculate gap times and in-turn, access coverage. For example, if the number of accesses is 1, then the gap time is equal to the difference between the analysis period and the access duration, and the access coverage percentage is equal to the quotient of the gap time and the scenario duration, subtracted from one.

Once these calculations are performed for an RSO, the script determines the maximum gap time for any satellite with multiple breaks in access and stores this value in a separate array. The access coverage values for each RSO are also appended to a separate array. The script then removes the satellite from the chain object in STK and repeats the whole process for each subsequent RSO in the scenario. Once every RSO in the scenario has been evaluated, the average max gap period and average access coverage percentage are determined for the constellation and stored in a separate matrix. The script will then reset all the previous values and test the next constellation in the queue. Once all the constellations in the set have been evaluated, the matrix containing the max gap and access coverage information is exported to a separate file and analyzed in Microsoft Excel.

ANALYSIS RESULTS

The analysis was run with varying parameters for numbers of satellites, the different sensor types, altitude above GEO as shown in Fig. 3 below. While not an all-encompassing analysis, these parameters provide insight into the trends and will help inform a much more detailed systems of systems analysis. Fig. 3 below shows the data for Sensor 1 across the altitudes as wells as constellation sizes. This was done with a zero-degree sensor offset, meaning that the sensor boresight is pointed along the velocity vector. Fig. 3 highlights this as the sensor 1, with a smaller field of view, loses performance as the altitude gets higher because less of the field of view is located on the GEO belt. Other cases increased the sensor offset.

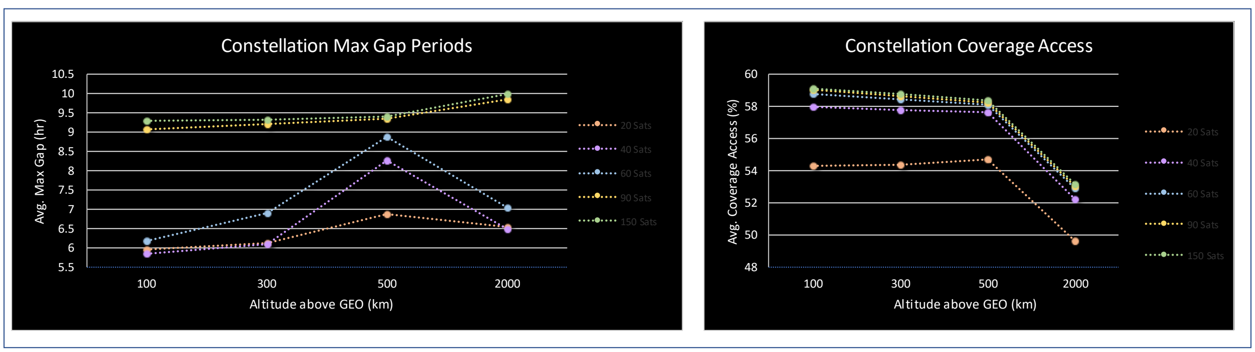

Fig. 3. Sensor 1 Orbit Analysis with a 0 Deg Sensor Offset

Based on the cases that were run, it can be difficult to compare statistics across the different architectures and sensor types. Some architectures perform very well in coverage but not in the average max gap period. Optimized architectures should balance the two parameters. Fig. 4 is an attempt to show all of the cases compared against each other for the average max gap period and custody measures of effectiveness.

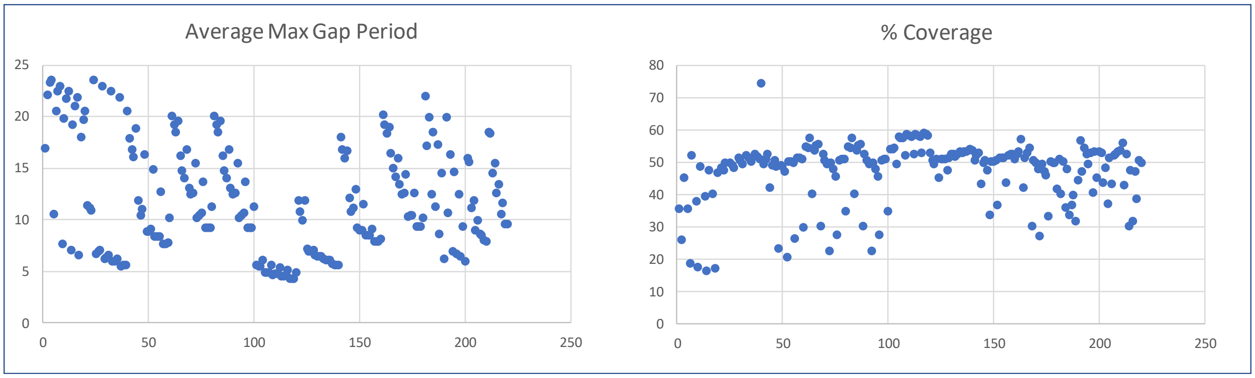

Fig. 4. Each architecture case compared against each other

Finally, sensitivity analyses were performed on the sensor parameters to understand the individual impacts of each parameter on the architecture performance. For example, is the field of view of the sensor more important than the detection range? How does the solar exclusion affect the performance? Fig. 5 shows a few of these analyses.

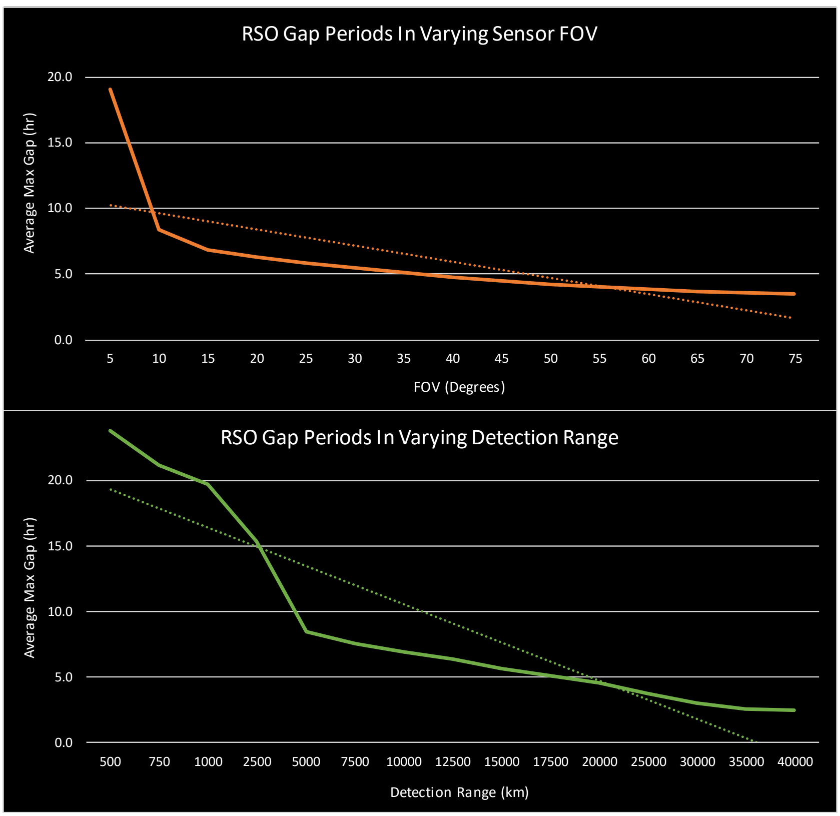

Fig. 5. Sensitivity Analysis against field of view (FOV) and detection range

IMPLEMENTATION

While the analysis above can easily show what parameters are more valuable in terms of space situational awareness (SSA) performance, they do not provide an assessment of how it will be implemented and the cost to implement. One important aspect to consider are the different platforms that can host these various sensors. Hosted payloads are one option that comes with its own set of challenges. For example, securing payload slots on various satellites that will effectively be spread around the GEO belt to cover relevant longitudes is a time and risk consuming approach. Depending on the size of the sensors, finding a satellite to host can be very challenging as well. Factoring in the timeliness of launches in order to have an up-and-running constellation is yet another challenge. On the other hand, CubeSats have become more reliable with maturing technologies that are cost effective. CubeSats also typically have a more flexible timeline as they are not the primary payload driving the overall launch and schedule. As launch providers work to drive down the costs, it becomes more realistic to launch many CubeSats at once rather than larger satellite platforms individually. CubeSats have their own disadvantages in capability. The larger sensors cannot be hosted on CubeSats due to size, weight, and power constraints as well as pointing limitations. Another drawback of CubeSats is their lifetime. The shorter lifetimes will require more replenishment satellites and, therefore, more launches. Microsatellites can host larger, more capable SDA sensors and, if size constrained, can still be a rideshare with other primes or on ESPA slots. The lifetime of these satellites are higher than CubeSats but their per unit costs will also be higher. Comparing the different constellations' performance against cost (Fig. 6) is a useful way of grounding the analysis and considering the holistic view. For this analysis, several factors were included in the rough cost estimate. The Non-recurring and recurring engineering of the design and build of the satellite and sensor along with the launch costs were included in the cost estimate. These were based on a 15-year mission which also included replenishment satellites as well as the associated replenishment launches. Ground operating costs were also included.

In order to provide a performance versus cost ratio, the Average Max Gap was converted to an availability number to have a high number in the numerator and divided by the cost of the architecture. This is a crude way to compare the different architectures but does provide a top-level comparison. For coverage, the percentage was divided by the cost and multiplied by 1000 to get whole numbers.

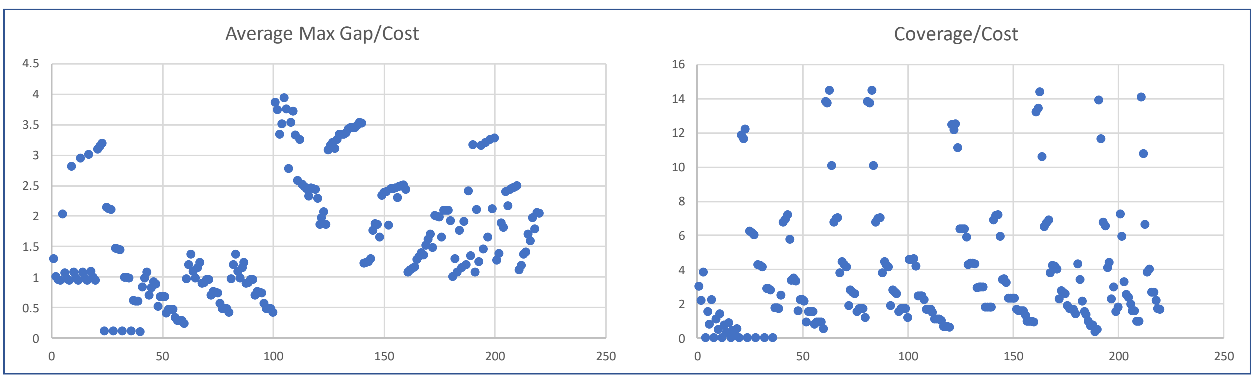

Fig. 6. Performance Parameters Divided By Cost Shows More Valuable Architectures

Based on Fig. 6, several correlations can be drawn. A few peaks of performance in the Average Max Gap plots show the optimum architectures for minimizing that gap. Table 2 below shows the 4 clustered peaks and the architecture values. Table 3 below shows the 5 peaks for coverage over cost.

Table 2 – Comparison of the Different Peaks for Gap/Cost

	Peak 1	Peak 2	Peak 3	Peak 4
Sensor	Sensor 2	Sensor 1	Sensor 2	Sensor 2

Constellation Size	20	40	150	150
Altitude	500 km	100 km	500 km	2000 km
Sensor Offset	0 Deg	15 Deg	15 Deg	30 Deg
Satellite Class	Microsat	Microsat	Microsat	Microsat

Table 3 – Comparison of the Different Peaks for Coverage/Cost

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5
Sensor	Sensor 4	Sensor 5	Sensor 5	Sensor 2	Sensor 5
Constellation Size	20	20	20	20	20
Altitude	500 km	500 km	500 km	500 km	500 km
Sensor Offset	0 Deg	0 Deg	15 Deg	30 Deg	30 Deg
Satellite Class	CubeSat	CubeSat	CubeSat	Microsat	CubeSat

Looking at these results from Tables 2 and 3, it shows that to minimize gap periods, the microsats with sensor 2 (15 Deg FOV) provides the best performance overall from the 500km orbit. There are also a few cases where the higher number of satellites provides a high overall value as well. For coverage, the wider field of view sensors generally provide the most value while the 500 km orbit seems to be the best basing location. Also of note: the higher constellation sizes did not provide as much value. The added performance of more sensors does not offset the costs associated with the larger constellation. These are just some of the analysis observations as there are numerous ways to interpret the data.

CONCLUSION

This analysis was meant as a starting point to understand the factors and trends in space-based GEO SSA constellations with a focus on timely observations to detect maneuvers and propagate following those maneuvers. The results do show that a space-based system can provide significant benefits and timely observations that will augment the ground based SDA systems. Further analysis is required at greater depths to truly optimize a GEO based constellation. In addition, slew and scan patterns should be added along with modeling of the jitter and drift effects of the platform to provide a realistic assessment of the performance. Also, additional parameters such as a mixed constellation above and below GEO as well as velocity and anti-velocity vector pointing will help maximize the constellation performance. This analysis should be incorporated into a system of systems analysis that includes ground based, space based, and multi-phenomenology sensors and basing locations. This would drive the requirements for a space-based architecture and potential future acquisitions.

REFERENCES

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[2] James Yoder, *Stuff in Space*, 2015, stuffin.space.