



**OPTIMIZATION OF GEOSYNCHRONOUS SPACE SITUATIONAL
AWARENESS ARCHITECTURES USING PARALLEL COMPUTATION**

THESIS

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AFIT-ENV-MS-18-M-202

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

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THESIS

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Michael S. Felten

Major, USAF

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Abstract

Improving Space Situational Awareness (SSA) remains one of the DoD's top priorities. Current research at the Air Force Institute of Technology (AFIT) has shown that modeling and simulation of Geosynchronous Earth Orbit (GEO) SSA architectures can identify optimal combinations of ground and space-based sensors. This thesis extends previous research by expanding design boundaries and refining the methodology. A genetic algorithm examined this increased trade space containing 10^{22} possible architectures. Experimental trials that would have taken over 100 years on a desktop computer were completed in weeks using a high-performance computer containing over 125,000 cores. The results of the optimizer clearly favor 1.0-meter aperture ground telescopes combined with 0.15-meter aperture sensors in a 12-satellite polar GEO constellation. The 1.0-meter aperture ground telescopes have the best cost-performance combination for detecting Resident Space Objects (RSOs) in GEO. The polar GEO regime offers increased access to GEO RSOs since other orbits are restricted by the 40° solar exclusion angle. When performance is held constant, a polar GEO satellite constellation offers a 22.4% reduction in total system cost when compared to Sun Synchronous Orbit (SSO), equatorial Low Earth Orbit (LEO), and near GEO constellations. This methodology has much greater utility than simply GEO SSA architecture evaluation. Scripting and parallel high-performance computing opens the possibility of solving an entirely new class of problems of interest to the DoD. The results of this research can educate national policy makers on the benefits of various proposed upgrades to current and future SSA systems.

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I greatly appreciate the guidance and mentorship I received from this committee. The utility of this project was greatly enhanced through their expert direction. I envision the results of this research guiding future satellite and ground sensor acquisitions toward the most beneficial technologies. I would like to thank the generous men and women at Analytical Graphics Incorporated for the educational use of their STK Engine. I would also like to give a special thank you to the other members of the space modeling and simulation team and wish them the best as they move forward in their respective careers. Most importantly, I would like to thank my loving wife for supporting me as I worked through this endeavor.

Michael S. Felten

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List of Acronyms

AFIT	Air Force Institute of Technology
AGI	Analytical Graphics, Incorporated
CubeSat	Cube Satellite
DoD	Department of Defense
DSRC	DoD Supercomputing Resource Center
FOR	Field of Regard
GA	Genetic Algorithm
GEO	Geosynchronous Earth Orbit
GEODDS	Ground-Based Electro-Optical Deep Space Surveillance
GUI	Graphical User Interface
HPC	High-Performance Computer
IAA	International Academy of Astronautics
JDMS	Journal of Defense Modeling and Simulation
ICBM	Intercontinental Ballistic Missile
ICSSA	IAA Conference on Space Situational Awareness
LCC	Life-Cycle Cost
LEEDR	Laser Environmental Effects Definition and Reference
LEO	Low Earth Orbit
MOGA	Multi-Objective Genetic Algorithm
NASA	National Aeronautics and Space Administration
NICM	NASA Instrument Cost Model

NOCM	NASA Operations Cost Model
PSO	Particle Swarm Optimization
RSO	Resident Space Object
SA	Simulated Annealing
SBSS	Space-Based Space Surveillance
SE	Systems Engineering
SNR	Signal to Noise Ratio
SSA	Space Situational Awareness
SSCM	Small Satellite Cost Model
SSN	Space Surveillance Network
SSO	Sun-Synchronous Orbit
SST	Space Surveillance Telescope
STK	Systems Tool Kit
USCM	Unmanned Space Vehicle Cost Model

OPTIMIZATION OF GEOSYNCHRONOUS SPACE SITUATIONAL AWARENESS ARCHITECTURES USING PARALLEL COMPUTATION

I. Introduction

Statement of the Problem

Detecting and tracking smaller and smaller Resident Space Objects (RSOs) is a significant step toward improving Space Situational Awareness (SSA). However, in the current congested, contested, and competitive space domain (Dacres, 2016), continuous observation of some orbital regimes is required. One orbital regime of particular interest due to its unique orbital period is Geosynchronous Earth Orbit (GEO). The ability to predict non-friendly maneuvers—which is critical in the protection of our high-value space assets—is dependent on high-fidelity GEO SSA (Brissett, 2017). Knowledge of who is operating what systems, the capabilities of those systems, and awareness of typical day-in-the-life operations are all required to maintain awareness and guarantee attribution for all activities in GEO.

The problem is the current Space Surveillance Network (SSN) architecture is unable to provide continuous coverage of all RSOs in GEO. Gaps in coverage and a lack of capable assets to maintain custody of RSOs are the two biggest limitations of the SSN (Abbot & Wallace, 2007). Combining these limitations with the increasing number of satellites in orbit and the increase in covert RSO maneuvers further exacerbates the current GEO SSA problem. This research specifically addresses this problem by proposing an optimal combination of ground and space-based sensors that provides near continuous observation of the 813 RSOs in GEO as identified by the 2016 spacetrack.org catalog.

Research Objectives

The purpose of this research was to propose a near-optimal architecture for effective and efficient high-fidelity GEO SSA and identify how that architecture varies throughout the year. Because the Department of Defense (DoD) operates in a financially constrained environment, total life cycle cost of the GEO SSA system was weighted equally with the minimum detectable RSO size and the overall latency of the system. This ensured the optimizer identified the most cost-effective architecture.

Investigative Questions

The specific research questions this thesis answers are:

1. What combination of ground and space-based sensors provide the most cost-effective architecture for a high-fidelity GEO SSA system?
2. How does the optimal architecture change throughout the year because of Earth-Sun angle variations?

Thesis Overview

This thesis includes two major sections: ‘Optimization of GEO SSA’ and ‘GEO SSA Extensions: Polar GEO and Twilight Imaging’. The first section was written during the preliminary phase of data generation. During this phase, the focus of the research was on improving the optimizer enough to allow an expansion of the trade space. This would allow expansion beyond previously identified upper bounds as well as investigation of entirely new orbital regimes. Preliminary trials demonstrated the utility of Particle Swarm Optimization (PSO) over Multi-Objective Genetic Algorithm (MOGA). However, enhancements in other components of the methodology facilitated the necessary trade

space expansion. These enhancements included: elimination of redundant tasks, improved efficiency for job submission, doubling population size to 192, halving the number of generations to 50, accelerated data verification, increased parallelization via distribution to more nodes, and improved data generation reliability. Since these enhancements facilitated expansion of the trade space to 1000 times larger than the foundational methodology, focus shifted from improving the optimizer to examining the trade space.

The second section of this thesis, ‘GEO SSA Extensions: Polar GEO and Twilight Imaging’, focuses on the results of the trade space analysis. Enhancements to the foundational methodology include: examination of the polar GEO regime, ground-based twilight imaging, satellite learning curve evaluation, and expansion of the orbital trade space. This section was written after all the results were identified and analyzed. Results using the foundational methodology (Stern, Wachtel, Colombi, Meyer, & Cobb, 2017) are included as well as results from the expanded methodology. The new results obtained with the foundational methodology link the results from the expanded methodology. This facilitates an incremental improvement in the overall methodology rather than an entirely new approach with potentially unverified results. Verification of the expanded methodology was accomplished by eliminating any potential bias from the satellite learning curve. This ensured the selection of any particular satellite orbital plane was solely based on the advantages of that orbital regime.

The final section of this thesis discusses overall conclusions from this research. These conclusions summarize the final chapter of the journal article. This section also highlights the significance of the findings from this research. Finally, it recommends future areas of study and actions that should be taken as a result of this work.

II. Optimization of GEO SSA

This section of the thesis contains a conference paper that was accepted to the first annual International Academy of Astronautics (IAA) Conference on Space Situational Awareness (ICSSA) on August 1st, 2017. The paper was published on November 7th 2017 and presented to the ICSSA on November 14th, 2017.

ABSTRACT

Maintaining Space Situational Awareness (SSA) of the operational activities in the space domain remains one of the DoD's top priorities. In the ever-increasing congested and contested space environment, assuring operators and maintainers have the right mix of sensors to meet SSA requirements is paramount. Gaps in coverage and a lack of capable assets to maintain custody of Resident Space Objects (RSOs) limit the ability to provide persistent SSA. Current research at the Air Force Institute of Technology (AFIT) has shown that a genetic algorithm can provide utility in identifying optimal Geosynchronous Earth Orbit (GEO) SSA architectures given incremental improvements on commonly used ground-based and space-based optical systems. This paper expands the previously identified boundaries by examining different optimization techniques such as Simulated Annealing (SA) and particle swarm optimization, while updating the launch and operational cost models, improving the inherent scheduling algorithms, and incorporating emerging technologies such as ground-based daylight imaging in order to refine the output of the previous research. Specifically for this paper, a GEO SSA scenario is explored. The updated model will more accurately define the cost and performance tradeoffs of any given GEO SSA architecture and the merits of the different optimization techniques are reported

and compared. The results of this research can be used to educate national policy makers on the costs and benefits of various proposed upgrades to the current and future SSA architectures.

INTRODUCTION

There has been an exponential growth in the space domain in the last decade. Cheaper access to space has broken the previous barriers to entry for companies and nation states. Maturing rocket technology and the emerging field of CubeSats are the two primary factors driving this trend. Earlier this year, India launched 104 satellites into Low Earth Orbit (LEO) from a single rocket (Barry, 2017). As the number of satellites in space increases, the probability of a collision also increases. In order to minimize the likelihood of an unintentional collision, improved Space Situational Awareness (SSA) is required.

The space domain has grown from a force multiplier to a warfighting domain itself (Smith, 2017). Like land, sea, and air, space will be a domain for future struggles for power. The ability to have insight into tactics, techniques, and procedures of our adversaries is paramount. Persistent SSA is the foundational requirement needed to provide our top-level leadership a clear picture of what is going on in the space domain.

All Resident Space Objects (RSOs) larger than 10 cm are currently tracked via the United States Space Surveillance Network (SSN). Figure 1 illustrates the approximated 29,000 objects in orbit greater than 10 cm (Wiedemann, 2016).



Figure 1. Space objects larger than 10 cm (Wiedemann, 2016)

The 10 cm threshold for RSO tracking was not selected because smaller objects are of no concern to operational satellites. It was chosen because of the inability of the current system to detect objects smaller than 10 cm (M. Baird, 2013). Since these objects are not actively tracked, they do not have orbital predictions that could provide an operational satellite warning of a close approach. Because of this, objects smaller than 10 cm pose the greatest passive threat to today's operational satellites. Objects as small as 1 mm carry enough energy—traveling at 7 kilometers per second—to cripple an operational satellite. Figure 2 below illustrates the predicted number of objects 1 mm or larger currently in orbit.



Figure 2. Space objects larger than 1 mm (Wiedemann, 2016)

The newest Air Force SSA sensor ORS-5 launched in August of 2017. Also known as SensorSat, this satellite operates in a LEO equatorial orbit designed to maximize the detection capabilities of Geosynchronous Earth Orbit (GEO) RSOs. When this sensor becomes operational, it will improve the SSN ability to maintain custody of the current GEO space catalog (Brissett, 2017). In 2018, the re-introduction of the Air Force's Space Fence will drastically improve detection capabilities of small RSOs in GEO. Together, these will complement existing SSA provided by GEODDS, SST and SBSS.

Detecting and tracking smaller RSOs is a significant step toward improving SSA. However, in the current congested, contested, and competitive space domain (Dacres, 2016), the problem extends beyond RSO identification and tracking. Characterization of RSOs builds upon the "detect and track" mindset of traditional SSA. Knowledge of who is operating what systems, the capabilities of those systems, and awareness of typical day-in-the-life operations are all part of RSO characterization. The ability to predict non-friendly maneuvers—which is critical in the protection of our high-value space assets—is dependent on high fidelity RSO characterization (Brissett, 2017). The future of SSA is RSO characterization.

Even with the inclusion of ORS-5 and Space Fence, the ability to adequately characterize all RSOs of interest may be insufficient. Gaps in coverage and a lack of capable assets to maintain custody of RSOs are the two biggest factors of concern regarding the current SSN. Additional detection assets are needed to enable persistent coverage and enable RSO characterization. However, the optimal cost-effective number, size, capability, and type of assets required is unknown (Tanaka, 2017).

The purpose of this research is to develop a near-optimal architecture for effective and efficient GEO RSO characterization. Specifically, the focus of this research will be identification of architectures to enable persistent RSO characterization. The most-likely future technology will be included in the analysis in order to avoid development of an already obsolete network. Ground-based daylight imaging and near-IR are two likely future technologies that will greatly contribute to the SSA mission. Because of the long acquisition timeframe of major U.S. space programs, these technologies will likely be mainstream by the time any future SSN upgrades can be implemented. Therefore, these technologies will be incorporated into the analysis. The specific research questions this paper will address are:

1. How can particle swarm optimization and simulated annealing optimization be applied to GEO SSA architecture modeling and evaluation?
2. What is the near-optimal architecture for a high-fidelity GEO RSO characterization system?
3. How does the above architecture change with the inclusion of the two most likely future SSA technologies: ground-based daylight imaging and near-IR detection?

This research will build upon previous results that utilized a Multi-Objective Genetic Algorithm (MOGA) to identify a near-optimal GEO SSA architecture (Stern, Wachtel, Colombi, Meyer, & Cobb, 2017). The performance of Particle Swarm Optimization (PSO) and Simulated Annealing (SA) will be evaluated against MOGA to determine the most efficient method of trade space evaluation. By increasing the efficiency of the optimization routine, expansion of previously defined boundaries (shown in Table 1) is possible.

Table 1. Design Space (Stern et al., 2017)

Design Parameters	Possible Values
Number of Ground Telescopes, Diego Garcia	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Haleakala	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, La Palma	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Mauna Kea	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, IAO	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Mount Graham	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Paranal, Chile	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Siding Spring	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Socorro, NM	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
LEO Sun-Synchronous Altitude (km)	500, 600, 700, 800, 900, 1000
LEO Sun- Synchronous Satellites per Plane	0, 1, 2
LEO Sun- Synchronous Planes	1, 2
LEO Sun- Synchronous Aperture Dia. (m)	0.15, 0.30, 0.45, 0.60, 0.75, 0.9, 1.0
LEO Equatorial Altitude (km)	500, 600, 700, 800, 900, 1000
LEO Equatorial Number of Satellites	0, 1, 2, 3, 4
LEO Equatorial Diameter (m)	0.15, 0.30, 0.45, 0.60, 0.75, 0.9, 1.0
Near GEO Observer Alt. (km from GEO)	-1000, -500, 0, +500, +1000
Near GEO Observer Number of Satellites	0, 1, 2, 3, 4
Near GEO Observer Aperture Dia. (m)	0.15, 0.30, 0.45, 0.60, 0.75, 0.9, 1.0

The results of this research can be used to inform policy makers and budget authorities about the most cost-effective means to achieving improved GEO SSA capability. It specifically focuses on enabling RSO characterization and including the two most likely future SSA technologies. In this way, the near-optimal architectures developed through this research are consistent with the high-level SSA goals and inclusive of likely future SSA technology enhancements. The results of this research detail a cost-effective

approach to better monitor friendly and non-friendly RSOs to improve the security of our national assets.

BACKGROUND

Space has become an increasingly important domain for the United States, both economically and militarily. The proposal for the creation of a Space Corps in the 2018 National Defense Authorization Act exemplifies this importance (Thornberry, 2017). The Space Corps will enable more efficient operation in a domain that currently hosts 1400 operational satellites (Tanaka, 2017). The purpose of this research is to develop a near-optimal architecture for effective and efficient GEO RSO characterization. Identification of the most cost-effective systems can be used to educate decision makers and budget authorities. The concepts this research focuses on include computational analysis, space modeling, architecture design, optimization techniques, and cost analysis.

The threat of Intercontinental Ballistic Missiles (ICBM) in the Cold War required the United States to build massive radar stations in the Northern Hemisphere. After the collapse of the Soviet Union, these radar stations were under-utilized. At the same time, space was getting more crowded so these radar sites began working on the SSA mission (M. A. Baird, 2013). The effectiveness of radar is drastically reduced as the distance to the object is increased. This makes these radar sites only effectively useful for LEO SSA.

Complementing the detection of RSOs through missile warning radar sites, optical telescopes are used to detect light reflected—usually from the sun—off an RSO. Detection of an RSO requires a large enough signal-to-noise ratio from the background noise. A typical value of 2.5 is large enough to ensure detection through an optical telescope (Früh

& Jah, 2014). There are two ways an optical telescope can be used to detect RSOs. If the orbital parameters of the object are known, the telescope can track that object across the sky and measure the streaks of light generated by the stars in the background. Alternatively, the telescope can fix its position on the background stars. In this instance, the streak of light through the frame can be used to identify the RSO's orbital parameters.

Optical telescopes operating as a payload on an orbiting satellite function in a very similar manner to a ground-based telescope but with several inherent advantages. Weather and other atmospheric interference is not an issue for an orbiting platform. The system can operate 24/7 as opposed to the nighttime only operation of ground-based platforms. And there are particular orbital regimes that enable enhanced detection capability. The LEO equatorial orbit that ORS-5 will eventually operate in allows increased exposure time when detecting objects in GEO since the satellite is always in the same plane as the target RSO.

In today's budget constrained environment, cost is generally a major consideration for every Government program. Two questions drive future funding and technology development: What type of platforms provide the greatest operational capability and what combination and type of sensors provide the greatest utility? This research is a continuation of previous optimal design using lifecycle cost (LCC) as either the sole objective or one of multiple objectives. LCC includes development cost, procurement cost, launch cost, operation and sustainment cost, and disposal cost of these solutions (Stern et al., 2017).

The cost models for space-based optical telescopes scale linearly with the weight of the satellite, and the weight of the satellite scales linearly with the aperture diameter (Stahl, Henrichs, & Luedtke, 2011). Thus, the aperture size of any space-based GEO observation satellites can be used as a design parameter in this model. A similar form of

cost estimation can be used to obtain ground telescope cost estimates. Optical observatories built for astronomical observation have an estimated total cost that scales with aperture diameter raised to the 2.45 power (Van Belle, Meinel, & Meinel, 2004). These cost estimates can be used to identify an approximate cost for each system based upon how many ground- and space-based assets are included. Other cost estimates used to refine the final model include: Unmanned Space Vehicle Cost Model (USCM), the Small Satellite Cost Model (SSCM), the NASA Instrument Cost Model (NICM), and the NASA Operations Cost Model (NOCM).

The trade space of this research includes analysis of different architecture characteristics. There is nearly an infinite combination of sensors, systems, and models that could be used to accomplish the SSA mission. Because of the large number of variables in this analysis, coupled with lengthy simulation time for each candidate solution, the best optimization technique is one that can be run most efficiently on parallel computers. This allows solutions to be found on a reasonable timeframe. The DoD Supercomputing Resource Center (DSRC) and their High Performance Computer (HPC) capabilities allows parallel evaluation of thousands of architecture combinations at once and significantly reduces the wall time when solving large-scale optimization problems (Thompson, Colombi, Black, & Ayres, 2015). This was identified as a limiting factor in a previous research attempting to identify optimal space architectures. Their trade space contained 10^{19} combinations of ground-based and space-based assets (Stern et al., 2017). Evaluation of every architecture is not possible with these many combinations of possibilities. A heuristic search method of efficiently evaluating the trade space is required. Even with utilization of a heuristic search algorithm, a HPC is a critical component of this

methodology. Without the computational horsepower the HPC provides, evaluation of complex SSA architectures using this approach is not possible.

In order to determine the most efficient optimization routine for this application, Particle Swarm Optimization (PSO), Multi-Objective Genetic Algorithm (MOGA), and Simulated Annealing (SA) will be evaluated. These optimization techniques will be compared against each other for run time, accuracy, and verification/validation of each technique. Run time is defined as the time necessary for the algorithm to converge to a solution within a predefined set of tolerances. The accuracy will be dependent on the overall score of the suggested optimal architecture. The score is based on the total system cost, minimum detectable object size, and the time lag between subsequent observations. Through identification and implementation of the most efficient optimization routine, the previously defined boundaries can be expanded in order to obtain a more robust solution. A more practical assessment will be qualitative benefits of implementing various algorithms on a loosely coupled HPC, using a priority scheduler to assign computation jobs to processing nodes and cores.

METHOD

In order to identify a near-optimal architecture for GEO SSA, a methodology to simulate systems of systems must first be developed. This method must be able to accurately output desired performance parameters in order to score each architecture. For this research, the three objectives are total architecture cost, minimal detectable object size, and overall latency of the system. A robust optimization routine will identify which architecture has the highest score when evaluated against these three parameters.

The method developed for robust GEO SSA architecture generation involves several software components. Python and Analytical Graphics, Incorporated (AGI) System Tool Kit (STK) are used to generate and score GEO SSA architectures. Below is a summary of the detailed initialization, generation, and evaluation procedures found in the Stern et al. (2017) methodology.

The initialization is the first step, and requires the most coordination between modules. A python script must be able to run in the Linux operating system, open the STK program, input the desired parameters through AGI “connect” interface, and activate the subsequent generation and evaluation modules. This generates an architecture of SSA sensors that can be evaluated probabilistically. In order to maximize the utility of a HPC, an internal batch scheduling system prioritizes jobs based on the number of cores needed and run (Stern et al., 2017). This ensures the HPC is utilized as close to 100% as possible. It also drives the procedures for the initialization of this methodology.

A Python script is used to identify the program input parameters and the programs to execute. The input parameters include estimated run time, number of RSOs, and architecture bounds. These parameters are fed into the modeling simulator STK program and then evaluated via the *Inspyred* (Garrett, 2012) optimizer program.

The first step of the generation process for this methodology is tied to the use of a Genetic Algorithm (GA). In order for a GA optimization routine to run, it must first be provided with a population (or two) of random architectures. All attempts are made to cover the design space in the initial population by using different random combinations of a starting sequence. The initial architecture estimate is represented as a gene sequence and fed into the optimization package *Inspyred* (Garrett, 2012). The python script defines

population size, genetic mutation rate, crossover parameters, scoring criteria, and selection criteria. This provides the GA with all the necessary parameters to generate architectures, score the architectures, crossover the highest scored architectures, mutate those architectures, and score the architecture again.

After an architecture is generated, output files related to the performance of the architecture are generated from STK. A combination of STK generated reports are used throughout this process. The reports were necessary to identify which architecture assets can detect and identify an RSO, and when. Moon phase, lunar zenith angle, lunar phase angle, target zenith angle, solar phase angle, range to target, azimuth, and elevation are all used to calculate realistic access from every sensor to every RSO identified in the target deck (Stern et al., 2017).

Since any robust architecture will identify several assets that can observe a given target at a given time step, a scheduler is needed in order to identify and prioritize what asset should look at what target. Additionally, there may be time steps where an RSO cannot be seen by any asset. This quickly turns into an unsolvable traveling salesman problem. In order to attempt to optimize the architecture and not the scheduler, a simple latency-based scheduler was implemented for this research. Stern et al. (Stern et al., 2017) defined this complex scheduling algorithm in detail. The scheduler identifies which RSO has gone the longest amount of time without an observation and schedules the best available asset to observe that RSO. This process repeats until every available asset has an RSO to observe. Then the time steps forward one increment of 30 seconds and the entire scheduling process repeats. The output of the scheduling algorithm is the overall latency of observations. This latency can be used as an input to score the architecture.

The smallest size object that can be detected varies for each asset of a GEO SSA architecture. Detector size and distance to target are two of the primary drivers to RSO detection. Since the sun is the largest source of illumination for objects orbiting at GEO, the sun incidence angle also is a primary driver for RSO detection. The specifics of how to calculate a minimum detectable RSO is defined by Stern et al. (2017). Their analysis used a Signal-to-Noise Ratio (SNR) of 6 as a minimal threshold for RSO detection. Any RSO that returned a SNR of 6 or greater was assumed to be observable by that detector. This research will simplify the calculations required to determine if an RSO at GEO is observable by using apparent magnitude. The apparent magnitude of any RSO is defined in the Equation 1:

$$m - m_0 = -2.5 \times \log_{10} \frac{E}{E_0} \quad \text{Eq 1.}$$

where

m = apparent magnitude

m_0 = apparent magnitude of reference body

E = observed irradiance at a specified bandwidth

E_0 = reference irradiance at a specified bandwidth

and irradiance is defined by:

$$E = \sqrt{\frac{\phi}{4\pi d^2}} \quad \text{Eq 2.}$$

where

ϕ =luminosity over a specified bandwidth

d = distance to the target

Refinement of the above methodology will enable incorporation of additional architecture parameters. For this research, daylight imaging and near-IR detection will be examined. Daylight imaging allows detection of RSOs longer into the dawn and earlier prior to dusk. This increases the operational capability of every ground based imaging detector in the SSA architecture. The addition of near-IR detectors to the architecture should decrease the current limitations of optical detectors to identify and track RSOs in the Earth's shadow during eclipse season.

Pisacane (2016) showed how a score can be assigned for each architecture that varies depending on detector performance for small RSOs in GEO. The score of every architecture is used to determine the near-optimal architectures.

RESULTS

The results detailed in this paper include the final results using Multi-Objective Genetic Algorithm (MOGA) on the AFRL supercomputer Spirit (Stern et al., 2017) as well as the preliminary assessment of a Particle Swarm Optimization (PSO). Future work will incorporate a Simulated Annealing optimization routine and a finalized PSO for comparison. These three optimization techniques will be evaluated against each other using AFRL's newest supercomputer Thunder. This additional work will be integrated into the results and conclusions prior to March of 2018.

Due to limitations of the MOGA used in the Stern et al. (2017) research, the longest scenario runtime possible was a single 24 hour period. In order to minimize the limitations of this approach, their research ran an STK scenario one day on the equinox and one day on the solstice. This approach bounds the limitations and advantages of any particular

orbital regime. The results of the Equinox run and the Solstice run (shown in Table 2) highlight how the near-optimal architecture varies depending on the Earth-Sun orientation.

Table 2. Multiple Objective Results (Stern et al., 2017)

Design Parameters	Equinox	Solstice
Number of near GEO Satellites	4	3
Aperture Diameter (m)	0.6	0.45
Delta Altitude from GEO (km)	1000	1000
Number of LEO Equatorial Satellites	0	3
Aperture Diameter (m)	-	0.3
Altitude (km)	-	900
Number of Sun Synchronous Orbit Satellites	0	0
Telescopes at Socorro, NM	4	4
Aperture Diameter (m)	1	1
Telescopes at Siding Spring	-	4
Aperture Diameter (m)	-	1
Telescopes at Paranal Chile	4	4
Aperture Diameter (m)	1	1
Telescopes at Mt. Graham	3	4
Aperture Diameter (m)	1	1
Telescopes at Indian Astro. Observatory	4	4
Aperture Diameter (m)	1	0.5
Telescopes at Mauna Kea	4	4
Aperture Diameter (m)	1	1
Telescopes at La Palma	-	3
Aperture Diameter (m)	-	1
Telescopes at Haleakala	4	3
Aperture Diameter (m)	1	1
Telescopes at Diego Garcia	4	1
Aperture Diameter (m)	1	0.5

With the exception of the 0.5-meter telescopes at the Indian Astronomy Observatory and Diego Garcia, the most cost-effective telescope size for a ground based SSA sensor has an aperture of 1 meter. The exclusion of any sun synchronous orbit satellites is understandable given that this orbital regime is designed to optimize observations of the Earth, not of the GEO belt. Maximizing the number of near GEO assets is understandable given the substantial advantage gained by being so close to the target

RSOs. The only result that is counterintuitive is the lack of any equatorial LEO sensors for the Equinox STK run. The advantages of this orbital regime should be consistent regardless of the time of year. The satellite will always be in the same plane as the RSOs in GEO so should always have a significant exposure time advantage.

The differences in the above results stimulates more questions about the architecture performance during the timeframe in-between Equinox and Solstice. The ability to evaluate scenarios that are weeks or even months long continues to be one of the major efforts of this research. Currently, integration of the optimization routines onto the newest AFRL supercomputer, Thunder, has slowed progress towards this goal. The successful execution of the goals outlined in this paper depends on the ability to integrate these new optimization routines onto Thunder.

Comparing preliminary results obtained from a scaled-down version of this problem show significant PSO advantages over MOGA. First and foremost, PSO does not require an initial guess. With MOGA, the initial guess can affect the final result based on how close this initial guess is to a local minimum. Using a PSO eliminates this potential error introduction into the analysis. The PSO also does not require knowledge of the previous iterations. This should decrease the memory requirement for the optimization algorithm. If these enhancements can be imported onto the HPC, the scenario time frame can be increased, while increasing the previously defined boundaries; expanding the potential number of near GEO satellites and the number of ground-based telescopes at each location.

CONCLUSION

The results of previous AFIT research as well as on-going research prove the utility of model-based SSA architecture evaluation. Running these analyses on high power computers compounds that utility. Integration of these algorithms onto a supercomputer prove to be the most challenging yet also most essential component of this research.

Modeling and simulation of complex SSA architectures provides a unique ability to understand the costs and benefits of different combinations of sensor technologies. The ability to run thousands of simulations in parallel allows analysis of architecture performance in a timely fashion. After this research is finalized, results will be compared to previously identified architectures in order to verify the overall method as well as built a more refined and more complete analysis tool.

The results of this research can inform decision makers how to build the most cost-effective GEO SSA architecture. It can also be used as a source selection tool to evaluate opposing contractor bids. Adding an orbital regime to the trade space or modifying the capabilities of a particular sensor requires minimal changes to the base code. This flexibility allows this research to be used as a platform upon which any number of very specific problems can be analyzed. Future integration of a robust scheduling algorithm will further enhance the capabilities of this analysis tool.

The next phase of this research will be finalized prior to March of 2018. The enhancements included in this phase include integration of a direct ascent to GEO servicing mission, expansion of the previously defined architecture boundaries, increasing the 24-hour run time to several days, and incorporation of a more robust and efficient optimization algorithm.

III. GEO SSA Extensions: Polar GEO and Twilight Imaging

This section of the thesis contains a journal article that will be submitted to the Journal of Defense Modeling and Simulation (JDMS). This journal is a quarterly publication that focuses on military and defense related modeling and simulation.

ABSTRACT

Improving Space Situational Awareness (SSA) remains one of the Department of Defense's top priorities (DoD's) top priorities. Current research at the Air Force Institute of Technology (AFIT) has shown that modeling of Geosynchronous Earth Orbit (GEO) SSA architectures can identify optimal combinations of ground and space-based sensors. This paper extends previous GEO SSA research by expanding design boundaries and refining the methodology. A genetic algorithm was used to examine this increased trade space containing 10^{22} possible sensor combinations. Experimental trials that would have taken over 100 years on a desktop computer were completed in weeks using a high-performance computer containing over 125,000 cores. The results of the optimizer clearly favor 1.0-meter aperture ground telescopes combined with 0.15-meter aperture sensors in a 12-satellite polar GEO constellation. The 1.0-meter aperture ground telescopes have the best cost-performance combination for detecting Resident Space Objects (RSOs) in GEO. The polar GEO regime offers increased access to GEO RSOs since other orbits are restricted by the 40° solar exclusion angle. When performance is held constant, a polar GEO satellite constellation offers a 22.4% reduction in total system cost when compared to Sun Synchronous Orbit (SSO), equatorial Low Earth Orbit (LEO), and near GEO constellations. Scripting and parallel high-performance computing opens the possibility of

solving an entirely new class of problems of interest to the DoD. The results of this research can be used to educate national policy makers on the benefits of various proposed upgrades to current and future SSA systems.

INTRODUCTION

Advancements in technology have enabled cheaper access to the space domain (Früh & Jah, 2014). Reusable rocket technology and the emerging field of CubeSats drive this trend and increase the number of operational satellites in space. In 2017, India launched 104 satellites into Low Earth Orbit (LEO) from a single rocket (Barry, 2017). This increased access to space drives the need for increased Space Situational Awareness (SSA) in order to minimize the likelihood of an unintentional collision. Geosynchronous Earth Orbit (GEO) is of particular interest because of the exact altitude requirements needed to maintain a 23 hour and 56 minute period (Marlow et al., 2017). This research focuses on modeling and simulation of ground and space-based sensors in order to identify near optimal sets of architectures to best enable persistent coverage of GEO Resident Space Objects (RSOs).

The space domain has grown from a force multiplier to a warfighting domain itself (Smith, 2017). Like land, sea, and air, space will be a domain with future struggles for dominance. The ability to have insight into tactics, techniques, and procedures of our adversaries is paramount. Persistent SSA is the foundational requirement needed to ensure accountability of any malicious activity in space (Dacres, 2016). Maintaining near continuous coverage of the GEO belt serves as a deterrent and protects high value GEO assets. High-fidelity SSA protects future exploitation of the GEO belt for satellite

operation. A satellite breakup in GEO could propagate space debris throughout the orbit causing a cascading effect that effectively eliminates the possibility of any satellite operation in that orbital regime (Tanaka, 2017).

All Resident Space Objects (RSOs) larger than 10 cm are currently tracked via the United States Space Surveillance Network (SSN). Figure 3 illustrates the approximated 29,000 objects in orbit greater than 10 cm (Wiedemann, 2018).



Figure 3. Space objects larger than 10 cm (Wiedemann, 2018)

A 10 cm threshold for RSO tracking was selected because the current system cannot consistently detect and track objects smaller than 10 cm (M. Baird, 2013). However, objects as small as 1 mm carry enough energy—traveling at 7 kilometers per second—to cripple an operational satellite (Tanaka, 2017). Since these objects are not actively tracked, they do not have orbital predictions that could provide an operational satellite warning of a close approach. Because of this, objects smaller than 10 cm pose the greatest passive

threat to today's operational satellites. Figure 4 visually illustrates the predicted number of objects 1 mm or larger currently in orbit.

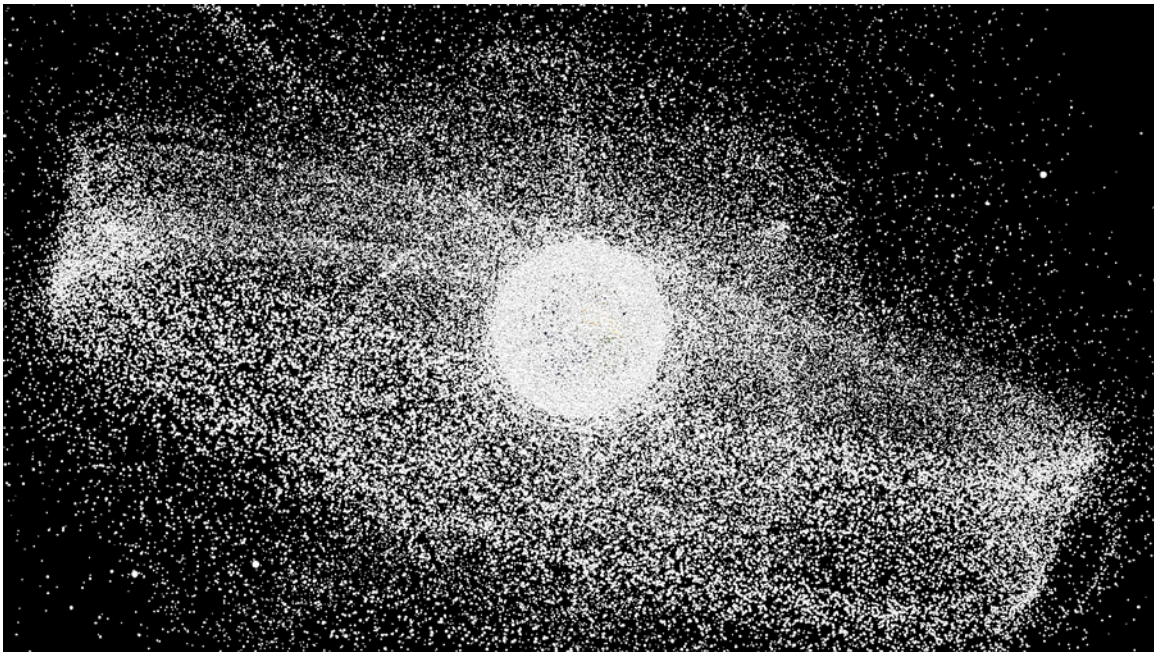


Figure 4. Space objects larger than 1 mm (Wiedemann, 2018)

The newest Air Force SSA sensor—ORS-5—launched in August of 2017 (Clark, 2017). Also known as SensorSat, this satellite operates in an equatorial LEO designed to maximize the detection capabilities of GEO RSOs. When this sensor becomes operational, it will improve the SSN's ability to maintain custody of the current GEO space catalog (Brissett, 2017). In 2018, the re-introduction of the Air Force's Space Fence will drastically improve detection capabilities of small RSOs in GEO. Together, these will complement the existing SSA provided by the Ground-Based Electro-Optical Deep Space Surveillance (GEODDS) network, the Space Surveillance Telescope (SST) and the Space-Based Space Surveillance (SBSS) satellite.

Even with the inclusion of ORS-5 and Space Fence, the ability to adequately detect and track all RSOs of interest may be insufficient. Gaps in coverage and a lack of capable

assets to maintain custody of RSOs are the two biggest factors of concern regarding the current SSN (Abbot & Wallace, 2007). Additional sensors are needed to enable persistent coverage of all the RSOs in GEO. However, the optimal number, telescope aperture size, ground location, orbital plane, and type of sensor(s) required is unknown (Tanaka, 2017).

The purpose of this research was to propose a near-optimal architecture for effective and efficient high-fidelity GEO SSA as well as determine how that architecture changes as the Earth-Sun angle varies throughout the year. A high-fidelity system minimizes the latency between subsequent RSO collects and minimizes the detectable object size. Primarily this research used modeling and simulation through vast trade space analysis to determine what combination of ground and space-based sensors provide the most cost-effective architecture for a high-fidelity GEO SSA system. Secondly, the research determined how the optimal architecture changed throughout the year because of Earth-Sun angle variations.

This research builds upon previous results that utilized a Multi-Objective Genetic Algorithm (MOGA) to identify near-optimal GEO SSA architectures for two specific days of the year: the summer solstice and spring equinox (Stern, Wachtel, Colombi, Meyer, & Cobb, 2017). Refinement and enhancement of this methodology was shown to increase the efficiency of the dynamic simulation and optimization software used for generation and evaluation of executable architectures (Garcia & Tolk, 2015). These enhancements facilitated an expansion of the previously defined trade space boundaries in order to create the new design space defined in Table 3.

Table 3. Design Space

Design Parameters	Possible Values
Number of Ground Telescopes, Diego Garcia	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Haleakala	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, La Palma	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Mauna Kea	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, IAO	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Mount Graham	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Paranal, Chile	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Siding Spring	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Number of Ground Telescopes, Socorro, NM	0, 1, 2, 3, 4
Ground Telescope Aperture Dia. (m)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Polar GEO Altitude (km from GEO)	-300, -200, -100, 100, 200, 300
Polar GEO Satellites per Plane	0, 1, 2, 3, 4, 5, 6
Polar GEO Planes	1, 2
Polar GEO Aperture Dia. (m)	0.15, 0.30, 0.45, 0.60, 0.75, 0.9, 1.0
LEO Equatorial Altitude (km)	500, 600, 700, 800, 900, 1000
LEO Equatorial Number of Satellites	0, 1, 2, 3, 4, 5, 6
LEO Equatorial Diameter (m)	0.15, 0.30, 0.45, 0.60, 0.75, 0.9, 1.0
Near GEO Observer Alt. (km from GEO)	-300, -200, -100, 100, 200, 300
Near GEO Observer Number of Satellites	0, 1, 2, 3, 4, 5, 6
Near GEO Observer Aperture Dia. (m)	0.15, 0.30, 0.45, 0.60, 0.75, 0.9, 1.0

Development and refinement of a unique modeling and simulation toolset was required to efficiently search a design space that includes 10^{22} possible combinations of architectural elements. The complete toolset includes Python and Linux scripting, AGI's Systems Tool Kit (STK), MOGA implementation, and a High-Performance Computer (HPC). This toolset can be used as an analysis workbench for diverse types of evaluation for very large trade spaces. The results of the research can be used to inform policy makers

and budget authorities about the most cost-effective means to achieving a persistent GEO SSA capability. Cost constraints and performance targets can be easily modified to generate new tailored optimal architectures. Modifications to the input parameters enables analysis of emerging technologies and could be used as a source selection tool to evaluate proposals to focus program funding. The possibilities for application of this research to future space and non-space related modeling and simulation applications is boundless.

BACKGROUND

Space has become an increasingly important domain for the United States, both economically and militarily. Conflict in this domain is inevitable (John, 2002) and ensuring the survival of the currently 1400 operational satellites (Tanaka, 2017) through any future conflict is critical. The concepts this research focuses on include computational analysis, space modeling, architecture design, cost analysis, performance simulation, parallel evaluation of executable architectures, and multi-objective optimization.

The threat of Intercontinental Ballistic Missiles (ICBM) in the Cold War required the United States to build massive radar stations in the Northern Hemisphere. After the collapse of the Soviet Union, these radar stations were under-utilized. At the same time, space was getting more crowded so these radar sites began working on the SSA mission (M. Baird, 2013). This method of RSO detection vastly improved the tracking capability of RSOs in LEO (Ackermann, Kiziah, Zimmer, McGraw, & Cox, 2015). However, the effectiveness of radar is drastically reduced as the distance to the object is increased. This limitation makes these radar sites only effective for the LEO SSA mission.

Complementing the detection of RSOs through missile warning radar sites, optical telescopes are used to detect light reflected—usually from the Sun—off an RSO. Because optical telescopes are passive sensors, they do not suffer from the distance limitations as drastically as radar sensors. It follows that optical sensors are the ideal instrument for GEO SSA. Detection of any RSO requires a high signal-to-noise ratio from the background noise. A typical value of 2.5 is large enough to ensure detection through an optical telescope (Früh & Jah, 2014). There are two ways an optical telescope can be used to detect RSOs. If the orbital parameters of the object are known, the telescope can track that object across the sky and measure the streaks of light generated by the stars in the background to back out that RSO's orbital elements. Alternatively, the telescope can fix its position on the background stars. In this instance, the streak of light through the frame can be used to calculate the RSO's orbital parameters (Dacres, 2016).

Optical telescopes operating as a payload on an orbiting satellite function in a very similar manner to ground-based telescopes but with several inherent advantages. Weather and other atmospheric interference is not an issue for an orbiting platform. The system can operate 24/7 as opposed to the nighttime only operation of current ground-based telescopes. However, a solar exclusion angle exists for all space sensors that limits the sensor's Field of Regard (FOR) to within a defined threshold of the solar disk (Scott, Wallace, Sale, & Levesque, 2013).

There are particular orbital regimes that enable increased detection opportunities for GEO RSOs. This research explores a polar orbit at an altitude similar to GEO in order to minimize the effect of the solar exclusion angle. The geometry of a polar GEO satellite provides increased access for targeting RSOs in the GEO belt. An equatorial LEO allows

increased exposure time when detecting objects in GEO since the satellite platform is always in the same plane as the target RSOs. This provides a 10x improvement in detection opportunity (Ackermann et al., 2015). A near GEO satellite has the advantage of being very close to GEO RSOs and therefore has an enhanced detection capability. These orbits were selected as inputs for the optimizer because they are highly capable for GEO SSA.

In today's budget-constrained environment, cost is generally a major consideration for every program. Two questions drive future funding and technology development: What type of platforms provide the greatest operational capability and what combination of sensors provide the greatest utility? This research was a continuation of previous optimal design using lifecycle cost (LCC) as one of multiple objectives to optimize. LCC includes development cost, procurement cost, launch cost, operation and sustainment cost, and disposal cost of these solutions (Stern et al., 2017).

The cost models for space-based optical telescopes scale linearly with the weight of the satellite, and the weight of the satellite scales linearly with the aperture diameter (Stahl, Henrichs, & Luedtke, 2011). Thus, the aperture size of any space-based observation satellite can be used as a design parameter in this cost model. A similar form of cost estimation can be used to obtain ground telescope cost estimates. Optical observatories built for astronomical observation have an estimated total cost that scales with aperture diameter raised to the 2.45 power (Van Belle, Meinel, & Meinel, 2004). These cost estimates can then be used to identify an approximate cost for each system based upon how many ground and space-based assets are included. Other estimates used to refine the final cost model include: Unmanned Space Vehicle Cost Model (USCM), the Small Satellite

Cost Model (SSCM), the NASA Instrument Cost Model (NICM), and the NASA Operations Cost Model (NOCM) (Stern et al., 2017).

There is nearly an infinite combination of sensors that could be used to accomplish the SSA mission. Because of the large number of variables in this analysis, coupled with lengthy simulation time for each candidate solution, the best optimization technique is one that can be run most efficiently parallelized. This allows solutions to be found in a reasonable timeframe. The DoD Supercomputing Resource Center (DSRC) and their HPC capabilities allow parallel evaluation of thousands of architecture combinations at once and significantly reduces the wall time when solving large-scale optimization problems (Thompson, Colombi, Black, & Ayres, 2015). This was identified as a limiting factor in previous research attempting to identify optimal space architectures (Stern et al., 2017). In the previous SSA architecture study, the trade space contained 10^{19} combinations of ground-based and space-based assets. Evaluation of every architecture is not possible with such a high number of possible sensor combinations. A heuristic search method to efficiently evaluate the trade space is required. Even with utilization of a heuristic search algorithm, the HPC is a critical component of this methodology. Without the computational resources the HPC provides, evaluation of complex SSA architectures using this approach would take decades.

METHODOLOGY

The method used for this research involves accurately modeling and simulating the orbital dynamics of 813 Resident Space Objects (RSOs) in GEO, ground telescope performance at various locations, and space-based sensors in varying orbits (Stern et al.,

2017). This simulates a ground or on-orbit sensor attempting to detect and track objects in the GEO belt. Advanced algorithms are then used to sort, schedule, and then optimize the sensor selection.

The methodology can be divided into two steps. First, the access data from every possible sensor to every target was calculated. This generated a massive amount of data that can then be filtered, sorted, and analyzed in step two. Tens of thousands of reports contain the data required to perform access calculations for every sensor to every RSO at every time step. After the data was analyzed, three objective functions were optimized. For this research, the three objectives optimized were: total architecture cost, minimal detectable object size, and overall latency of the system. The robust multi-objective optimization routine using a genetic algorithm identified which architecture had the highest score when evaluated equally against these three objectives.

Initialization was the first step, and required the most coordination between modules on the HPC. A Python script was used to open STK, identify the program input parameters, and the algorithms to execute. A combination of STK generated reports was used throughout this process. The reports were necessary to identify which sensors could detect and identify an RSO at each time step. Moon phase, lunar zenith angle, lunar phase angle, target zenith angle, solar phase angle, range to target, azimuth data, and elevation data were all used to calculate realistic access from every sensor to all 813 RSOs identified in the target deck. By utilizing an AFRL HPC to run the initialization step of this methodology, computational resources were accelerated by a factor of 170. In order to maximize the utility of the HPC, an internal batch scheduling system prioritized jobs based on the number of cores needed (Stern et al., 2017). This ensured the HPC was utilized as

close to 100% as possible. Operation on the HPC required a Linux based Python script to open the STK program, input the desired parameters through AGI “connect” interface, and activated the subsequent generation and evaluation modules. The input parameters included estimated run time, RSO orbital parameters, evaluation window dates, time step, and architecture boundaries. These parameters were fed into the STK program to define access from every possible sensor to every RSO at each time step throughout the simulation; 24 hours sampled every 30 seconds.

Since any robust architecture will identify several assets that can observe a given target at a particular time step, a scheduler was needed in order to identify and prioritize what sensor should look at what target. Additionally, there may be time steps where an RSO cannot be seen by any sensor. In order to optimize the architecture and not the scheduler, a simple latency-based scheduler was implemented for this research. Stern et al. (2017) defined this complex scheduling algorithm in detail. The scheduler identifies which RSO has gone the longest amount of time without an observation and schedules an available sensor to observe that RSO. This process repeats until every available sensor is scheduled to observe an RSO. Then the time steps forward one increment of 30 seconds and the entire scheduling process repeats. The results of the scheduling algorithm provide the overall latency of the observations. This latency was used as an input to score the performance of the architecture.

The smallest size object that can be detected varies for each asset of a GEO SSA architecture. Sensor size and distance to target are two of the primary drivers for RSO detection. Since the Sun is the largest source of illumination for objects orbiting at GEO, the sun incidence angle was also a primary driver for RSO detection. The specifics of how

to calculate a minimum detectable RSO was defined by Stern et al. (2017). Their analysis used a Signal-to-Noise Ratio (SNR) of 6 dBm as a minimal threshold for RSO detection. Any RSO with a SNR of 6 dBm or greater was assumed to be observable by that sensor.

The capability of any ground-based sensor to detect RSOs in GEO varies depending on atmospheric transmission. The Laser Environmental Effects Definition and Reference (LEEDR) toolset was used to estimate the atmospheric transmission for each possible telescope location. Additionally, previous research by Stern et al. (2017) restricted ground site operation during the twilight and daylight hours. This research expanded the operational capability of ground sensors by allowing imaging of RSOs during twilight. Space-based sensors have the capability to operate 24/7 and were only restricted from observing targets within a 40° exclusion angle of the Sun.

The second step for this methodology identified a candidate architecture to evaluate. Every candidate architecture can be evaluated based on how that architecture performs against the three objectives: cost, detection size, and latency. However, since there are 10^{22} total possible sensor combinations to make up one architecture, a brute force approach was not possible. To combat this, a MOGA optimizer program was used to intelligently search the design space. In order for a MOGA optimization routine to run, it must first be provided with a population of two random architectures. All attempts were made to cover the design space in the initial population by using different random combinations of a starting sequence. This was provided via a Python script containing all the possible values for each architecture element. The initial architecture estimate was represented as a gene sequence and fed into the MOGA optimization package *Inspired*

(Garrett, 2012). Another Python script defined population size, genetic mutation rate, crossover parameters, scheduling algorithm, selection criteria, and scoring criteria.

The foundational methodology used a population size of 96 for 100 generations. Every trial evaluated 9,600 architectures based on total architecture cost, minimal detectable object size, and overall latency of the system. Pisacane (2016) details how a score can be assigned for each architecture that varies depending on sensor performance for small RSOs in GEO. This score was combined with the mean latency identified by the scheduler and the total system cost to obtain a final value score for each architecture. This provides the GA with all the necessary parameters to generate architectures, score the architectures, crossover the highest scored architectures genes, randomly mutate those architectures, and repeat for each generation.

Value was determined based how the architecture performs against the three objectives: total system cost, minimum RSO detectable size, and system latency. Architecture performance for each of the three objectives was evaluated independently then normalized to obtain a score for each objective. These scores were then combined with an equal weighting for all three objectives and then normalized between zero and one.

Refinement of this methodology allowed additional analysis of GEO SSA characteristics as well as expansion into additional trade spaces. For this research, five enhancements increase the utility of the refined methodology. The first enhancement added limited daylight imaging to the ground site detection capability. Daylight imaging allows detection of RSOs longer into the dawn and earlier prior to dusk. Specifically, the periods of Astronomical Dawn, Nautical Dawn, Civil Dawn, Civil Dusk, Nautical Dusk, and Astronomical Dusk were added to the previous Umbra-only ground site operation.

Depending on ground site latitude location, this added approximately 71.8 minutes of ground telescope operation on either side of night.

The next three enhancements were applied to the space component of the architecture. First, the previously defined boundaries that limit any particular architecture to a maximum of four satellites in a plane was expanded to six. This allows further exploration of the trade space since previous results often maximized this architecture characteristic (Stern et al., 2017). Secondly, the SSO regime was eliminated as a design parameter since previous results rarely selected this orbital regime over the other two orbital regime options of equatorial LEO and near GEO (Stern et al., 2017). Equatorial LEO has a distinct advantage over SSO due to the shared orbital inclination of the GEO target satellites. This geometric advantage provides satellites in equatorial LEO a 10x sensitivity increase with the same aperture diameter (Ackermann et al., 2015) and was likely the reason previous research rarely selected SSO sensors.

The final space enhancement added 2 planes with a capacity of six satellites per plane in a polar GEO configuration. This orbit provided an average percent access to the GEO belt of 89%. This is significantly higher than the percent access provided from an SSO orbit, 57%, and near GEO, 75% (Vallado, Ackermann, Cefola, & Kiziah, 2016).

These space element changes, combined with the increased ground site operation improved the total system collection capability. It also increased the trade space from 10^{19} total possible sensor combinations to 10^{22} . The increased time needed to search this larger trade space was offset by efficiencies gained from the refined methodology. Data generation was accelerated by a factor of six while data evaluation was accelerated by a factor of three. A summary of the revised architectural elements is defined in Figure 5.

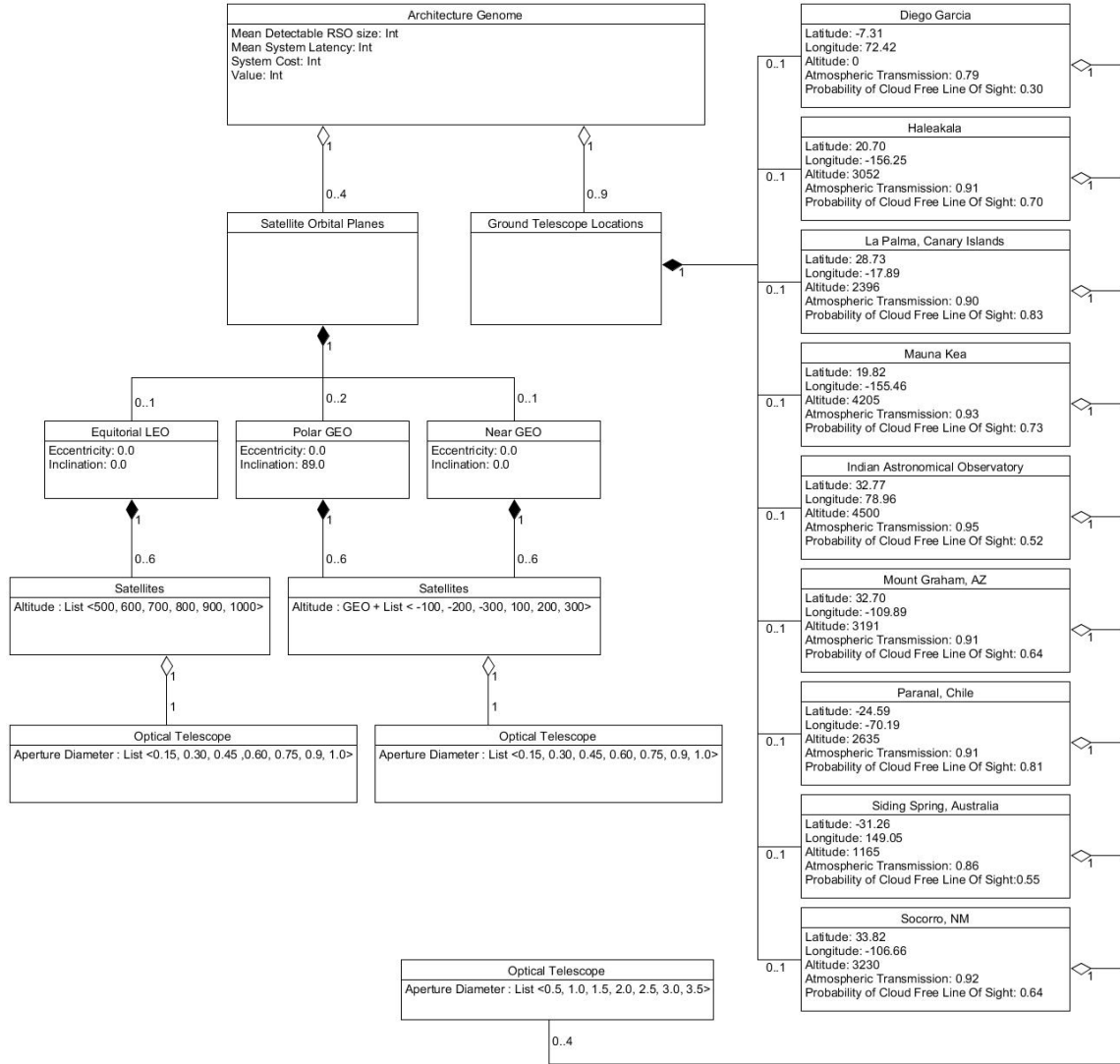


Figure 5. Revised Architecture Element Definitions

The final methodology enhancement was accomplished through improvements and refinement of how jobs are requested, scheduled, and distributed on the HPC. These enhancements include: elimination of redundant tasks, improved efficiency for job submission, doubling population size to 192, halving the number of generations to 50, accelerated data verification, increased parallelization via distribution to more nodes, and improved data generation reliability. Early trials indicated that reduction in the number of

generations to 50 had little impact on the final selected architecture. The total number of architectures evaluated per trial was still 9,600 and the best value architectures were typically discovered consistently by generation 25, as can be seen in Figure 6.

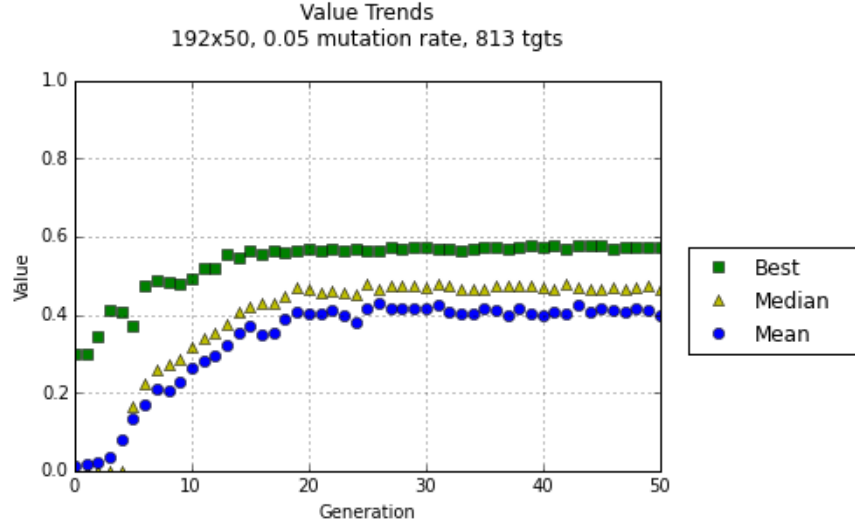


Figure 6. Value Trends by Generation

These enhancements greatly increased the modeling capability of this methodology. An optimization run that simulates 9600 architectures for 24 hours previously required three days to complete but can now be accomplished in a single day. This efficiency facilitated expansion of the trade space to 1000 times larger than previous research.

RESULTS

The results detailed in this paper include the baseline results using a MOGA on a decommissioned HPC (Stern et al., 2017) as well as three sets of results using a MOGA on a new HPC. The foundational methodology was used for the first set of results while the refined methodology was used for the more encompassing final two sets of results.

Due to limitations of the MOGA used in the Stern et al. (2017) research, the longest scenario runtime possible was a single 24 hour period. In order to minimize the limitations of this approach, their research ran an STK scenario one day on the spring equinox (21 March) and one day on the summer solstice (21 June). This approach bounds the limitations and advantages of any particular orbital regime. The results of the equinox run and the solstice run (shown in Table 4) highlight how the near-optimal architecture varies depending on the Earth-Sun orientation.

Table 4. Multiple Objective Results (Stern et al., 2017)

Design Parameters	Equinox	Solstice
Number of near GEO Satellites	4	3
Aperture Diameter (m)	0.6	0.45
Delta Altitude from GEO (km)	+1000	+1000
Number of LEO Equatorial Satellites	0	3
Aperture Diameter (m)	-	0.3
Altitude (km)	-	900
Number of Sun Synchronous Orbit Satellites	0	0
Telescopes at Socorro, NM	4	4
Aperture Diameter (m)	1	1
Telescopes at Siding Spring	-	4
Aperture Diameter (m)	-	1
Telescopes at Paranal Chile	4	4
Aperture Diameter (m)	1	1
Telescopes at Mt. Graham	3	4
Aperture Diameter (m)	1	1
Telescopes at Indian Astro. Observatory	4	4
Aperture Diameter (m)	1	0.5
Telescopes at Mauna Kea	4	4
Aperture Diameter (m)	1	1
Telescopes at La Palma	-	3
Aperture Diameter (m)	-	1
Telescopes at Haleakala	4	3
Aperture Diameter (m)	1	1
Telescopes at Diego Garcia	4	1
Aperture Diameter (m)	1	0.5

Generally, the most cost-effective telescope size for a ground-based SSA sensor has an aperture of 1 meter. The exclusion of any sun synchronous orbit satellites is understandable given the previously identified advantages of an equatorial LEO satellite. Maximizing the number of near GEO assets on the Equinox is understandable given the substantial advantage gained by being so close to the target RSOs.

In order to establish a baseline for the refined methodology, the first experiment used an identical methodology as used in the previous research. Once the above solstice and equinox trials were simulated and repeatable, a single run was completed on May 11th in order to obtain results from a day in between the solstice and equinox. This links the foundational methodology to the refined methodology. The results are shown in Table 5.

Table 5. Multiple Objective Results 11 May

	21 March	11 May	21 June
Number of near GEO Satellites	4	3	3
Aperture Diameter (m)	0.6	0.45	0.45
Delta Altitude from GEO (km)	+1000	+500	+1000
Number of LEO Equatorial Satellites	0	4	3
Aperture Diameter (m)	-	0.3	0.3
Altitude (km)	-	700	900
Number of Sun Synchronous Orbit Satellites	0	0	0
Telescopes at Socorro, NM	4	3	4
Aperture Diameter (m)	1.0	0.5	1.0
Telescopes at Siding Spring	0	0	4
Aperture Diameter (m)	-	-	1.0
Telescopes at Paranal Chile	4	0	4
Aperture Diameter (m)	1.0	-	1.0
Telescopes at Mt. Graham	3	4	4
Aperture Diameter (m)	1.0	1.0	1.0
Telescopes at Indian Astro. Observatory	4	3	4
Aperture Diameter (m)	1.0	0.5	0.5
Telescopes at Mauna Kea	4	3	4
Aperture Diameter (m)	1.0	0.5	1.0
Telescopes at La Palma	0	3	3
Aperture Diameter (m)	-	1.5	1.0

Telescopes at Haleakala	4	4	3
Aperture Diameter (m)	1.0	1.0	1.0
Telescopes at Diego Garcia	4	3	1
Aperture Diameter (m)	1.0	1.0	0.5
Architecture Performance			
Size (cm)	52.3	53.6	60.5
Latency (min)	81.0	47.0	42.8
Cost (\$B)	1.49	1.75	1.56
Value	0.302	0.393	0.399

It is interesting to note that the optimal architecture for May 11th keeps a similar near GEO architecture from the solstice but also favors maximizing the equatorial LEO satellites. It also continues the trend of not selecting any satellites in SSO. On the ground, the reduction of 1.0-meter telescopes is compensated by adding nine 0.5-meter telescopes and three 1.5-meter telescopes.

The refined methodology used for the remaining results was intended to explore the additional trade space, enhance system collection capability, and expand the limitation of four satellites per plane maximum. In order to prevent time of year bias from driving the solution, 18 trials were performed. Three days per month from January to June encompass the complete geometry of any architecture since July to December will mirror the first six months of the year. Ground site operation was expanded to include twilight. Two planes of polar GEO satellites with a maximum of six satellites per plane was added. The maximum satellites per plane in equatorial LEO and near GEO was also set to six. The space telescope 40° solar exclusion angle, 95% satellite learning curve, and the ground telescope 20° minimum elevation angle were all maintained from the foundational methodology.

Data analysis was also refined to simplify the synthesis of the data. Rather than defining what aperture diameter telescope to include at each ground site, a high-level

program management approach was used to bin ground telescopes by aperture size. Total number of each aperture size ground telescopes was used as a parameter to differentiate architectures. This can be accomplished since ground telescope costs are modeled using aperture size and not geographic location. This simplified the data analysis in order to more clearly differentiate between optimal combinations of ground and space-based sensors. Total number of ground telescopes using each aperture size can be directly compared to total number of space telescopes using each aperture size.

Table 6. Multiple Objective Results with Refined Methodology

	Ground Telescopes				Space Telescopes			Performance			
	0.5-meter Aperture	1.0-meter Aperture	1.5-meter Aperture	2.0-meter Aperture	Aperture	#	Orbit	Size (in cm)	Latency (in min)	Cost (in \$B)	Value
1-Jan	5	6	8		0.15	12	Below Polar GEO	29.4	40.7	1.11	0.59
11-Jan	4	20			0.15	12	Above Polar GEO	28.1	39.2	1.04	0.61
21-Jan		3	10		0.15	12	Above Polar GEO	27.4	51.1	1.15	0.56
1-Feb		13	5		0.15	12	Above Polar GEO	26.9	48.6	1.10	0.58
11-Feb		19		2	0.15	12	Above Polar GEO	24.3	51.5	1.14	0.58
21-Feb		7	7		0.15	12	Above Polar GEO	31.0	60.3	1.10	0.52
1-Mar			5		0.15	12	Above Polar GEO	20.1	78.8	0.97	0.51
11-Mar		5	9		0.15	10	Below Polar GEO	19.2	82.5	1.04	0.49
21-Mar		3	7		0.15	12	Below Polar GEO	26.0	83.8	1.04	0.46
1-Apr		11	4		0.15	12	Below Polar GEO	23.1	70.7	1.04	0.52
11-Apr		19	2		0.15	12	Above Polar GEO	21.9	54.7	1.07	0.58
21-Apr		9	3	1	0.15	12	Below Polar GEO	33.5	52.8	1.10	0.53
1-May		18	1		0.15	12	Below Polar GEO	25.1	49.0	1.04	0.59
11-May		13	6		0.15	12	Below Polar GEO	23.7	46.4	1.11	0.60
21-May	3	13	5		0.15	12	Below Polar GEO	37.4	44.2	1.10	0.55
1-Jun		10	10		0.15	12	Above Polar GEO	21.7	42.3	1.19	0.61
11-Jun		15	3		0.15	12	Above Polar GEO	25.0	43.2	1.07	0.61
21-Jun	2	6	6		0.15	12	Below Polar GEO	33.8	43.9	1.17	0.56

The first thing that stands out is the maximization of the polar GEO regime for all trials except March 11th. This is most likely due to the restriction of a 40° solar exclusion angle on all satellites. This restriction impacts the polar GEO satellites less due to the geometry of the observing satellites in that plane to the RSOs in GEO. The selection of a slightly above or slightly below GEO altitude for the polar satellites appears arbitrary. The advantages a polar GEO SSA constellation provides stand out when comparing results

directly with the previous obtained optimal architectures using the foundational methodology. Table 7 directly compares these results.

Table 7. Foundational Methodology Compared with Refined Methodology

Date	Methodology	Ground Telescopes			Space Telescopes			Performance			
		0.5-meter Aperture	1.0-meter Aperture	1.5-meter Aperture	Aperture	#	Orbit	Size (in cm)	Latency (in min)	Cost (in \$B)	Value
21-Mar	Foundational	29			0.6	4	Super GEO	52.3	81.0	1.49	0.30
21-Mar	Refined		3	7	0.15	12	Polar GEO	26.0	83.8	1.04	0.46
11-May	Foundational	9	11	3	0.3 & 0.45	7	Equatorial LEO & Super GEO	53.6	47.0	1.75	0.39
11-May	Refined		13	6	0.15	12	Polar GEO	23.7	46.4	1.11	0.60
21-Jun	Foundational	5	26		0.3 & 0.45	6	Equatorial LEO & Super GEO	60.5	42.8	1.56	0.40
21-Jun	Refined	2	6	6	0.15	12	Polar GEO	33.8	43.9	1.17	0.56

The refined methodology increases the overall value of the GEO SSA architecture for all three dates previously analyzed. Size and cost are the two most improved performance criteria. For all three dates, the total number of ground telescopes was reduced while increasing the number of larger 1.5-meter aperture telescopes. The increased size performance was originally thought most likely due to the increased sensitivity of these 1.5-meter aperture ground telescopes. However, the January 11th results from the refined methodology demonstrate a low size RSO can be detected without any large aperture diameter ground telescopes. Therefore, the polar GEO satellites must be significant contributing factors to the RSO detection sensitivity of this architecture. Since the polar GEO satellites are not affected by the 40° solar exclusion angle as dramatically as equatorial LEO and near GEO, they can offer a better RSO detection capability. In all cases, the total architecture cost was reduced. This significantly increased the value score of the identified architectures.

The reduced cost of these architectures could be a result of the 95% learning curve applied to satellite acquisition costs. The learning curve formula is defined in Equation 3:

$$Total\ lot\ cost = T1 \times N^{1+\frac{\ln 0.95}{\ln 2}} \quad Eq\ 3.$$

where

$T1$ = the production cost of the first satellite

N = number of satellites

The polar GEO regime has the greatest potential reduction in per unit cost since the maximum number of polar GEO satellites was set at twelve. This was likely a contributing factor to the selection of that orbit. An experiment was conducted to examine the impact of the production cost learning curve. The results in Table 8 use an identical methodology as the results in Table 6 except the learning curve was changed from 0.95 to 1.00. This eliminated any potential bias towards space-based sensors because of the learning curve.

Table 8. Multiple Objective Results with Elimination of Satellite Learning Curve

	Ground Telescopes					Space Telescopes			Performance			
	0.5-meter Aperture	1.0-meter Aperture	1.5-meter Aperture	2.0-meter Aperture	2.5-meter Aperture	Aperture	#	Orbit	Size (in cm)	Latency (in min)	Cost (in \$B)	Value
1-Jan	9	16				0.15	12	Polar GEO	36.1	36.5	1.19	0.57
11-Jan		15	6			0.15	12	Polar GEO	23.9	42.9	1.35	0.58
21-Jan		12	6			0.15	12	Polar GEO	30.6	45.4	1.32	0.55
1-Feb	2	13	6			0.15	12	Polar GEO	26.5	48.6	1.33	0.55
11-Feb	1	18	1			0.15	10	Polar GEO	25.7	55.4	1.12	0.56
21-Feb		10	2			0.15	12	Polar GEO	32.7	61.6	1.17	0.50
1-Mar		18				0.15	10	Polar GEO	29.2	69.2	1.08	0.49
11-Mar		12	3			0.15	8	Polar GEO	21.8	84.8	0.99	0.48
21-Mar	7	12	3	1		0.30	5	Equatorial LEO & Super GEO	26.0	83.8	1.34	0.46
1-Apr		15	2			0.15	10	Polar GEO	25.4	70.2	1.16	0.50
11-Apr	2	10	4			0.15	12	Polar GEO	24.0	54.7	1.24	0.55
21-Apr		5	4	1		0.15	12	Polar GEO	29.5	59.8	1.24	0.51
1-May		10	5			0.15	12	Polar GEO	22.4	52.7	1.26	0.56
11-May	4	13	3			0.15	12	Polar GEO	26.7	46.8	1.24	0.57
21-May		13	2	1		0.15	12	Polar GEO	35.3	46.3	1.27	0.53
1-Jun		19				0.15	12	Polar GEO	25.1	43.6	1.21	0.59
11-Jun		13	5			0.15	12	Polar GEO	24.0	42.6	1.30	0.59
21-Jun	1	7	6		1	0.15	12	Polar GEO	32.9	44.8	1.38	0.53

The results show that even without the learning curve, the polar GEO satellites are preferred in all cases except on the equinox. The selection of three equatorial LEO satellites on the equinox does match earlier results from Stern et al. (2017) but does not match their final data set. This difference illustrates the variability involved when analyzing such a large trade space. In all cases, the value of the architecture was increased when including a 95% learning curve. The closest value between the two runs occurs on the equinox where elimination of the learning curve decreased the architecture value from 0.4582 to 0.4552. The fact that these two vastly different architectures have such a close score in value partially explains why the optimizer selects equatorial LEO and near GEO regimes over polar GEO on the equinox. Another interesting observation is that all the runs with the learning curve set at 95% were cheaper except for February 11th, March 1st, and March 11th. These dates correspond to the only dates (other than the equinox) where the total number of polar GEO satellites was decreased. All this leads to the conclusion that the optimizer selected the polar GEO regime over equatorial LEO and near GEO primarily because of the increased utility of that orbital plane geometry.

In order to define one GEO SSA architecture that is optimal year-round, the most common architectural components were selected. The architecture defined on February 1st using a satellite learning curve and June 11th without a satellite learning curve was the most commonly selected architecture by the optimizer. Because it was the most commonly selected architecture, it is likely the highest performing architecture throughout the year. Future work can simulate this architecture on every day of the year and compare that average performance with the average performance of any other architecture selected by the optimizer.

The identified architecture with the most optimal year-round performance is highlighted in red in Table 6. Two planes with six satellites per plane in a polar GEO orbit was identified as the space component to this optimal architecture. These two planes are separated by a 90° offset longitude of ascending node and mean anomaly. The complete orbital elements are: eccentricity equal to 0.000988, semi-major axis of 42,457 kilometers, 89° inclination, a longitude of ascending node set to 0° and 90° respectively, an argument of periapsis of 180° , and a mean anomaly set to 0° and 90° respectively. The ground component includes thirteen 1.0-meter aperture telescope and five 1.5-meter aperture telescope distributed at various locations around the globe. While other combinations of ground sensors are optimal on different days, this specific architecture was the only combination of ground sensors selected by the optimizer on two independent days.

CONCLUSION

The results of previous AFIT research as well as on-going research demonstrate the utility of model-based GEO SSA architecture evaluation. Running these analyses on HPCs compounds that utility. Trade space analysis and architecture evaluation on this scale would not be possible without the use of the HPC. The ability to run thousands of simulations in parallel allows analysis of architecture perturbations in a timely fashion. This leads to faster problem orientation and solution identification. A single four-core desktop machine would take more than 100 years to repeat the modeling, simulation, and evaluation conducted in this research.

Modeling and simulation of complex GEO SSA architectures provides a unique ability to understand the costs and benefits of different combinations of sensor

technologies. Visualizing the performance and cost tradeoffs from different components of the architecture is difficult since the trade space is so large and contains so many architectural elements. A parallel coordinates diagram can help visualize paths through multiple inputs in order to achieve a selected output. The relationship between different numbers of ground aperture sensors and different orbital regimes for value scores between 0.40 and 0.61 is highlighted in green in Figure 7. Darker lines indicate a stronger correlation to architectures with the high value score highlighted in green.

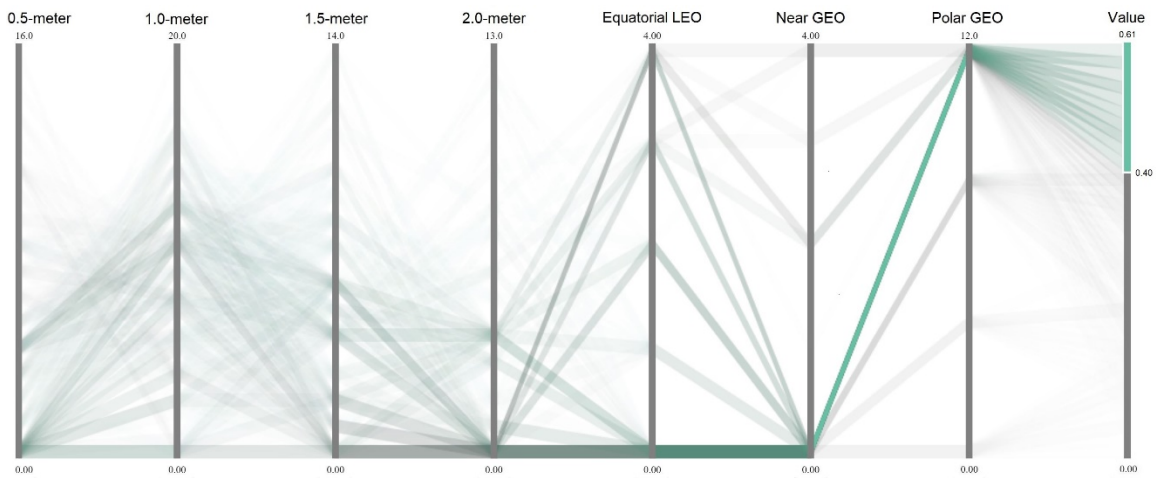


Figure 7. Parallel Coordinates Diagram for Architecture Elements

All architectures that scored higher than 0.40 in equal weighted value used a 12-satellite polar GEO space component. This exemplifies the utility of this specific orbital regime. The importance of the 1.0-meter aperture ground telescope is clearly seen from the spike in total number of 1.0-meter aperture ground telescopes. The dark green line emanating from the base of the near GEO column illustrates that very few high-scoring architectures used a near GEO satellite constellation.

The selection of specific ground telescope locations and aperture sizes is dependent on their compliment with a twelve-satellite polar GEO constellation divided equally into

two planes. Other ground telescope locations and aperture sizes can be selected and combined with the polar GEO constellation but should be considered a complimentary package with the space component only as a complete set. The identified optimal architectures are only optimal architectures for the single day that architecture was evaluated. Each of these optimal architectures have varying performance throughout the year. Figure 8 illustrates the performance, cost, and value variability for each optimal architecture.

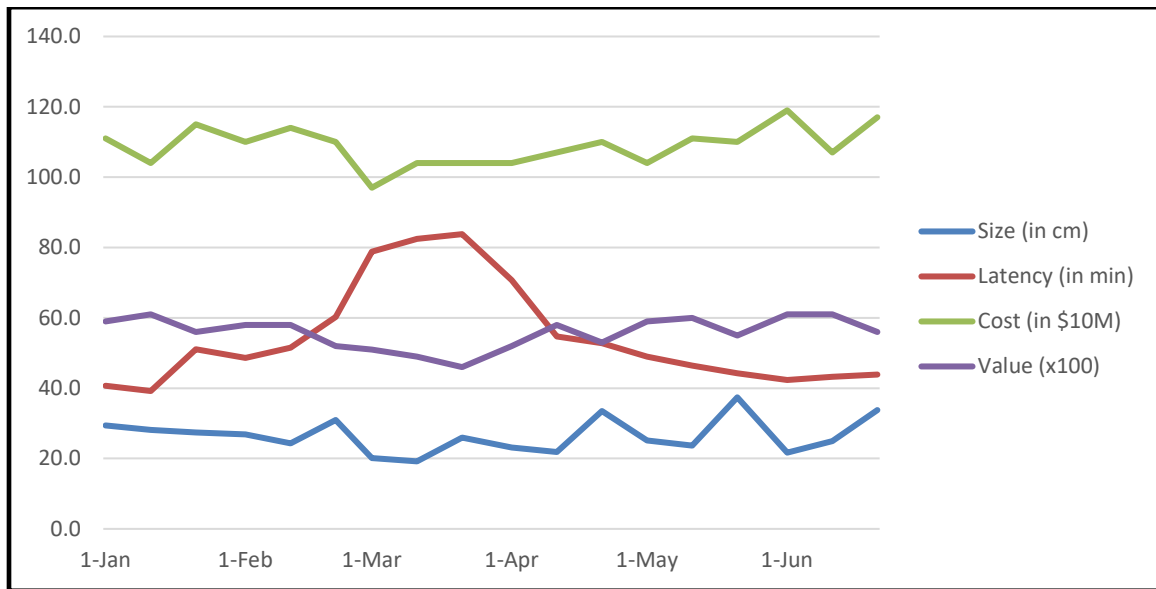


Figure 8. Optimal Architecture Performance Variation by Time

In this Figure, lower size and latency correspond to better performing architectures. The total system cost is identified in tens of millions of dollars. The value score is normalized from zero to 100 to show the overall value of the architecture when weighing all three performance criteria equally.

Since the optimal combination of ground-based and space-based sensors change throughout the year, this research identified the most commonly selected architecture as the most-likely year-round optimal architecture. This architecture is identified in Table 9.

Table 9. Final GEO SSA Architecture

Ground Telescopes		Space Telescopes		Performance			
1.0-meter Aperture	1.5-meter Aperture	0.15-meter Aperture	Orbit	Size (in cm)	Latency (in min)	Cost (in \$B)	Value
13	5	12	Polar GEO	26.9	48.6	1.10	0.58

These results form a complete ground and space-based system architecture with the greatest value in pursuit of a high-fidelity GEO SSA system. This architecture mirrors other optimal architectures found on different days of the year. The performance of this specific architecture is not guaranteed to be the most optimal architecture on any specific day but should offer the most optimal year-round performance.

The methodology designed by Stern et al. (2017) and refined through this research has a much greater utility than just as a tool for GEO SSA architecture evaluation. It can be used as a source selection tool to evaluate opposing contractor bids, a simulation tool for efficient evaluation of very large trade spaces, or an analysis workbench for comparison of emerging technologies. Scripting and parallel high-performance computing opens the possibility of solving an entirely new class of problems.

IV. Final Conclusions and Recommendations

Chapter Overview

This chapter summarizes the complete scholarly thesis. It contains conclusions from the overall effort of the research as well as a summary of specific findings as stated in the journal article. The significance of this research is explained. It also contains recommendations for actions that should be taken and potential future areas of study.

Conclusions of Research

The intent of this research was to improve knowledge of cost and performance tradeoffs for GEO SSA architectures by answering two research questions:

1. What combination of ground and space-based sensors provide the most cost-effective architecture for a high-fidelity GEO SSA system?
2. How does the optimal architecture change throughout the year because of Earth-Sun angle variations?

Various combinations of ground and space-based sensors were found on different days of the year. One architecture was selected as optimal for two independent days of the year and therefore selected as the most cost-effective architecture for a high-fidelity GEO SSA system. This architecture includes twelve 0.15-meter aperture sensors hosted on polar GEO satellites in two equal planes combined with thirteen 1.0-meter and five 1.5-meter aperture ground telescopes at varying locations. The space component of this optimal architecture is defined in Table 10.

Table 10. Optimal Space Architecture

Satellite Orbital Elements
Two Planes
Six satellites per plane
Eccentricity 0.000988
Semi Major Axis 42,457 km
Inclination 89°
Longitude of ascending node 0° & 90°
Argument of Periapsis 180°
Mean Anomaly 0° & 90°

The specific ground locations, aperture sizes, and number of telescopes selected by the optimizer for the date this optimal architecture was identified can be found in Table 11.

Table 11. Optimal Ground Architecture

Ground Telescope Locations
Three 1.0-m at La Palma, Canary Islands
Two 1.0-m at Mouna Kea
Four 1.0-m at IAO
Four 1.0-m at Siding Spring Australia
Three 1.5-m at Paranal, Chile
Two 1.5-m at Socorro, NM

The second research question was answered by identifying the optimal architecture found on several different days of the year and analyzing how that architecture changes as a result of the Earth-Sun angle variations. The changes in optimal architecture components can be found in Table 12.

Table 12. Optimal Ground Architecture Variations by Time

	Ground Telescopes				Space Telescopes			Performance			
	0.5-meter Aperture	1.0-meter Aperture	1.5-meter Aperture	2.0-meter Aperture	Aperture	#	Orbit	Size (in cm)	Latency (in min)	Cost (in \$B)	Value
1-Jan	5	6	8		0.15	12	Below Polar GEO	29.4	40.7	1.11	0.59
11-Jan	4	20			0.15	12	Above Polar GEO	28.1	39.2	1.04	0.61
21-Jan		3	10		0.15	12	Above Polar GEO	27.4	51.1	1.15	0.56
1-Feb		13	5		0.15	12	Above Polar GEO	26.9	48.6	1.10	0.58
11-Feb		19		2	0.15	12	Above Polar GEO	24.3	51.5	1.14	0.58
21-Feb		7	7		0.15	12	Above Polar GEO	31.0	60.3	1.10	0.52
1-Mar			5		0.15	12	Above Polar GEO	20.1	78.8	0.97	0.51
11-Mar		5	9		0.15	10	Below Polar GEO	19.2	82.5	1.04	0.49
21-Mar		3	7		0.15	12	Below Polar GEO	26.0	83.8	1.04	0.46
1-Apr		11	4		0.15	12	Below Polar GEO	23.1	70.7	1.04	0.52
11-Apr		19	2		0.15	12	Above Polar GEO	21.9	54.7	1.07	0.58
21-Apr		9	3	1	0.15	12	Below Polar GEO	33.5	52.8	1.10	0.53
1-May		18	1		0.15	12	Below Polar GEO	25.1	49.0	1.04	0.59
11-May		13	6		0.15	12	Below Polar GEO	23.7	46.4	1.11	0.60
21-May	3	13	5		0.15	12	Below Polar GEO	37.4	44.2	1.10	0.55
1-Jun		10	10		0.15	12	Above Polar GEO	21.7	42.3	1.19	0.61
11-Jun		15	3		0.15	12	Above Polar GEO	25.0	43.2	1.07	0.61
21-Jun	2	6	6		0.15	12	Below Polar GEO	33.8	43.9	1.17	0.56

The space component of this architecture stays relatively constant throughout the year. Minor variations in satellite altitude of the polar GEO constellation do not appear to have an effect on the overall value of the system. The ground architecture variations are more apparent since there are significant differences in optimal ground architectures based on the simulation day. The 1.0-meter aperture ground telescope was the most commonly selected component for the majority of identified optimal architectures. The next most common ground telescope was a 1.5-meter aperture. This demonstrates the importance of 1.0-meter and 1.5-meter aperture ground telescopes for an effective and efficient high-fidelity GEO SSA system.

The refined methodology searched a trade space 1000 times larger than previous research. This expanded search identified architectures that had an increased value by nearly 50%. Value was calculated using an equal weighting on all three performance criteria: total system cost, minimum detectable object size, and the time lag between

subsequent RSO observations. The identified polar GEO satellites were a large contributor to the overall increase in value. When performance is held constant, a polar GEO satellite constellation offers a 22.4% reduction in total system cost when compared to SSO, equatorial LEO, polar GEO, and near GEO.

Significance of Research

The significance of this research can be divided into two primary components. The first area involves advanced parallel computation and data analysis. This specific component of the research depended on the availability and usability of the DSRC's HPC Thunder. Parallel computation enabled over 100 years' worth of analysis to be accomplished in weeks. The methodology refined as part of this research contains a tool set for efficient evaluation of very large trade spaces. Application of this tool set could be applied to any large data set; it is not limited exclusively to GEO SSA architecture analysis.

The second significant component of this research is AGI's STK engine. Integration of the STK engine with the processing power of the HPC allowed unprecedented SSA architecture analysis. The ability to script inputs to STK provided an exponential efficiency improvement over the standard Graphical User Interface (GUI). This enabled increased exploration of different orbital planes and led to the final selection of the three evaluated orbital regimes: equatorial LEO, polar GEO, and near GEO.

Recommendations for Action

The utility of a polar GEO regime for observation of RSOs in GEO was demonstrated from this research. The author recommends any program office with an SSA mission, especially for GEO SSA, examine the polar GEO regime for placement of future

SSA satellites. Depending on where the program office is in the satellite development lifecycle, the author recommends pursuing a multiple satellite constellation with each satellite hosting a single 0.15-meter aperture optical sensor.

Recommendations for Future Research

There are several possible avenues for future research that could greatly enhance the utility and fidelity of this tool. These additional improvements can be divided into scheduler and non-scheduler related enhancements.

The scheduler algorithm used for this research has several potential areas of improvement. When an observation is made on a target RSO in GEO, only that one specific RSO is considered observed even if there are multiple RSOs in the sensor's FOV. The GEO belt contains sixty clusters of satellites within 0.6 degrees of each other in longitude (Abbot & Wallace, 2007). An updated scheduler could recognize these clusters as combined RSOs in order to take credit for multiple collects through a single observation window. This additional collection capability could greatly enhance the overall system latency.

A similar improvement could be made to decrease the observation window and enable more observations in any 24-hour period. The scheduler used for this research defines a 30-second observation window in order to account for slew and settle time between RSO collects. RSOs that are close together require less slew time. An updated scheduler could take advantage of this reduced slew time to accomplish multiple collects within one 30 second window by weighting smaller angular difference RSOs higher than

RSOs with a large angular distance. This weight factor could also be used to prioritize certain RSOs over other based on importance.

Improvements not related to the scheduler include expansion of the boundaries and refinement of the current methodology. This research identified optimal solutions that are bound by the limitations of the input parameters. To improve this, future research could expand the possible number of satellite planes in polar GEO and incorporate the phase angle as a performance parameter to maximize coverage on a particular area of the GEO belt. Additional orbital regimes and total number of possible ground telescopes could also be considered to evaluate a larger trade space. Vallado et al. (2016) identify several possible orbits that have a high percentage access to the GEO belt while maintaining a solar exclusion angle. To combat the additional trade space evaluation, architectural elements that are rarely chosen could be eliminated from the trade space analysis to increase efficiency.

The satellite learning curve could be applied to classes of space vehicles instead of specifically to certain orbital regimes. This would apply the learning curve to all satellites with a particular aperture size regardless of operational orbit. The results of this would make the methodology more realistic but is not likely to change the output since the optimizer rarely selected other orbital regimes even when there was no satellite learning curve.

Future SSA architectures will undoubtedly utilize commercial systems. These commercial systems could utilize a fee based service to fill in coverage gaps or to perform general catalog maintenance. Modeling of these commercial capabilities could enhance the refined methodology included in this research. Incorporation of these commercial systems

may require adaptation of a more standard evaluation metric. These evaluation metrics are consistently used across the DoD and commercial in order to maintain consistency when evaluating different architectures.

Since the optimal combination of ground-based and space-based sensors change throughout the year, future analysis could simulate each optimal architecture on every day of the year and compare that average performance with the average performance of every other architecture selected by the optimizer. This would guarantee the identified optimal architecture provides the greatest year-round value for GEO SSA. And lastly, since operational, acquisition, and launch costs are always changing; these areas could be refined through future cost estimation research. These improvements could further expand the trade space and increase the efficiency and utility of this methodology.

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14. ABSTRACT Improving Space Situational Awareness (SSA) remains one of the DoD's top priorities. Current research has shown that modeling of GEO SSA architectures can identify optimal combinations of ground and space-based sensors. This thesis extends previous research by expanding design boundaries and refining the methodology. A genetic algorithm examined this increased trade space containing 10^{22} possible architectures. Experimental trials that would have taken over 100 years on a desktop computer were completed in weeks using a high-performance computer containing over 125,000 cores. The results of the optimizer clearly favor 1.0-meter aperture ground telescopes combined with 0.15-meter aperture sensors in a 12-satellite polar GEO constellation. The 1.0-meter aperture ground telescopes have the best cost-performance combination for detecting Resident Space Objects (RSOs) in GEO. The polar GEO regime offers increased access to GEO RSOs since other orbits are restricted by the 40° solar exclusion angle. When performance is held constant, a polar GEO satellite constellation offers a 22.4% reduction in total system cost when compared to Sun Synchronous Orbit, equatorial LEO, and near GEO constellations. The results of this research can be used to educate national policy makers on the benefits of various proposed upgrades to current and future SSA systems.					
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