Proliferated Sensor Network (PSN) Performance Study & Architecture Design Optimization

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ABSTRACT

The implementation of less capable, but more affordable sensors, distributed throughout a domain of interest, complement and augment more capable primary sensors. Proliferated Sensor Networks (PSN) provide persistent monitoring of the domain, resilience to natural and human made threats and uncued detection and alert of evolving events. Lockheed Martin, working with Curtin University in Australia, has been developing proliferated sensors for multiple mission applications including space domain awareness (SDA) and hypersonic vehicle tracking. Researchers at Lockheed Martin's Advanced Technology Center (ATC) are leading a study to explore the capability enhancement of PSNs on legacy architectures and optimization of the design of PSN architectures including design of the sensors themselves. Studies are being undertaken in both SDA and hypersonic defense. This paper will focus on the SDA mission but will reference lessons learned from the broader set of mission spaces and will explore two key attributes of PNSs for space security, persistence and resilience.

More capable systems, typically with larger collecting apertures, offer very good sensitivity and accuracy, but their costs prohibit construction and operation of more than a handful of units and with a typically narrow field of view, do not offer significant persistent observation of the domain. At the same time, PSN sensors typically sacrifice sensitivity and accuracy in the goal of affordability which is key to proliferation and thus persistent monitoring of the domain. The objective of Lockheed Martin's study is to optimize performance of the entire network, PSN plus primary sensors, against the population of objects of interest. This study also factors in domain attributes such as weather and the variability of object lighting. Optical systems, unlike many radio frequency (RF) systems, cannot operate when conditions are cloudy or when photometric performance is degraded as in the presence of high humidity or thin clouds. One obvious advantage to PSNs is that while one site might be impacted by weather, additional local or regional sites might be operating in good weather. Lighting conditions of target objects are also highly variable with the orientation of the object, solar phase angle and sensor line of site all contributing to object brightness that can vary by orders of magnitude. To a sensor at one site, an object may appear dim while at a site a few hundred kilometers away, the object may be bright.

This paper will attempt to formalize the concept of PSNs, summarize the current state of the art for PSNs, development of modeling and simulation tools, results of this study to date and propose next steps for research and development activity as well as recommendations for implementation of existing capabilities.

1. INTRODUCTION

Space is congested, competitive and contested; the number of objects reported on the Space-Track website at the time of writing was 44,800 with 8,600 of those being active satellites [1]. These numbers continue to trend upwards with ESA reporting 4,203 new objects on orbit in 2022 and 2,435 objects re-entering the Earth's atmosphere leaving a net increase of 1,768 objects over the year [2]. With planned launches continuing to rise and filings for new satellite constellations growing, operators are faced with a significant growth in conjunction warnings. A lot of unknowns remain about how this unprecedented boom in both space-based assets and debris will impact space and the Earth's environment [3]. There is ongoing discussion in the space research and industry community as to the severity of the impact of the growth in resident space object (RSO) population on satellite operations. As in other domains, i.e. air and maritime, many of these challenges can be addressed by increased surveillance and the risks from congestion managed, at least in the short term. The increase in how often operators maneuver, and the manner in which they maneuver, is more concerning and requires more than just an increase in surveillance but rather a change in overall approach to surveillance. SpaceX registered over 25,000 maneuvers between December 1 2022 and May 31 2023 with a doubling in the number of maneuvers over the previous six months [4]. If this trend continues, we would be looking at millions of maneuver event per year in the not-too-distant future.

Much of the development effort in the SDA community is in improving accuracy of observation and improving orbit determination and propagation capabilities. All this effort can be thwarted the moment an operator maneuvers their satellite, especially if such maneuver occurs just after the object was tracked. To address this challenge, we need to be working towards near continuous custody of objects. Orbit propagation and prediction are still essential for managing the large population of inactive debris. A sensor network capable of positively identifying and tracking every object at a cadence commensurate with its ability to maneuver is essential. The definition of what this tactical cadence is still needs further definition, but it is likely more than multiple times per day. As noted by Ackerman et al in their 2015 Space Symposium paper, we need to move from a mode of what could best be described as reconnaissance, obtaining "a momentary look at a region of space and then move on to look at other areas", to a mode of real surveillance [5].

We propose that a Proliferated Sensor Network (PSN) approach is necessary to address the tactical custody requirements for the space environment that is emerging today. A PSN, comprised of a large number of less precise, but more affordable sensors, distributed throughout the domain, augments existing sensor capabilities by early detection of changes in object state and by maintaining custody; not predictive custody, but rather positive custody achieved by handing observation over from one sensor to the next. There has been a gradual evolution to PSN like capabilities, but Lockheed Martin and our partners are working to formalize the structure of such sensor networks, more carefully defining requirements and following up with development in core areas such as sensor technology, sensor data processing, secure distributed networking, change detection and event driven tasking to higher echelon sensors. In this paper, we will attempt to formalize a definition for PSNs, consider a framework in which to evaluate architectures and trades, provide an early set of study results informing the benefits of PSNs and report on the development of our Full Custody Space Sensor Simulation (FCS3) which will support our work going forward.

2. PROLIFERATED SENSING NETWORK ARCHITECTURE

Traditionally, sensors have been designed to provide a very high level of sensitivity and measurement accuracy over a large field of regard as depicted in Fig. 1. With a large field of regard, in order to observe small objects, tens of centimeters or smaller, at long range, sensors must have sufficient sensitivity to detect very dim objects, dimmer than 18 visual magnitude. For an optical system, this level of sensitivity requires larger apertures, likely greater than

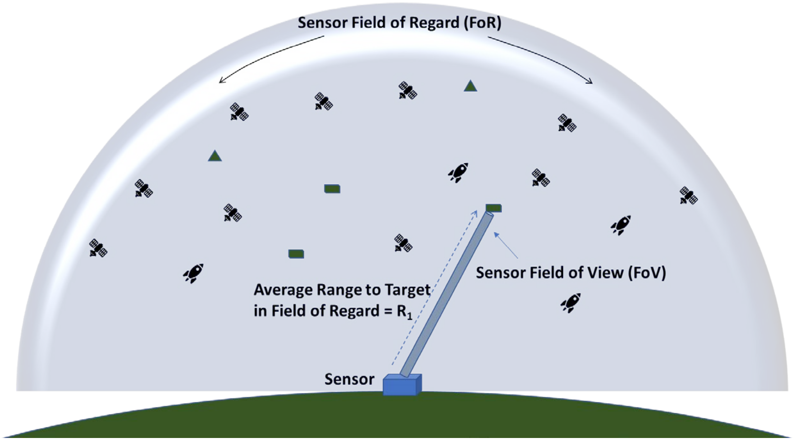


Fig. 1: Traditional SDA Sensor Architecture with High Capability Sensor.

1 meter. For an active radio frequency (RF) system, i.e. a radar system, more transmitting power and larger arrays of receiving antenna are required to observe small objects at a large distance. Measurement accuracy, typically some measure of positional uncertainty at the target, requires significant angular accuracy at the sensor when that sensor is a long range from the target. These factors naturally drive the cost of the sensors to be quite expensive. As reported previously at the AMOS conference in 2021, upgrading the existing GEODSS sensors would cost \$119 million, the Space Surveillance Telescope (SST) cost \$150 million for the telescope and 2 sensors and for a single Space Based Space Surveillance (SBSS) system, \$823 million [6]. Each of these systems has exquisite capabilities, but at a significant cost. With such price tags, these systems are not likely to be replicated in large numbers.

An alternate approach that would complement more traditional sensing systems would take advantage of a larger number of sensors distributed around and throughout an operational domain, each with significantly less capability in terms of sensitivity and measurement accuracy but delivering the same level of performance in aggregate (Fig. 2). The range from any one sensor in the network to any target of interest is, on average, greatly reduced. Given that the brightness of an object is a function of the inverse square of the range, shorter ranges mean less sensitive sensors are required. Smaller apertures and commercial off the shelf focal planes, which are cheaper to produce, will be put into play. Detailed analysis is yet to be undertaken to assess how each architecture compares in cost. That will be part of future analysis.

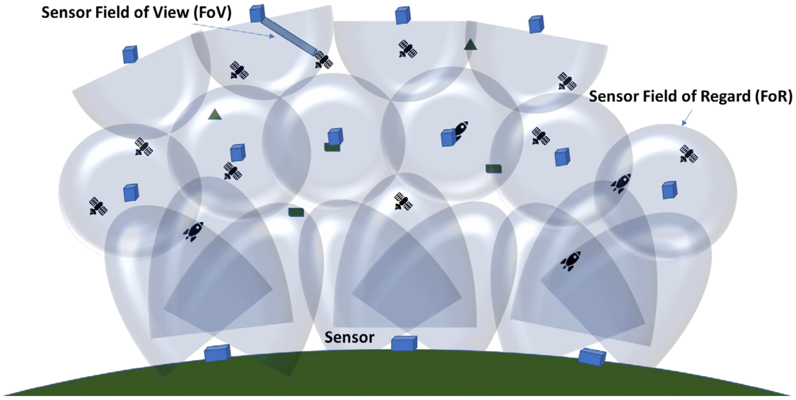


Fig. 2: Alternate SDA Sensor Architecture with Proliferated Sensors.

2.1 Custody and Sensing Diversity

One feature of a PSN is that the ratio of sensors to targets is increased. Most sensors, except for some extremely capable and one-of-a-kind like Space Fence, have a limited field of view which can be moved throughout the field of regard. Sensors typically engage one target at a time, possibly a few objects if they are clustered closely, although tracking multiple closely spaced object is no trivial matter [7]. With tens of thousands of objects, sensors spend very little time observing each and revisits each object infrequently. More sensors naturally increase the rate of revisit and or the time spent observing objects.

To maintain custody of objects, it is not necessary to have constant observation, but it must be at a rate sufficient to detect change. For a piece of debris that is completely inactive, the object is affected by external forces such as solar radiation pressure (SRP), local variations in Earth’s gravity, drag, charged party interaction, or impact with other objects. These objects need only be observed at a rate sufficient to update orbits to account for uncertainties in estimation of external forces and orbit propagation. Active satellite and even inactive satellites can change state at any moment by maneuvering, configuration change, deployment of new objects, breakup, etc. Such changes in state are already occurring and are expected to only increase dramatically as new and emerging capabilities are deployed. These objects do require very regular observation. PSNs uniquely contribute to addressing the growing requirements for frequent revisit of objects.

The observed brightness of an object depends on a number of factors including the object size, the geometry between the illumination source, object and observer (solar phase angle in the case of solar illumination), range to the target, atmospheric extinction and physical characteristics of the object. Often observers attempt to ascribe a correlation between object size and object brightness. In reality, the brightness of any particular object will vary significantly. A larger object will sometimes go undetected when a sensor would be expected to be able to see it while a smaller object that should not be visible, will be detected. A large-scale, proliferated network of sensors has a higher probability of detecting a dim object. As seen in Fig. 3, the same object, with brightness normalized for solar phase angle and range, can have brightness that varies over two visual magnitudes (factor of 5 in flux). This data was taken by FireOPAL systems positioned around Australia which observed the same objects at roughly the same time, but from a diverse set of viewing angles and object perspectives.

There are other aspects of sensor diversity that have yet not been fully investigated. Photometric data from different viewing angles and object perspectives measured near simultaneously, may contain information about object dynamics, identification, and aid in change detection. Observation diversity might also aid tracking and orbit determination efforts. For example, slant range can be estimated from optical observations from geographically disparate sensors looking at the same volume of space at the same time (via trigonometric parallax).

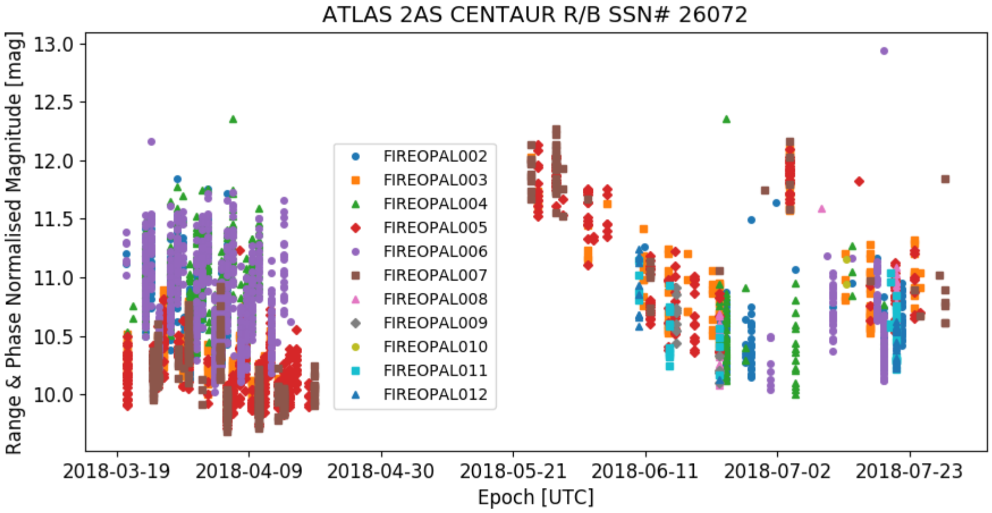


Fig. 3. Normalized brightness (for phase angle and range) for a rocket body observed from a diverse set of FireOPAL sensors around Australia as a function of date and time of observation.

2.2 Tasked, Survey and Uncued Collection

Most SDA sensors operate as a tasked sensor as they have a narrow field of view. With a field of view typically less than a degree, a tasked system is typically pointed towards a known object of interest, acquired, and tracked. Tasked sensors have a limited ability to search for an object if it cannot be initially acquired. Tasked sensors may be able to perform a limited search around where the object should be, but this may not extend beyond a few degrees. Tasked sensors generally only track one object at a time, as previously noted. Their advantage lies in that they can provide good tracking data and potentially other characterization data on known objects. Once provided a request to track an object, the process of tracking, from slewing to acquire, acquisition, collecting data on the object and preparation to move to the next target in the queue can take some number of minutes. In a night, a sensor may provide data on a limited number of objects. The GEODSS telescopes with a field of view of about 2 square degrees, can be tasked to observe an object and the neighborhood around that object, or may be tasked to perform a search of a limited area of the sky. The focus of the GEODSS system is on the GEO orbit limiting the amount of sky to be searched [8].

Telescopes such as the Pan-STARRS wide-field optical and NIR survey telescope have a field of view covering about 7 square degrees. The Space Surveillance Telescope, which has been relocated to Western Australia has a similar field of view but a larger collecting aperture [9]. Pan-STARRS, with a gigapixel detector, has an impressive etendue of $50m^2deg^2$ which allows it to complete a full survey of the night sky in about a week down to the 24th visible magnitude [10]. Pan-STARRS is used primarily for astronomy while SST is primarily focused on the space security mission. Given their ability to perform uncued search for very dim objects, they are ideal for discovery of new objects including very small debris. Still, in survey mode, they are inefficient at providing data on active systems at a tactical cadence.

An uncued sensor, typically one with a very wide field of view of many degrees, will be able to track many objects at one time and will track objects without being tasked. Any object that is detectable in the sensor field of view will be observed and reported. Objects in the field of view are extracted and processed as individual observations meaning a large number of objects can be observed simultaneously. These are not tasked sensors. They are collecting on anything they can detect be they known objects, new unknown objects or objects that may have moved or otherwise undergone some change. The field of view includes background stars which aid in astrometric calibration. Such sensors are not going to detect the smallest and dimmest objects, but that capability may not be required when looking for changes in objects and object behaviors as most objects capable of producing effects are larger objects. They are generally collecting and storing information for weeks to months or even years, depending on the data storage scheme. This data can be searched and long histories constructed on objects that become targets of interest. This helps address the unknown unknowns problem.

2.3 Event Alerting & Sensor Hierarchy

There is no one fits all sensor solution for SDA. SDA requires comprehensive understanding of all resident space objects in all orbital regimes, their behavior, what is normal and what is not normal, the space environment and any factor that could impact space operations. As noted in the Space Forces Space Doctrine Notes in 2022, “SDA is fundamental to the conduct of all space operations and is dependent on integrating ISR and environmental monitoring information across all orbital, terrestrial and link segments” [11]. Every government, civil and commercial sensor currently contributing to SDA is necessary. Nothing in the approach to PSNs replaces these existing sensors and likely those capabilities need to be greatly expanded.

Existing sensors are resource limited. They require a method to prioritize and schedule activities that is in reaction to ongoing events and not just based on predetermined lists. The primary role for PSNs in the SDA hierarchy is to monitor as much of the space domain at a tactical cadence, conduct change detection and event recognition, and use this information to inform other sensors. Alerting to possible events enables more capable sensors to respond to near real time activities. Adversaries and other potential threats are not always easy to identify, especially as the number and nature of operators in space has grown beyond the traditional space actors. There is a lot of work that we can draw upon from the transient astronomy community. Much of what is exciting in astronomy happens on short time scales, from minutes to weeks. Astronomers have been honing capabilities to recognize transient events in sky surveys, categorize these events, prioritize alerts and disseminate the alerts to enable immediate follow-up by other astronomers and instruments [12].

In SDA, understanding and predicting an objects behavior, and thus the behaviors of the operators, requires an extensive history in order to establish what is normal and what is not normal. This history is not just temporal, as in data collected intermittently for a long period of time. The history involves more regular collection, temporarily and geographically, throughout an object’s day in the life. Observing a satellite from the same location at the same time every day may be uninformative, as the satellite always seems to be doing the same thing, but this can also be very misleading. The satellite may be very active and varied in its activity in other parts of its orbit. Without a complete history, it is hard to establish real patterns and to understand what is normal and not normal. PSNs have the capacity to contribute to the collection of these more complete histories.

2.4 Sensor Network Resiliency

In broad terms, resilience is the ability for a system including all of its constituent part to operate to some degree and provide threshold capability in the face of adverse events, and or the ability to rapidly recover from a degraded condition. U.S. Space Force and Space Systems Command have set goals to increase resiliency in the space architecture by the year 2026 [13]. Resilience is not limited to the satellites that we fly, but to everything that ensures delivery of critical services including satellite ground stations and space domain awareness systems. Systems with exquisite capabilities are not inherently resilient. Because they are very expensive, they are not produced in large quantities, or even quantities greater than one, and therefore if they fail, capability essentially goes to zero. The risk and operational threat posed to such capabilities has only increased from both nefarious means and less nefarious means – such as severe weather conditions, power system failure, loss of network connectivity or communications or even issues in supply chain for critical replacement components.

Physical defenses, backup systems and enhanced cyber security are all approaches to addressing resiliency through system robustness, but disaggregation may offer more resilience by spreading capabilities across distributed systems [14]. PSNs are disaggregated systems and for SDA offer a significant improvement in resilience. In many cases, multiple sensors may have the ability to observe the same object so if one sensor is offline due to weather, reliability issues or physical damage or loss, another sensor can continue to provide information. If there is not overlap in sensor coverage, there may be degradation in the rate of revisit of an object, but there will still be some continued capability. Since PSN sensors are more affordable and often use more commonly available commercial off the shelf componentry, there is built in supply chain resilience for maintenance and reconstituting capability by building and deploying additional sensors which is more cost effective and quicker as compared to a very capable sensor.

Since sensors are at physically separated locations throughout an operating domain, on a variety of potential platforms such as the ground, space based or on a maritime or mobile system, direct physical attach of the whole network would be extremely difficult. The sensor systems will be connected over a variety of communication network channels or even a variety of communication networks making cyber-attacks on the system more difficult. Optical sensors cannot operate through clouds and even RF system performance can be degraded in heavy precipitation or through external electromagnetic interference, but with distributed systems, there is a high likelihood that a significant portion of the sensor network will not be impacted.

There is a tradeoff between resilience and robustness. Making a sensor system highly reliable, likely greater than 99.9% reliable can be expensive. Reliability requires a great deal of redundancy, extensive software engineering and selection of more expensive components and suppliers. While it is still desirable to have a reliable sensor, and one that provides a certain level of quality in data, because system outage does not have catastrophic impacts on the mission, the reliability metric does not require so many nines.

It is most likely that services from PSNs will come from commercial entities. These data services will be integrated with government data. Accepting data from commercial entities requires a level of trust. Without careful consideration to the design of PSNs including sensor performance, network security, maintenance and servicing of the system and even modernization of the capability to address new mission requirements, all manner of resilience can be lost [15].

3. PROLIFERATED SENSORS AND PLATFORMS STATE OF THE ART

3.1 Overview of the FireOPAL System

The FireOPAL system is a real-world example of a PSN (Fig. 4). The system has been under development since 2018 in partnership with Lockheed Martin and Curtin University [16, 17]. FireOPAL comprises a distributed network of ground based, standalone, fixed mount optical sensors designed to monitor a large number of RSOs at high cadence (see Fig. 4 below). It is an uncued system that reports observations of all objects of sufficient brightness that move through its very wide field of view. With a field of view of hundreds of square degrees, more than 100 satellites may be observed simultaneously in one image. To date, more than 20 FireOPAL sensor system have been built and deployed around Australia. The hardware comprises a majority of COTS components including a small aperture prime lens (80-100mm), large format CMOS detector, and modest computational resources. Each unit has sufficient computational resources to process a full frame image every 5-10 seconds and reports metric observations in near real time. The observations have been shown to have an accuracy of 1-2 arcseconds for angles, less than 1 millisecond uncertainty for timing, and less than 10% uncertainty in absolute flux. During one clear night, a single sensor typically generates tens of thousands of observations of hundreds of satellites. FireOPAL has been shown to meet, and some cases, exceed the requirements and guidelines set by the US Air Force Space Command Instruction 10-610 "Space Situational Awareness Metric Data Integration Guidelines for Non-Traditional Sensors". The capabilities of FireOPAL have also been demonstrated at several recent Sprint Advanced Concept Training events.

3.2 FireOPAL Data Processing Architecture and Advanced Algorithm Development

Custom image processing has been developed to identify, calibrate, and report observations of objects that appear to move like a satellite through each FireOPAL sensor field of view.

The near real time processing system comprises three families of detection algorithms, run in parallel, that identify long streaks ('LEOs'), short streaks ('MEOs') and quasi-stationary objects ('GEOs'). Astrometric and photometric calibration is performed using in-frame background stars proximate to the satellite observations. For streaks, time-adjacent frames are used to determine the direction of motion for the streaks. For quasi-stationary objects, several frames are combined to increase the sensitivity to faint objects in GEO. To aid with post-processing, an attempt is made to correlate each observation with satellites in the public space-track.org catalog. The identity of any satellites predicted to be near an observation and moving in a similar direction are used to tag the observations. However, because FireOPAL is an uncued system, this suggested correlation needs further processing in order to be confirmed or refuted. A high-performance, low-latency middleware system aggregates and publishes all results to end users; the calibrated results are typically sent to users in less than 10 seconds after the shutter closes for each image.

Fig. 4: Picture of the FireOPAL system near Uralla, NSW.

An experimental image processing system is also under development. This system uses algorithms that enable the detection of extremely faint objects (signal-to-noise ratio ≈ 1 in a single image). This image processing is a variant of a track-before-detect approach and is computationally intensive. It uses a hierarchical Radon transform extended into the time domain, identifying patterns in the noise between consecutive images. This has been used to demonstrate the detection of more than 90% of all objects in the space-track.org public catalog predicted to move through the FireOPAL field of view. Additional investment is being made to improve the performance of this system to enable it to run in near real time.

3.3 Next Generation FireOPAL Sensor Improvements

The low-cost, modular nature of FireOPAL and use of COTS hardware mean that upgrades to the system can be rolled out over time with little disruption to operations. The rapid pace of improved performance of commercial CMOS detectors and CPUs mean that key capabilities of FireOPAL, such as angular resolution, sensitivity, and cadence, will also improve commensurately. For example, CMOS detectors with hundreds of megapixels each are now commercially available. Low-cost technical refreshes, on the order of once every couple of years, are another principal advantage of PSN like FireOPAL.

3.4 Inovor Hyperion Space Based SDA System

Inovor is developing a space-based space domain awareness platform named Hyperion, Fig. 5, designed to provide an affordable constellation of satellites flying in LEO providing SDA services on objects in LEO, MEO, and GEO and Cis Lunar orbits. We are using Hyperion in our simulations as the basis for a space based PSN. Operating in a constellation, multiple sensors would observe a GEO object from multiple vantage points simultaneously in support of object tracking, characterization, and identification. Hand over from one satellite in the constellation to another, means we can maintain persistent custody of any MEO or GEO object. Hyperion is built on Inovor's 12U Apogee bus and that uses a novel computer vision system developed with the Australian Institute for Machine learning to aid in detection of very faint objects from a set of images using machine learning algorithms.

Fig. 5: Drawing of Inovor's Hyperion SDA sensor on 12U Apogee bus flying in LEO with the engineering design unit shown in the inset.

4. METRICS FOR PROLIFERATED SENSING NETWORKS

Developing architectures for PSNs requires exploring a complex trade space including metrics like persistence, sensor sensitivity, tracking accuracy, imaging resolution, cost and resilience. We have just started exploring this trade space and there is much work to be done. The simulation tool has been a limiting factor in this work. In Section 6 we will discuss the development of the Full Custody Space Sensor Simulation (FCS3) which we expect will aid in a more informative exploration of these trades. To date, most of the work has focused on addressing custody of objects, with many of the other metrics fixed to performance of existing sensors. While this is a good starting point, we would like to better understand how to optimize the architecture including sensor design as well as the networking, data ingest and data analytics around the sensors.

4.1 Custody & Persistence

We model custody as the degree of observation persistence measured in two different ways, the first the rate of re-observation of an object, which we refer to as the revisit time and the second, the number of independent observations in a period of time. There is a subtle difference between the two. The revisit time is a good metric if looking at a global network of sensors, especially if those sensors are optical and only able to operate at night, as some portion of the sensors are likely in the dark at any time of day. In looking at revisit time, we are trying to minimize the time gaps between observation where an event such as a maneuver can go unnoticed. As the revisit time goes to zero, we are in effect always observing the object and would detect any observable changes as they happen.

Constant observation of everything may not be an achievable goal in the short term. The question remains, how do we define an objective revisit time? If an object maneuvers, we likely have some time after that event before we must track it again to prevent losing the object or losing the ability to positively identifying that object. Over time, the object will drift further away from its predicted orbit and these tasks will become more difficult. At this stage in our studies, we might declare a heuristic assumption that a *threshold* revisit time for any sensor network should be less than 10 hours with an *objective* revisit time of around 1-hour. We are planning future activities to explore optimal objectives for revisit time.

The second metric noted above was the number of independent observations in a period of time. This is a good metric if we are looking at PSNs limited to a smaller geographic region. Without global coverage, half of the day or more might be in daylight and for an optical system, this would create large gaps in revisit time. Sensing diversity is another factor in custody. More independent observations over longer portions of an object's orbit will help improve object tracking and orbit determination. Multiple independent observations of the same object at the same time will also contribute to pose determination, developing behavior histories and object signatures and identification.

4.2 Sensitivity

We treat sensor sensitivity as a fixed input to current simulations. Sensor performance is anchored to data collected over the last few years by fielded sensors. This data was collected during clear skies, but clear skies will represent a range of conditions from photometric quality nights to non-photometric nights that can include high cirrus clouds, and so represents average sensor performance. We use the average observed brightness, measured in visual magnitude, for an object of a given size at a given range. When the simulation is employing the actual catalog of space objects, the object size is derived from the published radar cross section (if known). Where we use hypothetical objects, we define the object size and brightness. In the current simulations, if the average object brightness exceeds the threshold sensor sensitivity, it is tracked.

As previously discussed, there can be a lot of variability in object brightness. From the data collected, we see variability in the brightness of objects at the same solar phase angle just due to the pose of the object. To a lesser extent there can be variability of brightness within the same class of objects depending on their materials and material aging, although not likely to the extent observed in SpaceX's painted DarkSat [18]. Future simulations will include a catalog of observed object brightness and brightness statistics from fielded sensors seeding a Monte Carlo brightness model.

As we extend the study of PSNs, we wish to explore the trade space around sensor sensitivity making sensitivity a variable, typically represented by collecting aperture size. With the FireOPAL sensor, we attempted to maximize sensitivity within the constraints of low cost, commercially available hardware. That still leaves open the question: what does 'good enough' look like? There is a trade between system performance and numbers of systems, both driving complexity and cost in different ways.

4.3 Accuracy and Resolution

Field of view for a sensor is a primary driver for tracking performance or imaging resolution. When employing existing commercial focal planes, we are limited to a fixed number of pixels. In a wide field of view system, the field of view projected onto a single pixel, the instantaneous field of view, is large, thus limiting sensor angular resolution. Sensors with a narrow field of view have better performance in this regard, but they suffer from other challenges including platform jitter, the number of objects that can be tracked per unit time, and a reliance on mount models to determine pointing angles. We have not factored tracking accuracy and resolution into our simulations and studies to date. We have assumed that the sensors modeled have sufficient sensitivity and tracking accuracy.

With the FireOPAL system, we have achieved operationally relevant performance in this regard, as tested in various exercises. There is a computational cost to achieving this performance. An expectation of the PSN approach is a reduction ofthe average range between any one sensor and target. This relaxes the requirement for angular resolution of a sensor potentially driving sensor costs down, but increasing the number of sensors requires, a cost trade that will be investigated. In future studies we will trade accuracy and resolution against other design variables.

4.4 Cost

Cost can be a contentious issue to discuss in a public forum. For competitive reasons, many companies are not inclined to publish cost data. As the commercial SDA market gets its start, market participants may also be less inclined to share cost data as it could set pricing expectations. Even in an apples-to-apples comparison of a system there will be a lot of variation in cost estimates. We have not factored cost into the simulation yet, but our intent is to implement a simple parameterized sensor solutions using rough categories as seen in Table 1.

Cost Category	Cost Range
Level A	<$50K
Level B	$50K-$200K
Level C	$200K - $500K
Level D	$500K - $1M
Level E	$1M - $10M
Level F	$10M - $100M
Level G	>$100M

Table 1: Parameterized Cost Metrics for Future PSN Trade Studies.

4.5 Resilience

Resilience may be the most difficult factor to quantify. The easiest metric to consider is the increase in revisit time with the elimination of sensors from the network. This is where we are currently at in our studies. If there were only one sensor normally in operation, and it went out of operation, of course we would be blind, and if there were a very large number of sensors in the network, and only a few became inoperable, this would result in a small degradation in performance. These boundaries are not very interesting though. In the real world, clusters of sensors may be offline at points in time due to large scale weather events or possibly localized network outages. The number of operable sensors in a network is not a very good representation of reality, beyond the impact of individual sensor reliability and we are seeking better metrics and methods to assess and represent resilience. We are working on a simulation capability, described below, that will allow us to simulate more complex scenarios and events.

Our concerns are not just limited to the sensors themselves. A worst-case event could be a failure at a central C2 node that takes the whole network offline. The United States Federal Aviation Administration has experienced a number of such events on their aging infrastructure, including two fires that disrupted communications in Chicago in 1988 and again in 2014 with long lasting impacts to air travel nationwide [19]. If we are going to truly address resilience, we need to factor in the design of the network and properly model failures at different levels of the network from the local site up to the central C2.

Resilience is not just about operating through the outage but must also factor in recovery time from the event. A weather system moving through a region might take ground based optical sensors offline, but sensors might be back online the next evening after the weather moves through. At the same time weather can bring about long periods of cloudy nights and take ground bases systems offline for days or weeks. Network outages caused by software failures may only last a few minutes where hardware damage can take hours, days or weeks to repair. In the case of the FireOPAL system, there are multiple sensor units that are kept in reserve and can be put in operation to replace a failed unit. This requires personnel to physically remove and replace the sensor unit, which can be completed in a matter of a few hours. In the case of a larger narrow field optical system, recovery from hardware failures can take a lot longer. In March of 2010, the azimuth drive on the AEOS telescope failed requiring six months to formulate a repair plan with the replacement drive installed in August of 2011 [20]. The replacement of satellite-based platforms can take even longer although that is changing with lower cost satellites that can be kept in reserve for rapid launch, spare on orbit systems and responsive launch opportunities [21].

5. INITIAL MODELING AND SIMULATION RESULTS

5.1 Modeling of a Global Network of FireOPAL Sensors

We have constructed a number of sensor laydown across the globe and using STK, have looked at the revisit time for a global network of FireOPAL sensors against low Earth satellites. We assume these sensor sites are distributed around the Earth in rings at different latitudes and at equal spacing in longitude. The sensors are set up to provide complete sky coverage above 30 degrees off the horizon. This requires more than 50 camera apertures to tile across the whole sky. We did not attempt to model anything beyond the ability for a sensor site to have access to an object. It was assumed that this was an object larger than a 6U cubesat and would be detectable by the FireOPAL sensor. Sensor access requires that the sensor is in the dark and the satellite is sunlit. The satellite was orbited in circular orbits at altitudes from 500km to 5000km and with inclinations of 0 to 60 degrees. The orbit was simulated over a period of 12 months to collect sufficient statistics and to sample lighting conditions throughout all seasons. It was assumed that the weather was clear at each sensor site and the sensors were always operating normally. The sites are random, and we did not attempt to place sensors on land or a site that would be suitable for hosting a sensor.

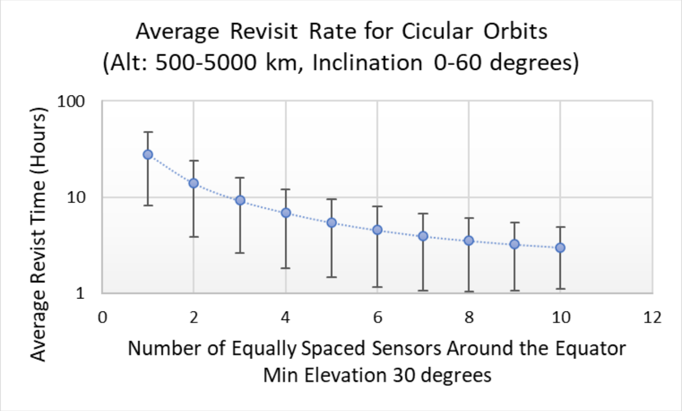


Fig. 6: Analysis of an equatorial network of FireOPAL sensors monitoring LEO Satellites.

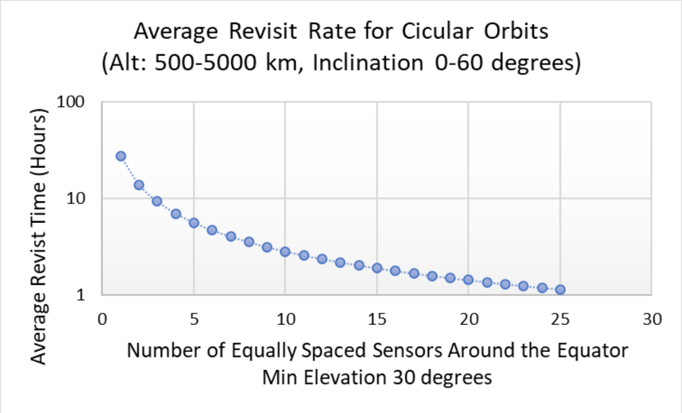


Fig. 7: Analysis of an equatorial network of FireOPAL sensors monitoring LEO Satellites with target of 1-hour revisit times.

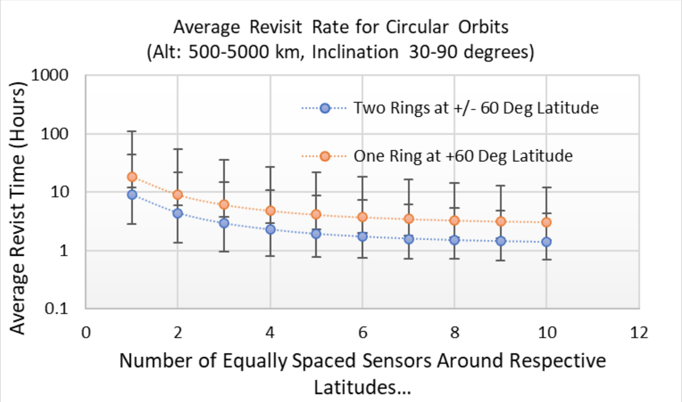


Fig. 8: Analysis of an rings of FireOPALs placed at higher latitudes.

Fig. 6 shows the average revisit time for a network of sensors equally spaced in longitude at the equator. The error bars represent one standard deviation of the data. With 3 sites around the equator, we can get an average revisit time of under 10 hours. To have revisit times under 10 hours at least 68% of the time, we need to have 5 sites around the equator. Even at 10 sites we are not yet achieving the 1-hour objective.

Looking at Fig. 7, we need at least 25 sites around the equator in order to obtain an average revisit time of 1-hour. This might be a daunting number of sites for conventional tracking systems although some commercial GEO SDA sensors already have similar sized networks already in operation. This should be achievable for a network of more affordable PSN sensors.

We have modeled the location of sensors at higher latitudes, at 60 degrees above and below the equator Fig 8. These sensors cannot see lower inclination orbits so in this case we model satellites from 30 to 90 degrees inclination as we would not capture low inclination objects. We model in the same manner as the equatorial sensor networks. With two rings of sensors, we can approach our objective of 1-hour revisit rates on a large percentage of the population with 10 sites on each ring or a total of 20 sensors. This is not dissimilar to the result for equatorial sensors but would possibly provide more resilience to weather conditions.

5.2 Modeling an Australian Network of FireOPAL Sensors

Because we currently operate a FireOPAL site in Uralla near the east coast of Australia, we started a parallel modeling activity to inform the optimal methods to tile sensors on the sky and possible expansion of that network to multiple sites in Australia. Like the current configuration at the site in Uralla, we tile sensors across the GEO belt for full GEO coverage. To capture LEO and MEO objects, we construct one or more fences parallel to the equatorial plane. This is different than the simulations in Section 5.1 where we assumed we completely covered the sky above 30 degrees elevation. This is a more realistic, and affordable, approach. Fig.9 shows three different coverage schemes that are used in the 4 models defined in Fig. 10. with either 5 sites or 10 sites across Australia. In Fig. 9, the dots represent a resident space object at some point in time as an example of the coverage. The equatorial plane and GEO belt can be recognized by the concentration of dots through the upper set of boxes.

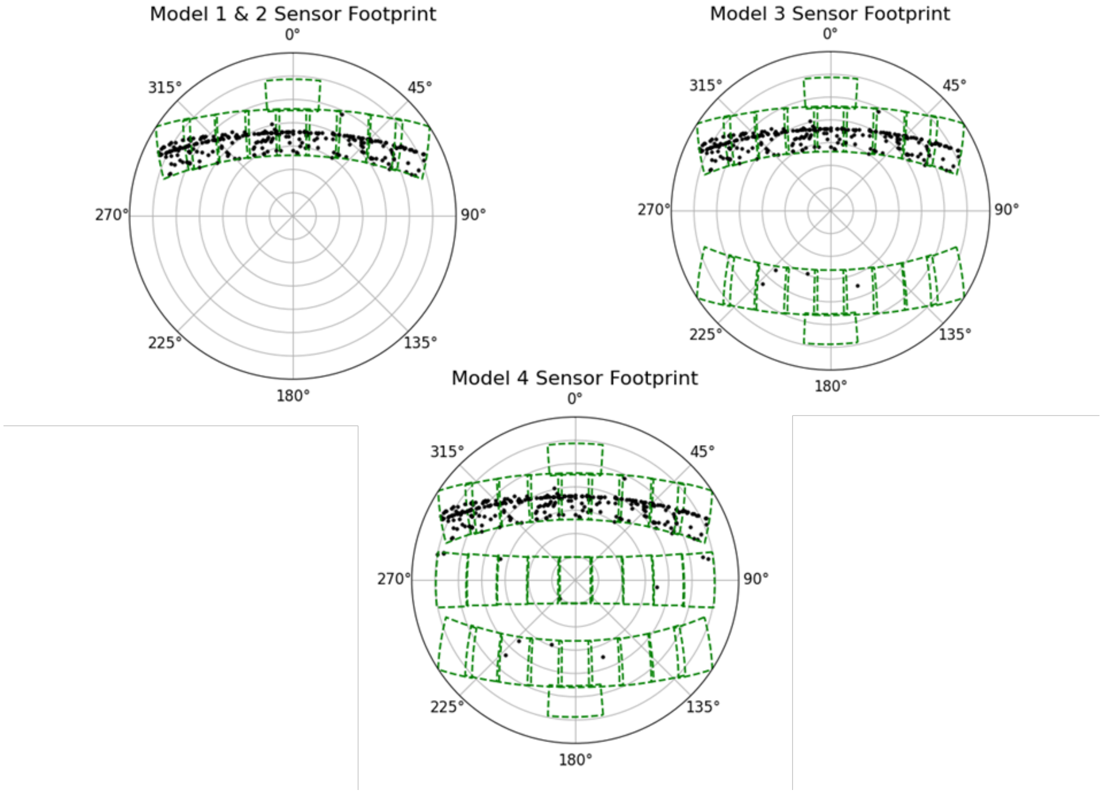


Fig. 9: Tiling schemes of FireOPAL sensor field of views across the sky, with the outer ring representing 20 degrees elevation, the center of the circle being local zenith and the top of the circle facing north.

In this simulation, we are limiting ourselves to the 5 or 10 sites in Australia. We are using 20,000 objects from the catalog and propagating each orbit in STK which returns an access report for the sensor configurations in each of the four models. The orbits are propagated for 30 days over which time we compute statistics on observations. An independent observation is defined as observations separated by 10 seconds which aligns to the FireOPAL frame processing time. Each of the 20,000 objects from the catalog has been observed by FireOPAL in the past so are considered detectable. The objects are only observed when they are sunlit, the sensor is in the dark and the object is within one of the fields of view.

We are interested in assessing the number of independent observations obtained for any one object, but we also have looked at the number of independent observations per visit of the satellite where a visit is defined the occasion of one orbit over the region. A visit is only counted if there are at least three independent observations made during that pass. Looking at Fig. 10, the median number of independent observations in a month ranges between 219 and 623 depending on the model used. Half of the catalog will have more observations with some numbering in the thousands per month. Doubling the number of sites across Australia has the same impact as adding another line of sensor fields of views. There is a 20% increase in observations with only 5 sites by adding a third line of sensors to the field of view.

Optimizing sky coverage seems to have a larger impact than the number of sites. The number of independent observations per visit has a median value of 6-7 for all models with many objects having 10 or more independent observations. Independent observations per visit tends to favor more sites over more sky coverage, but not significantly enough to warrant the cost of additional sites.

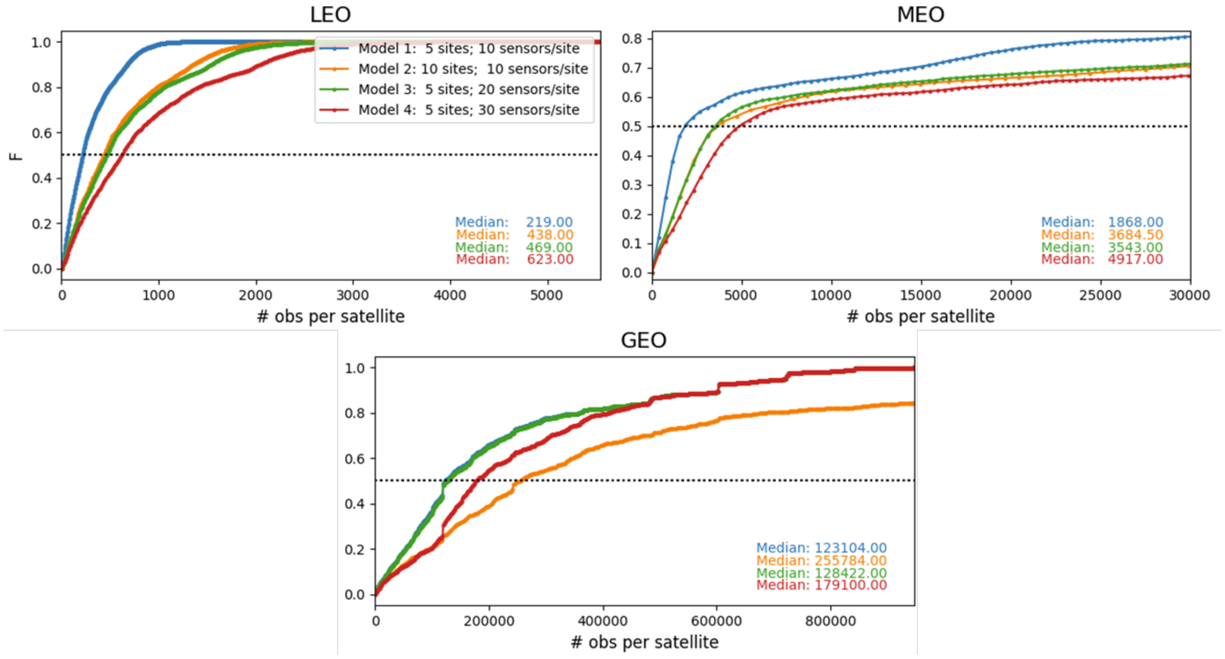


Fig. 10: Cumulative distribution function of the number of independent observations of unique objects in the public space catalog over a thirty-day period for each of the four models defined in the upper left plot.

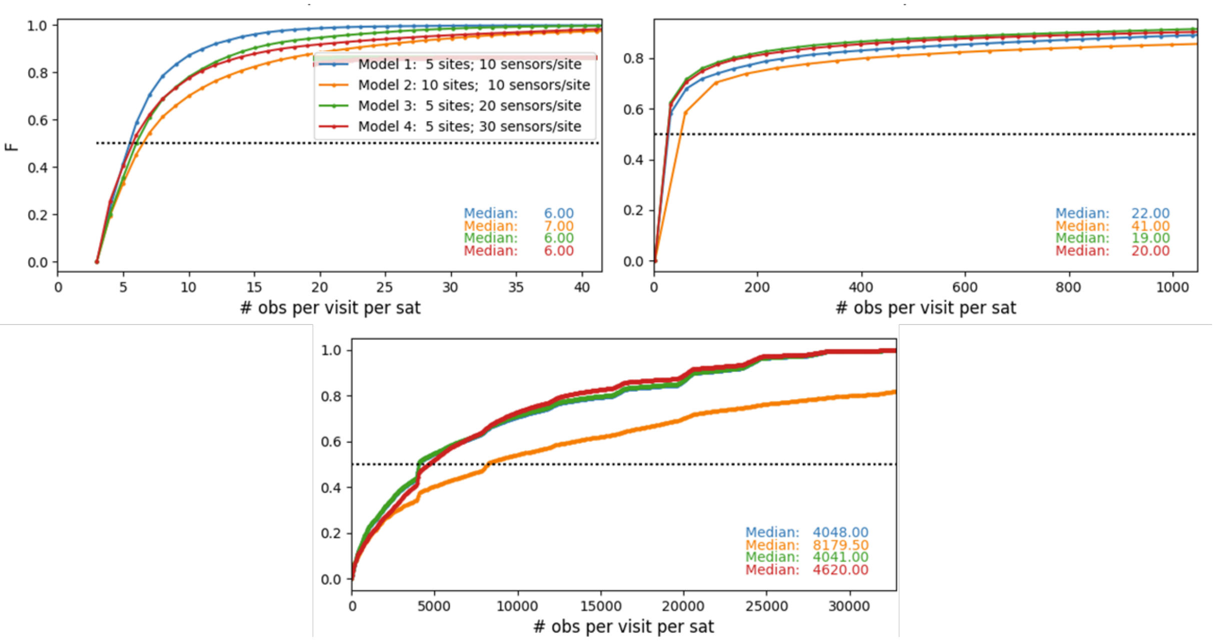


Fig. 11: Cumulative distribution function of the number of independent observations of unique objects in the public space catalog per visit for each of the four models defined in the upper left plot.

6. FULL CUSTODY SPACE SENSOR SIMULATION (FCS3)

The analysis in Section 5.1 was performed directly in STK with more traditional simulation constructs. This approach highlights some of the advantages of PSNs, but is really idealized as we are not dealing with factors such as maneuvering objects, weather, sensor reliability, network availability, accurate object signatures, etc. If we are to understand PSNs and SDA more generally, we require more capable simulation frameworks. We posed this challenge to our group of high school and college interns working with Lockheed Martin under the Nebula^{TM} Intern Program. Our students, working with software staff and subject matter experts initiated the development of a solution called the Full Custody Space Sensor Simulation (FCS3) which will become our platform for studying PCNs and developing architectures and algorithms.

6.1 Nebula™ Intern Program Overview

The Nebula™ Intern Program is an innovative approach to the early-career employee experience at Lockheed Martin Space. The program consists of high school and college students focused on STEM-related degree paths, who work in small project teams to achieve a minimally viable product (MVP) in just 10 weeks. These MVP's go through an intake process by the subject matter experts (SME)/mentor teams which assisted the interns throughout the summer and integrated into programs for normal business use. The interns and SME's/mentors meet regularly throughout the intern period to ensure the project remains within scope and provides opportunities for coaching as well as knowledge sharing across the group. The Nebula™ Intern Program also provides an intern scrum master, team lead, and technical point of contact which assist the project teams with management, oversight, and any technical needs throughout the summer. This model has been effective in reducing delays in project deliverables as well as creating a space where project teams can operate in concert with their peers to solve problems without the involvement of program management.

Fig. 12: Interns presenting the FCS3 model at the 2023 Nebula Intern Showcase.

6.2 Project Overview and Unity Engine Modeling Framework

The Nebula™ Intern Program team, pictured in Fig. 12 presenting their work at the Lockheed Martin Waterton facility, led the development of the Full Custody Space Sensor Simulation (FCS3) tool, Fig. 13, which is a space security digital twin simulation modeling SDA services in a real-world environment including weather, system reliability, geographic location and other physical parameters not typically modeled. The simulation was developed using a game engine, specifically the Unity Game Engine. Game engines such as Unity and Unreal stand to advance the ability to simulate complex real-world scenarios.

Unity was selected due to its accessibility for new developers. Launched in 2005, Unity was designed to support the development of realistic, fast running multiplayer video games and has been at the heart of many successful and profitable game franchises. The power of Unity has been adopted into many fields outside video game development including the aerospace, automotive, film making and robotics industries. Today's video games reflect more accurately the complex interaction of agents in the real world than do traditional black box simulation.

The Deep Reinforcement Learning (DRL) and robotics communities have been at the forefront in adoption of simulation environments like Unity for their power in generating rich sensory environments, accurate physics and physical complexity, speed, and an easy environment to build and run simulations [22]. While games present game players with a realistic and immersive 3D environment, algorithm development and artificial intelligence and machine learning (AI/ML) tool development can benefit from the same environment. The simulation can be easily configured, reconfigured, or configured dynamically in response to the ongoing simulation.

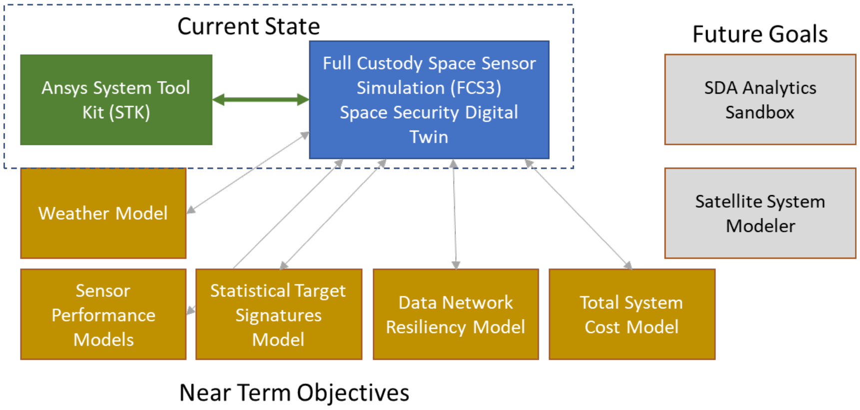


Fig. 13: Full Custody Space Sensor Simulation (FCS3) architecture.

We have chosen the Unity Engine framework because of its accurate built in physical world but also because it can integrate in many other modeling and simulation tools that run in the background. Currently, we have integrated the Unity Engine with Ansys's System Tool Kit to model satellites and sensor access, but in the future, we intend to further integrate object trackers and orbit determination tools, weather models, hardware reliability models, schedulers and tasking agents, behavioral assessment tools and satellite behavior models that add the reality of human operators. The potential exists to also integrate with other more complex digital twin tools such as Nominal System's spacecraft digital twin platform, which itself is built on the Unreal gaming engine [23].

6.3 Current Implementation

6.3.1 World Views

FCS3 uses a "Globe View" and a "Map View" to display the positions of sensors and satellites on earth. The Cesium Developer platform is used in the "Globe View" to implement a full-scale realistic globe. This globe is capable of calculating accurate latitude, longitude, and altitude data and loads high resolution 3D geospatial tiles when zooming. In the application, Cesium is used to show the location satellites and sensors on the earth. Real world modeling in this simulation creates an accurate environment for the user to run simulations of satellites, sensors, and the landscape based on the real world. The "Map View" portrays Earth on an equirectangular projection map. It shows the approximate locations of sensors and the traces of satellite orbits. The purpose of this view is to make it easier for the user to see an overview of the scenario in one frame.

6.3.2 Sensors and Satellites

There are two ground-based sensors implemented into FCS3: FireOPAL, which is a wide field-of-view (FOV) sensor, and the SPOT sensor, which is a narrow FOV sensor with satellite tracking capabilities. Both sensors were modeled in Autodesk Inventor to serve as a visual representation on the globe. The sensors can be modified, within the range of the sensor's capabilities, by changing azimuth, elevation, and FOV angle using sliders or input fields. The FireOPAL's azimuth can rotate from –180 to 180 degrees and its elevation ranges from 20 to 90 degrees. It also has two lens options: the 105mm lens with a 19.9 by 13.3-degree FOV and the 85 mm lens with a 24.4 by 16.3-degree FOV. The SPOT's azimuth can rotate from –150 to 150 degrees and its elevation ranges from 20 to 160 degrees. Its FOV ranges from 0.25 by 0.25 degrees to 1 by 1 degrees.

Satellites in FCS3 are added by the user - using the six Keplerian elements: periapsis, apoapsis, eccentricity, inclination, right ascension, perigee, and true anomaly – and represented in the scenario with a colored orbit line. Usage of these elements is imperative due to the elliptical nature of orbits, precession, orbital decay and other factors. Application of these six elements within the FCS3 project yields accurate satellite orbits about the globe, accurate orbit shifts as time progresses, and precise data reports.

6.3.3 Time Control

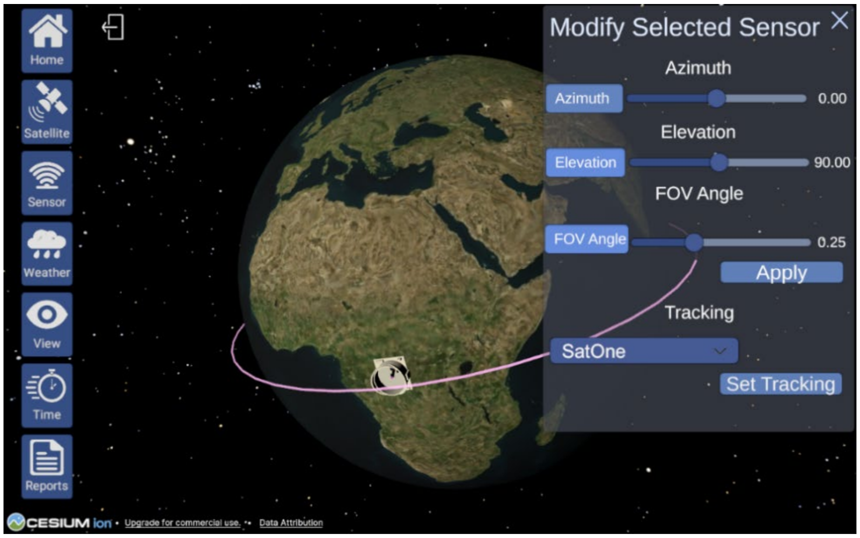
This simulation currently takes place on May 4th starting at noon within a 24-hour time period. The time scrubber controls hours:minutes:seconds and is capped out at 24:00:00. You can pause, resume, restart, rewind and jump forward in time. The purpose of the scrubber is to model what satellite orbits would look like within a set time of day, in addition to the day/night cycle.

6.3.4 STK Integration

The Ansys Systems Tool Kit (STK) runs in the background to calculate accurate access reports for FCS3. A marshal created by the Radiate project was included to connect the STK software to Unity and STK directories were added to the Unity project. Since STK runs completely in the background, there is no UI to change an object in STK versus Unity. Any addition, modification, or removal is done simultaneously to keep both scenarios updated. Scenarios can also be saved and stored from STK so a user can retrieve a previously made scenario to run or modify.

6.3.5 User Input

The UI is split into 3 sections: the navigation between viewpoints, the left panel of primary buttons, and the description/modification panels (Fig. 14). Navigation is what lets the user choose their viewpoints. The left panel of primary buttons allows the user to interact with the main capabilities of FCS3. If the user clicks a sensor in the scenario, a description panel pops up with location and modification information as well as a 3d model to better view the object. The UI is designed to be minimal and adaptable to a variety of platforms.



Modify Selected Sensor

Azimuth 0.00

Elevation 90.00

FOV Angle 0.25

Tracking SatOne

Fig. 14: Example user input window for the FSC3 model with sensor modification tool open.

6.3.6 Outputs

The primary output of FCS3 is access reports which are pulled from the STK software. Access reports are displayed in the UI with the start date/time, stop date/time, and duration of the custody of a satellite from a sensor. Once displayed, the user has the option to save the report to their computer as a text file.

6.4 Near Term Development Plans

As FCS3 continues to develop, there are a few key features that need to be added and updated. Weather conditions can inhibit a ground sensor from having custody of a satellite, so weather data will be pulled into the scenario to predict if a sensor's line of sight is obstructed. Surrounding terrain can also impact the line of sight of a ground sensor. For FCS3, using Cesium terrain generation, the sky visibility of a sensor can be calculated. Another feature to be added is a way to save sensor and satellite configurations for future use or to share with other teams. The satellite feature will be updated so that the user can select existing satellites and satellite constellations to put into the simulation. Lastly, a stretch goal is to add in clearance levels and login credentials so FCS3 can be implemented in a classified setting.

7. CONCLUSIONS AND FUTURE WORK

This paper has proposed that a Proliferated Sensor Network (PSN) approach provides a unique and lower cost solution to address the tactical custody requirements for the space environment; particularly as it becomes further contested, congested, and competitive. A PSN acts as a force multiplier through its augmentation of existing sensor capabilities by early detection of changes in object state and by maintaining custody – not predictive custody, but rather positive custody achieved by handling observations over from one sensor to the next. The benefits and comparative advantages derived from a PSN come at time we are witnessing a rapid proliferation in space-based assets. The need for on-orbit maneuvers is increasing exponentially, as seen in SpaceX's 25,000 maneuvers between December 1 2022 and May 31 2023. Equally, in a period marked by heightened geopolitical tensions, and lessons learned from Russia's invasion of Ukraine, credence to the benefits of a PSN become further evident. Government entities are shifting to accommodate for increased risk, underscoring time and time again the need to be able to rapidly track, identify, characterize, and anticipate the behavior of satellites in all orbits [23]. This was further exemplified by a recent agreement that agrees to inform commercial providers 'of emerging and imminent threats to their space assets' [24].

Many aspects of PSNs discussed here may appear obvious and some are already in practice in limited ways. What is lacking is a focused approach to developing, testing and implementing such solutions. We have lacked a comprehensive simulation tool to explore the architectures and trade spaces, there are barriers in integrating such capabilities into legacy systems and there is a significant amount of engineering that needs to be done not just in the sensors themselves, but in how we network a very large number of global sensors, how we secure data, from theft, interference and spoofing, how we ingest and manage the data and how we employ this data to inform decision making and respond to operators needs on a more tactical timeline. In addition to the engineering challenges, there is a myriad of policy, business model and geopolitical issues that need to be addressed. There cannot be a global view if there is not global coverage and cooperation.

One particularly challenging issue is that many legacy SDA mission systems were not designed to ingest and process data from a large-scale, heterogeneous proliferated network. For example, the cadence of observations from just a few FireOPAL sensors is known to be too high to be handled by some legacy systems. Another challenge is accepting and processing data from uncued/untasked sensors. A tasking system that periodically requests observations of particular satellites does not make sense when integrated with an uncued system like FireOPAL. The solution to these issues may require new kinds of mission systems to be developed to take full advantage of proliferated sensor networks.

We believe that the SDA community will naturally adopt a PSN architecture, as has most terrestrial safety and security services. Our goal is to recognize that this evolution has benefit and to start planning for, designing and implementing PSNs in a more formal manner and with purpose. The potential is there to move to an agile and tactical sensing network that is providing near continuous custody of everything in the space environment, insights into behaviors and intent and real time operations support for missions including on orbit servicing. The PSN approach is not limited to the SDA mission. Much of this work is directly transferrable to mission areas like hypersonic missile defense and maritime domain awareness.

We will continue to build out the FCS3 simulation tool to evolve and evaluate PSN architectures exploring trades in sensor design and performance, real world resiliency challenges such as weather and network performance, networking of ground and space-based sensors, and total system costs. Our goal is that this framework will also support the development and testing of advanced SDA algorithms, AI/ML tools and event based dynamic sensor tasking techniques. This work continues to inform research and development activities on solutions that we are working on today including FireOPAL Hyperion, daytime tracking, dynamic sensor tasking, AI/ML applications and resilient networking. We will continue to look at new sensors and sensor platforms that could include unattended ocean drones, mobile platforms, satellites in cislunar and even lunar based sensors.

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