Space and Ground-Based SDA Sensor Performance Comparisons

Amelia Bloom, Joshua Wysack, Jacob D. Griesbach, and Anna Lawitzke
Ball Aerospace

1. ABSTRACT

Most Space Domain Awareness (SDA) papers focus on either ground-based or space-based sensors. Both need to be utilized to provide optimal coverage of all space domains. As a community, we are doing ourselves a disservice to silo ourselves into one sensor regime or another. To achieve space superiority, we need to use these sensors in concert with one another and optimize next-generation SDA funding to design architectures that draw upon the strengths associated with each sensor's regime. This paper will lay out the differences between ground-based vs space-based sensors, provide benefits and drawbacks for each sensor type, and recommend a solution space for achieving actionable space surveillance in the geosynchronous SDA regime.

A survey of current ground-based sensors will be presented along with their limitations and strengths. Discussions will include future capabilities and SDA timeliness requirements for actionable data. Ground-based sensor benefits include low life-cycle cost and ease of maintenance/upgradeability. The limitations of ground-based sensors include limited geosynchronous orbit (GEO) observations due to restricted geographic locations, solar exclusion, and weather outages. Space-based sensors will be shown to provide enhanced capabilities for tracking GEO resident space objects (RSOs). Space-based sensors can mitigate many of the ground-based sensor limitations. They can have smaller solar exclusions and no radiometric atmospheric loss. One shortcoming of spaced-based sensors is that they are more expensive to build, field, replenish, and upgrade with often longer timelines than ground-based sensors. SatComm can also often be limited, reducing or delaying the amount of data that can be transmitted to the ground. Gaps of the current state of space domain awareness GEO coverage will be discussed as well as potential gap fillers using a mixture of ground-based and spaced based sensors.

2. INTRODUCTION

2.1 Overview of Space Domain Awareness

In the last three years, the term and mission of "Space Situational Awareness" (SSA) was upgraded to become "Space Domain Awareness" (SDA), and the USSF was officially established. This wasn't simply rebranding. It marked a comprehensive change in our nation's approach to managing and securing the increasingly congested and contested space domain. However, the evolution is far from complete. Continuing to improve, expand and advance SDA capabilities to be more threat aware and relevant can improve preparedness for critical space assets, in a battlespace environment.

The conversion to SDA stemmed from the realization that awareness must be actor/intent-cognizant and timely - not only focusing on tracking space objects, but also a necessary element of Space Control to support the core USSF mission of Space Superiority. That means emphasizing characterization, timeliness, and proactive (in addition to reactive) strategies.

As Space Domain Awareness broadens from simply knowing the location of space objects to a deeper understanding of what those objects are, who put them there and why, and the potential threat they pose to critical national assets and our nation's security, the quality of data and the speed with which it is delivered become paramount.

2.2 SDA Architecture Design Approach

Ground and space-based sensors both have an important role to play as new sensor systems are added to augment current SDA capabilities. This paper focuses on observing GEO objects from visible optical telescopes with the perspective of SDA mission relevant mission performance needs. The advantages and disadvantages of ground and spaced-based sensor are explored by walking through an architecture comparison. Key considerations and metrics are derived from the high-level SDA mission needs. Architectures are built up of pre-defined ground and space observers which represent current Space Surveillance Network (SSN) sensors and anticipated future sensors. Ground only, space only, and combined architectures are explored to highlight advantages and disadvantages between the two observing regimes and finally an architecture design approach is recommended.

The prior work of Ackermann, et. al. [1] is acknowledged. In [1], the authors analyze and present architectures for "above LEO" satellite detection, whereas this work concentrates on GEO objects. The authors conclude that additional/larger ground-based optical sites are necessary with space-based augmentation by a series of sub-GEO observers provide a high-availability, cost-optimal architecture design point. In this paper, we do not consider sub/super GEO observers due to their difficulties with ground-communication networks. Such systems require full (360º) ground support coverage or can exhibit large store-and-forward downlink latencies that render them untimely for space domain awareness needs.

3. MISSIONS NEEDS DRIVE ARCHITECTURE DESIGN

3.1 Space Domain Awareness vs Space Traffic Management / Space Situational Awareness

Multi-national interests and the revolution of the space industry has created the obvious need to monitor, track, and assess resident space objects (RSOs). This overall need has a complex dichotomy, but can be simplistically broken down into two fundamental strategies:

(1) Space Traffic Management (STM) or Space Situational Awareness (SSA), which is the desire to routinely detect and track space objects to be able to predict their future positions. The primary mission here is to implement Collision Avoidance (ColA), where the primary focus is the prevention of satellite impacts and the generation of (highly detrimental) space debris. Here, space objects are assumed to proceed into the future the same way they have been observed to behave in the past.

(2) Space Domain Awareness (SDA) includes the emphasis on STM/SSA but more comprehensively adds the need to characterize and assess RSOs as potential threats. With this, SDA requires more-timely (near-real-time) monitoring of RSOs and inclusive assessments of what space objects (and ground effects) *could* do if they had suspect/nefarious intentions. As a result, SDA includes the concepts of potential maneuvers, threat baskets, courses-of-action, tactical decision support, and real-time common operating pictures that are not necessarily required if one is solely interested in STM.

So, whereas STM looks for collision predictions out as far as 7 days, typical STM CONOPS strives to monitor objects on a 1-2 times per day context. SDA threat relevance requires monitoring on the order of minutes to 1-2 hours. This essential need for SDA timeliness drives sensing requirements to reduce coverage gap times and all associated (data transmission and ground processing) latencies.

Uncorrelated Tracks (UCTs) continue to be problematic in both STM and SDA contexts. As sensors become more sensitive, the detection of smaller and more prolific space objects is commonplace. Satellites themselves are also becoming smaller (e.g. nanosats) and more prolific (e.g. mega constellations). As the number of detected space objects compound, the problem grows computationally at an exponential rate. In addition, these new detections must be catalogued in a way such that they can remain catalogued. (It is difficult for high-area-to-mass-ratio (HAMR) debris objects to be catalogued such that they are repeatably detected in the future.)

UCTs, when viewed in an SDA context, must be rapidly identified and assessed. This drives a need for sensor architectures to have minimal spatial/temporal coverage gaps, to even include coverage in difficult solar-phase angle geometries and diverse lighting conditions. When detected, cooperative sensors must be rapidly tasked/cued/scheduled to provide sufficient geometrical diversity to aid initial orbit determination state convergence. This drives a need to have multiple (more than one) timely sensor coverage of any individual space region.

3.2 Architecture and Sensor Design Considerations

With the pivot to SDA, key mission design considerations that have been identified are outlined below. Typical ground and space-based sensor performance against them are described.

Cost: Initial cost to develop and deploy ground sensors is generally significantly cheaper than space-based sensors. This is tied to sensitivity which scales with aperture size. It is much cheaper to develop large telescopes on the ground. For example, upgrading the existing GEODSS sensors cost $119 million [2] and the SST cost $150 million for the telescope and 2 sensors [3]. This is significantly less than a single SBSS for $823 but more than ORS-5 at $87 million [4]. Note that ORS-5 is estimated as 2 m_v less sensitive than the typical GEODSS performance and 4.5 less than SST. Appropriately designating mission requirements can reduce space-based sensor costs.

Astrometric Accuracy : Per AFSPCI10-601 Table A2.4 [5], Level 2 sensors providing SDA data to the UDL or other SDA databases require ≤5 arcsec accuracy, while level 1 sensors require ≤3 arcsec accuracy in each right ascension and declination of a resident space object (RSO). This requirement was set for ground-based sensors due to the increased distances between observer and RSO. For a Level 2 ground sensor looking at GEO RSO the resulting accuracy is 0.87 km. Assuming a Level 2 13 m_v sensor, a 1 meter target can be seen in ideal conditions at 16,200 km which requires a 0.39 km accuracy, while a highly sensitive 20 m_v system can detect the same object at 406,900 km requires a 9.86 km accuracy at the back of the search volume. The <5 arcsec accuracy was appropriate with all sensors were the same distance from their targets, but as SDA observers moved into space this angular requirement has driven inconsistencies with the data. One adverse effect is that it drives larger format FPAs, which in turn will require larger data rates, or necessitates a smaller IFOV which reduces FOV thus reduces revisit rates. Instead, we recommend setting an astrometric accuracy based on linear distance rather than angular accuracy. This will provide consistent accuracy across both ground and space sensors.

Lighting Conditions: Both ground and space-based optical sensors cannot detect RSOs that are in front of bright objects including the sun, the moon, and the earth. Ground-based sensors have large outages when they cannot observe during significant portions of the day. Figure 1 illustrates this daytime outage. Space-based sensors have similar constraints but can look closer to bright objects than ground-based sensors due to celestial background as opposed to atmospheric background. Both types of sensors are also similarly constrained by solar phase angle and eclipse conditions where the RSO is in Earth or Moon shadow.

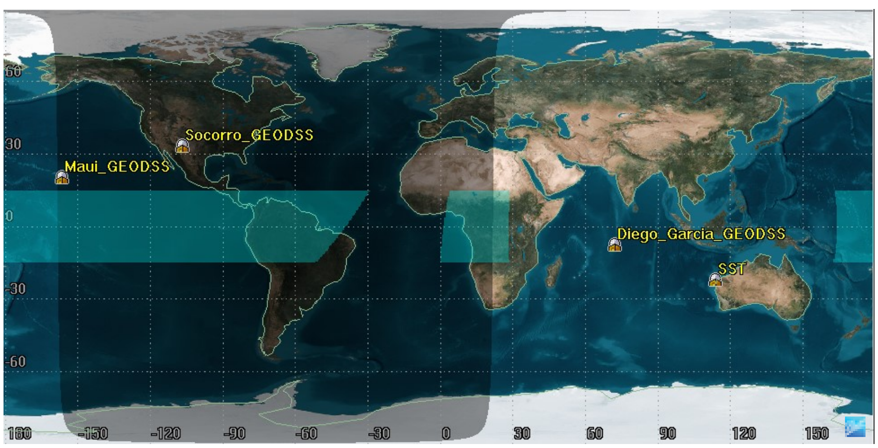

Figure 1: Example of daytime outage for ground sensors – The light blue swath is the volume of the geo belt projected onto the earth that is observed by the current SSN optical ground telescopes.

Weather: Ground-based sensors cannot see through the clouds and can also be adversely affected by strong winds. It is estimated that the three GEODS sites only have clear nights between ~ 40-50% of the time [6]. Space-based sensors have no such constraints.

Maintenance and Upgradeability: Ground-based sensors can be easily maintained and upgraded. GEODSS has been upgraded multiple times. Space-based sensors are static and must be replaced wholesale when they reach end of life. Focal plane arrays in space degrade faster due to the harsher radiation environment. This is worse in GEO than in LEO.

Agility: There are two main operational modes for SDA sensors, search and track. Search is used to cover large volumes of space to quickly detect and characterize new UCTs. Track is used to update position knowledge of existing RSOs to confirm they are where they are expected to be. Agility of the sensor constrains the volume of space that can be searched or the number of RSOs that can revisited within a mission relevant timeframe. Highly agile sensors have been demonstrated in space (SBSS) and on the ground (SST). Sensor designs like ORS-5 allow for search while remaining fixed but cannot track objects.

Communications: For ground-based sensors, the raw full frame imagery is available on the ground. For space-based sensors, comm channels to the ground can be limited and expensive. The amount of data to downlink quickly balloons if one considers proliferated constellations. Typically, LEO satellites must hand off between ground antennas with communication gaps on the order of hours unless they have direct access to TDRSS or other relay satellite systems. Tracking and Data Relay Satellite System (TDRSS) and commercial relay satellite systems are traditionally cost prohibitive, especially if full frame data is being sent to the ground. GEO satellites are typically stationary over the Earth which allow for a single, constant contact ground entry point for data transfer. Antennas for GEO satellites can be shared between satellites if a phased array antenna is used, which allows to a splitting of costs between numerous systems vs. a dedicated antenna. An alternative is push some of the processing on-board to detect observations and only downlink image chips or metric observations for a data reduction of ~100x and reduced connection time required between the vehicle and ground. This method results in a loss of data since the full frames cannot be recovered and re-processed using different methods. Time needed to downlink the data adds to the overall time from photon on detector to actionable information. For STM/SSA missions, this may not be significant but for threat relevant SDA missions this may be critical.

Processing Capability: Extensive resources such as "the cloud" exist to process the vast quantities of data that may be generated by a system consisting of dozens or hundreds of sensors. Available on-board processing hardware that is radiation hardened or tolerant is generally at least 10 years out of date compared to current laptops. On-board mission data processing (MDP) for data reduction purposes is often augmented by additional ground processing to produce mission relevant information. This approach is in use by systems such as SBSS.

Location: Each ground-based sensor can only observe RSOs that are overhead. This requires distributed sensors along multiple longitudes. Combined with clear sky weather considerations and high altitude increasing sensitivity, ideal locations are hard to come by. While space is increasingly congested, it is not densely populated and slots for sensors are widely available. Ground observers are constrained to the surface of the earth, but space observers can be distributed among a variety of orbits. A well designed architecture would take advantage of this to mitigate weather or lighting condition outages a single sensor might be experiencing with better viewing geometry from another sensor.

3.3 Performance Measures and System Modeling

Ideally, all RSO regimes of interest would be under constant surveillance. All known objects would be constantly tracked and new objects would detected almost immediately. Given the large volume of space of interest, even reducing the problem to GEO, this is impractical. Instead, metrics are defined that represent how close current and future architectures come to meeting this ideal: observability and revisit time.

Observability: The percentage of space a sensor is capable of viewing averaged over a pre-defined timeframe subject to relatively simple constraints such solar phase angle, the details of which are defined below. Sensor field of view (FOV) and agility are not considered.

- *Volume*: An altitude range of +/- 500 km around the geosynchronous belt was chosen to include the disposal belt. An inclination of 15 degrees captures 97% of the RSOs in this altitude range. Of the 1220 RSOs in the public Space-Track.org catalog [7], 35% are inclined between 10-15% so it's critical to capture this region. This was modeled using a discrete grid.
- *Exclusion Zones:* Solar: 90/50 degree half angle (ground/space), Lunar: 10 deg half angle, Earth: 10 degrees above the limb or horizon.
- *Time Frame:* 3 days centered around the equinox
- *Sensor Sensitivity:* Sensor sensitivity is modeled by defining the visual magnitude the sensor is capable of detecting (see Table 1).
- *Detectability:* A representative RSO of diameter 1 m and albedo of 0.2 considered at each grid point in the volume. After considering solar phase angle, it is considered detectable for that time slice if the visual magnitude is below the sensor sensitivity threshold.

These constraints technically allow for a ground-site to view a target in terminator lighting conditions while in direct sunlight. This may be optimistic for traditional optical observing CONOPs.

Maximum Gap Time: The maximum amount of time any point in the volume is unobservable. If an aggressive action was taken during this time, it would be not observed. Note: a gap time of 24 hours indicates part of the volume is never observable.

Future work will extend the observability and revisit time analysis to include capacity considerations. Capacity captures many additional constraints. Capacity accounts for individual sensor agility which limits how large a region can be searched or how many RSOs can be scheduled to be observed in a set amount of time. Additionally, capacity optimization can include optimizing scheduling algorithms that can task individual sensors or all sensors simultaneously to minimize the revisit time and optimize initial orbit determination (IOD) timelines for UCTs. Initial work on capacity optimization for the cislunar regime is presented in [8].

4. ARCHITECTURES

4.1 Architecture Definition Overview

Ground only, space only, and combined architectures are considered to highlight the capabilities of ground and space-based sensors against the SDA mission needs. These architectures are built up of ground and space-based sensor building blocks that are based on existing systems as well as reasonable future capabilities. Table 1 outlines the architectures examined in this paper.

4.2 Current Capability

4.2.1 Ground-Based Observers

The US Government Space Force owns and operates the Space Surveillance Network (SSN), which consists of ground-based radar and electro-optical sensors to detect and track RSOs [9]. Loosely speaking, SSN radars tend to focus on LEO/MEO/HEO objects, while the SSN optical telescopes focus on tracking GEO objects. Of course, there are exceptions to this, as there are a few radars in the network that can reach and track GEO objects, but these are generally special collections. Furthermore, optical sites can also sometimes track LEO/MEO/HEO objects, depending on their angular motion and solar illumination.

This paper focuses on the optimization of a sensor network architecture for tracking GEO objects, to specifically include GEO search. As such, we focus on the ground-based SSN electro-optical sensors for potential inclusion, and rule out SSN radars, as especially for GEO collections, are poorly suited/optimized for search. Of the SSN optical sensors capable of GEO search, we focus on the following elements:

- Ground Based-Electro-Optical Deep Space Surveillance (GEODSS) – 3 dedicated sites located at Diego Garcia, Maui, HI, and Socorro, NM. Each site consists of two 40” primary telescopes, each with a 2-degree field-of-view (FOV) and a third 15” auxiliary telescope with a 6-degree FOV. The Diego Garcia site is slightly different, operating with three 40” telescopes. Typical sensitivity has been modeled as 18 m_v, although actual performance varies with tasking parameters.
- Space Surveillance Telescope (SST) – 3.5m telescope located in Exmouth, Western Australia. SST provides a 6-degree FOV that is capable of scanning the night sky multiple times per night and can see objects as faint as 20.5 m_v.

Traditionally, the SSN operates by sending a list of collection targets to each sensor 1-2 times per day, and generally allows the sensors to schedule the order and timing of the target collections. GEO search is a special collection mode that breaks the older paradigm of nightly task lists. With GEO search, each ground-based sensor raster scans the nightly sky to attempt to catalog known and new space objects.

In addition to the government owned SSN, commercial SSA networks are becoming more capable and prolific as well. Companies, such as ExoAnalytic and Slingshot, operate global ground-based optical telescope networks that scan the nightly skies and maintain custody of known RSOs. They sell observation data, which consists of the detected RSO brightness and sky locations, to the general public. ExoAnalytic’s telescope network is larger, but Slingshot’s network consists of augmented telescopes that can detect LEO objects during the day.

4.2.2 Space-Based Observers

The SSN fuses in data from space-based optical sensors as well. These systems consist of the following:

- Space-Based Space Surveillance (SBSS) – a taskable dedicated SSA system located in a sun-synchronous LEO orbit that observes RSOs in MEO/GEO/HEO. SBSS was designed with a 30 cm aperture but not much is documented about the 2.4 megapixel detector. It was modeled as 18 m_v as [10] evaluated three potential FPAs and found the resulting visual magnitude 17.6 -18.5 m_v.
- ORS-5 "SensorSat" – a non-taskable dedicated SSA system in an equatorial LEO orbit that continuously scans the GEO belt.
- Geosynchronous Space Situational Awareness Program (GSSAP) – multiple optical systems in GEO that monitor GEO RSOs
- Sapphire (Canada) – a contributing optical SSA system in a sun-synchronous LEO orbit that observes RSOs in MEO/GEO/HEO.
- QZSS-Hosted Payload (Japan) – a future dedicated optical SSA system in GEO to monitor neighboring GEO RSOs; not launched yet

Space-based sensors offer geometric diversity to observe RSOs at lighting angles that can augment and complement ground-based sensors. For example, most ground-based optical sensors are limited to observe at local-night, but space-based sensors are able to collect more diversely, as they only need a favorable solar-phase angle, and they can often observe closer to the sun with a smaller solar-exclusion angle.

This paper considers only SBSS and ORS-5 contributions, as details on GSSAP are sparse.

Table 1: Observing Sensor Architecture Definitions

Domain	Case #	Name	Sensor	Sensitivity (visual magnitude)
Ground	1	Current Ground	3 GEODSS SST	18 20.5
	2	Future Ground	3 GEODSS SST Future GEODSS	18 20.5 18
Space	3	Current Space	SBSS ORS-5	18 16
	4	Future LEO	9 ORS-5	16
	5	Future Commercial GEO	50 Commercial GEO	13
	6	Future Exquisite GEO	3 Exquisite GEO	20
Combined	7	Current Combined (Cases 1 + 3)		
	8	Future Ground + LEO Cases (2 + 3)		
	9	Future Ground + Future Commercial GEO (Cases 2 + 4)		
	10	Future Ground + Exquisite GEO (Cases 2 + 5)		

4.3 Future Capability

4.3.1 Ground-Based Observers

Future ground-based observers are modeled as additional GEODSS. SST was considered but the price tag of $150 million makes the likelihood of funding of an entire network of SST's unlikely. For the two metrics under consideration, observability percentage and gap time, adding a single additional GEODSS optimized the results so only the single future ground configuration was included.

4.3.2 Space-Based Observers

Multiple future space-based observers were modeled to cover multiple orbital regimes, cost points, and sensitivities.

- ORS-5 – additional ORS-5s. Note that ORS-5 is MIT Lincoln Labs developed and therefore requires a tech transfer before additional units can be produced.
- Commercial GEO – modeled with a sensitivity of 13 m_v. Representative of a commercial off-the-shelf (COTS) star tracker quality sensor fielded as a hosted payload.
- Exquisite GEO – modeled with a sensitivity of 20 m_v. This is the sensitivity considered for future cislunar SDA missions in [8]. Economies of scale would come into play if cislunar and exquisite GEO sensors were the same as the radiation environments are similar.

5. Architecture Comparison

5.1 Architecture Performance

Table 2: Architecture Performance Summary – The Case #'s correspond to those in Table 1.

Case #	Name	Observability (%)	Max Gap Time (hours)
1	Current Ground	56.4	24
2	Future Ground	64.5	11.9
3	Current Space	51.3	7.4
4, 5, 6	Future Space	98 – 99	< 2
7	Current Combined	66.4	7.4
8, 9, 10	Future Combined	98 - 99	< 2

Given that ground-based sensors are significantly less expensive than space-based sensors and budget is always a big consideration, ground only architectures are evaluated to determine if any suitably meet SDA mission needs. The current capability of the SSN ground system (case 1) as outlined below was compared against a potential future architecture (case 2). Performance of these two architectures is captured in Table 2. A max gap time of 24 hours indicates that there are regions that the current system cannot observe. Figure 2 illustrates that this observability gap is centered over the Atlantic Ocean. The future ground architecture adds a single GEODSS to cover this gap. Numerous sensor configurations were considered but adding multiple ground sensors rendered no additional performance improvement over a single well-placed sensor. A maximum gap time of greater than 6 hours and average observability 65.4% of this optimized architecture doesn't meet the notional SDA requirements set at < 2 hours and 95%. This is before weather outages are considered and so the ground systems under consideration are not ideal as a complete SDA solution.

Next, consider the current combined architecture (case 7), which adds a single SBSS and ORS-5. Note that details on additional space contributors, such as GSSAP, are sparse and insufficient to model, so no claim is made about actual current capability. This architecture still falls short of SDA mission needs and doesn't exceed the capability of the future ground architecture even though cost is considerably more.
Now consider the conceptual future space architectures. They are built up of each of the sensor types (ORS-5, commercial GEO, exquisite GEO) until 95% observability and < 2 hour max gap time were met. This resulted in 9, 50, or 3 sensors respectively. This illustrates that multiple space only solutions can meet SDA mission needs as defined by the two chosen metrics while ground only cannot. There are various trade-offs between these solutions that are not captured in these two metrics. ORS-5 sweeps through the GEO belt but is not taskable. 50 commercial

grade GEO satellites may or may not be cheaper than 3 exquisite ones, once launch, operations, and comms to downlink ~17x the data are accounted for.

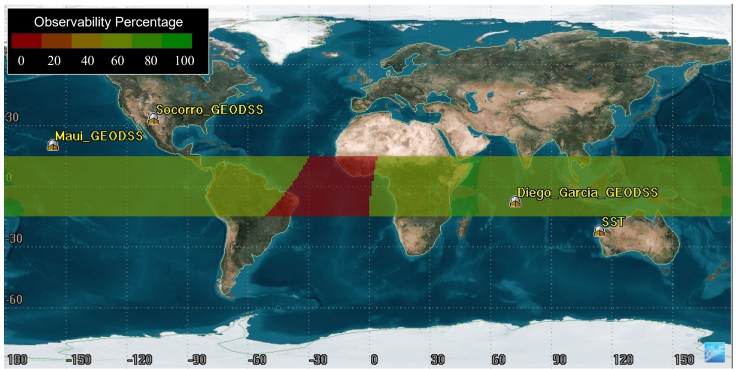

Figure 2: Current SSN ground telescope network Observability

Next, consider the current combined architecture (case 7), which adds a single SBSS and ORS-5. Note that details on additional space contributors, such as GSSAP, are sparse and insufficient to model, so no claim is made about actual current capability. This architecture still falls short of SDA mission needs and doesn't exceed the capability of the future ground architecture even though cost is considerably more. Now consider the conceptual future space architectures. They are built up of each of the sensor types (ORS-5, commercial GEO, exquisite GEO) until 95% observability and < 2 hour max gap time were met. This resulted in 9, 50, or 3 sensors respectively. This illustrates that multiple space only solutions can meet SDA mission needs as defined by the two chosen metrics while ground only cannot. There are various trade-offs between these solutions that are not captured in these two metrics. ORS-5 sweeps through the GEO belt but is not taskable. 50 commercial grade GEO satellites may or may not be cheaper than 3 exquisite ones, once launch, operations, and comms to downlink ~17x the data are accounted for.

5.2 Additional Considerations

It has been shown that ground-based sensors have disadvantages that can be overcome by space-based sensors, primarily daytime outages and weather. However, is it really true that space only is the best solution? To answer this, let's reconsider the metrics we chose. Observability and time gaps are critical for the SDA mission but are insufficient. As noted earlier, capacity analysis expands upon observability by including sensor FOV, agility, and the collaboration of multiple sensors to provide the coverage percentage of a volume. Just because a large percentage of a volume is observable, it doesn't imply that the entire volume can be searched in a mission relevant amount of time. Reference [8] addresses capacity for the cislunar domain and we recommend this approach be applied to the GEO regime as an extension of this work.

Observability coverage, gap durations, and capacity are important considerations for any potential space surveillance However, they only capture how often an RSO or an area of space is observed. Another important consideration is orbit determination. After all, simply detecting an RSOs presence with an observation does not necessarily mean that it can be localized or characterized. The process of localizing RSOs is to corroborate several observations to form an orbital state vector that not only conveys where the object is located (with uncertainty), but also can be used to predict where the object will be in the near future. Whereas observations may be reduced in dimensionality (e.g., optical observations only convey that an object is located in a certain direction from an observer), a full 6-DOF state vector conveys an objects 3D position with a 3D velocity estimate. This is paired with a full 6x6 covariance matrix to convey associated position and velocity uncertainties.

An important consideration is the time it takes to compute a full converged solution from an initial (new) object observation. Of course, this solution time greatly depends on the quality of the observation measurements, the angular diversity (dilution of precision) associated with the observations, and the number of initial observations available from each contributing sensor.

To put together a simple comparison, a number of simplistic "rules" were determined to attempt to provide a fair comparison between architectures:

- The target is a low-inclination GEO satellite
- Each sensor produces an observation every 30 minutes, if the sensor's observation constraints are satisfied
- Exclusion angles (solar, lunar, and earth) are the same the same as those used for the observability metric. Instead of *detectability*, a maximum solar-phase angle constraint of 90 degrees for ground and 150 degrees for space is applied.

For this trade the following elements were considered:

- A low-latitude (near equatorial) ground-based sensor
- Two GEO space-based sensors: one located 20-degrees East and another 30-degrees West of the target's longitude. Both GEO sensors are inclined several degrees and are roughly oppositely phased.

Figure 3 shows the observations simulated for the purpose of this orbit determination trade, which are the 30-minute intervals that pass all of the above sensor constraints. One can immediately ascertain the advantages of space-based observation vs. the night-time imaging constraints associated with ground-based optical SSA. This space-based advantage is very dependent on the space-based sensor's ability to image near the sun (solar exclusion angle) and operate at higher solar-phase angles.

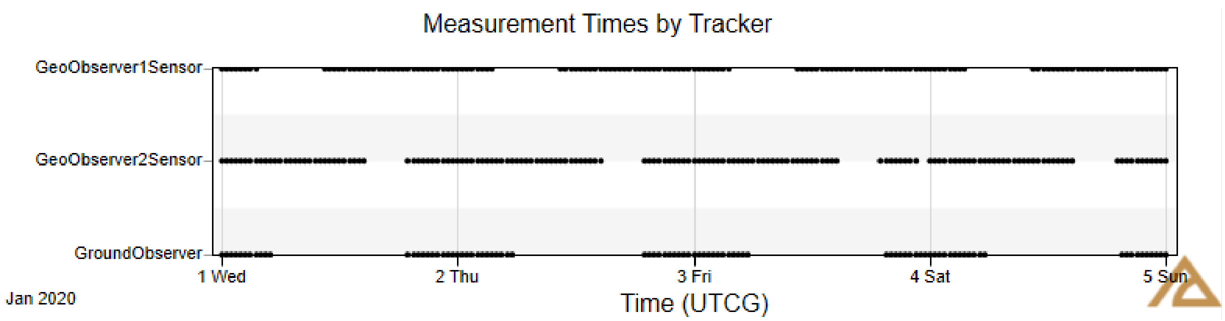

Figure 3: Simulated Observations Based on Sensor Constraints

Figure 4 illustrates the results of the orbit determination comparison. A major conclusion is that single sensor solutions take time to converge properly due to low observability of the target's orbital eccentricity, whereas multiple observers allow for quicker full uncertainty reduction sooner. Here, we see that all of the single space-observer architectures require almost a full-day or more to properly converge, with only the architectures utilizing both space-based observers converging within a half-day.

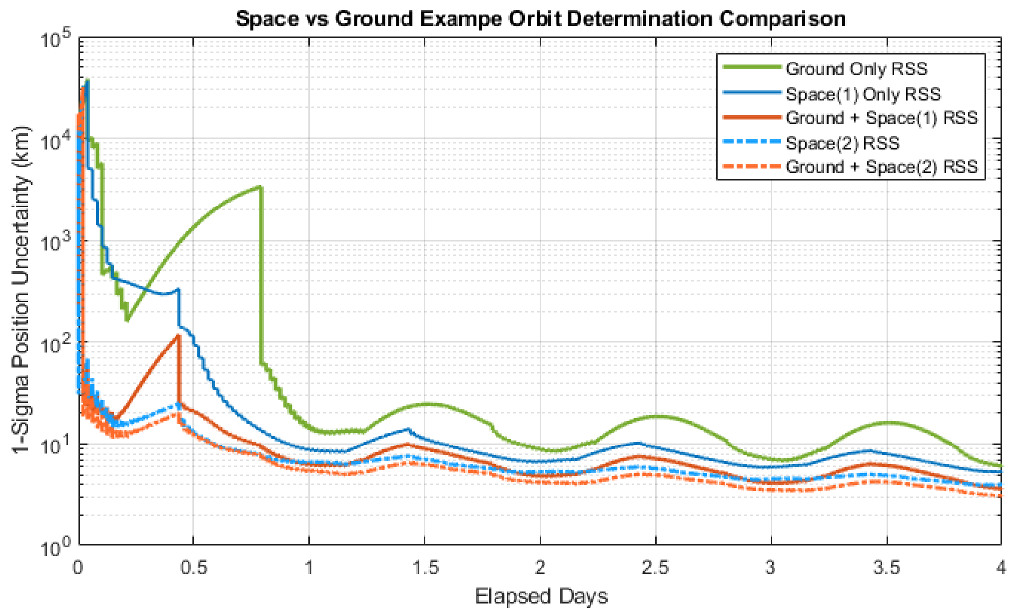

Figure 4: Surveillance architecture rough orbit determination comparison

This comparison is only presented in a simple attempt to convey the orbit determination advantages of ground and space-based architectures, but the results will be expected to vary based on specific target/observer details.

6. Conclusion

Space-based sensors can overcome ground-based sensor limitations like weather and daytime outages. However, space and ground working in concert provide timelier localization and characterization which are necessary to turn raw images into actionable intelligence. Given a set of mission priorities and requirements, space-based sensors should be allocated to the architecture to meet those needs that can only be met by space. Space-based sensors can meet some of the functionality that ground provides, so ground should be added to augment the existing space capability to minimize cost and maximize performance. Section 3.2 outlines numerous other considerations that may be critical to consider when designing architectures for the future of SDA. A natural future extension of this work would be to continue our collaboration with the University of Colorado to extend the multi-objective Monte Carlo search tree architecture design approach that is currently focused on the cislunar domain [11] to the GEO regime and to expand the objectives to include many of the considerations outlined here.

7. References

[1] M.R. Ackermann, R.R. Kiziah, P.C. Zimmer, J.T. McGraw, D.D. Cox, "A Systematic Examination of Ground-Based and Space-Based Approaches to Optical Detection and Tracking of Satellites", 31st Space Symposium, Colorado Springs, CO, April 14, 2015.
[2] S. Erwin. L3harris gets $119 million Space Force contract for deep-space telescopes. *SpaceNews*. September 21, 2020. https://spacenews.com/l3harris-gets-119-million-space-force-contract-for-deep-space-telescopes/.
[3] J. Foust. DARPA hands over space tracking telescope to the Air Force. *SpaceNews*. October 19, 2016. https://spacenews.com/darpa-hands-over-space-tracking-telescope-to-the-air-force/.
[4] SensorSat - ORS-5. *SpaceFlight101*. Retrieved August 22, 2022, from https://spaceflight101.com/ors-5/sensorsat.
[5] Air Force Space Command. Air Force Space Command Instruction 10-610, July 3, 2019.
[6] R.F. Bruck & R.H Copley. GEODSS Present Configuration and Potential. AMOS 2014.
[7] Space-Track. Space Surveillance Catalog. Space-Track.org retrieved July 20, 2022.
[8] J. Wysack, J. Correa, and N.O. Fahrner. Capacity-based Cislunar Architecture Optimization, AMOS 2022.
[9] D.A. Vallado and J.D. Griesbach. Simulating Space Surveillance Networks. Paper AAS 11-580 presented at the AAS/AIAA Astrodynamics Specialist Conference. July 2011.

[10] J. Du, J. Chen, B. Li, & J. Sang. Tentative design of SBSS constellations for LEO debris catalog maintenance. *Acta Astronautica*, 155, 379-388, 2019.
[11] M. Klonowski, M.J. Holzinger, N.O. Fahrner. Optimal Cislunar Architecture Design Using Monte Carlo Tree Search Methods. AMOS 2022.