A SYSTEMATIC EXAMINATION OF GROUND-BASED AND SPACE-BASED APPROACHES TO OPTICAL DETECTION AND TRACKING OF SATELLITES

Primary Author
Mark R. Ackermann, Sandia National Laboratories, mracker@sandia.gov
Coauthors
Colonel Rex R. Kiziah, United States Air Force Academy, rex.kiziah@usafa.edu
Peter C. Zimmer, J.T. McGraw & Associates, zimm@lodestar.org
John T. McGraw, J.T. McGraw & Associates, mcgraw@lodestar.org
David D. Cox, Sandia National Laboratories, ddcox@sandia.gov

Abstract
Space situational awareness is the cornerstone of our national strategy to maintain the freedom for all nations to operate peaceful systems in space. Ground-based radar systems are traditionally used for detection and tracking of space objects in low earth orbit (LEO), but optical systems are necessary for detection and tracking of satellites in higher orbits such as medium earth orbit, geosynchronous earth orbit and high earth orbit. Current optical surveillance approaches include both ground-based and space-based sensors. Each approach has its advantages and disadvantages and there are significant differences in cost for acquisition, operations, and maintenance. This paper presents a systematic examination of the characteristics of each approach and the relative merits of various combinations of ground-based and space-based sensors for detection and tracking of satellites at altitudes above LEO.

Introduction

Space situational awareness (SSA) is an important activity for national defense and for the safe operation of civilian satellites for economic purposes. The current approach to SSA for satellites in high orbits, such as the geosynchronous earth orbit (GEO) region, is comprised of a diverse collection of systems that include a long-established, well-conceived network of 1 m diameter aperture telescopes; a single, expensive, prototype 3.5 m ground-based telescope; a single, expensive pathfinder space-based system, and a low-cost demonstration space-based system presently in development. This current architecture suffers from latency, incomplete global coverage, and the inability to observe targets close to the sun. Also, the current network includes two costly assets that, for the foreseeable future, are unaffordable to replicate.

In this paper, we systematically evaluate and present the capabilities of various approaches to optical SSA and compare these strengths and weaknesses along with the relative value of each approach, as expressed in terms of the cost per observation. Based on these analyses, we propose a path forward that combines affordability with sensitivity and significantly reduced latency.

Background

Space Situational Awareness

One topic of current high importance to national security experts in many countries is that of SSA. Many equate SSA to satellite observing, but the topic is much richer, including all activities necessary to know what systems and debris are on orbit, exactly where they are at any specified time, where they are going, what they are doing, what their statuses of health are, and whether or not there will be potential conjunctions. While space is vast and commonly viewed as limitless, the volume useful for satellite operations around the earth is indeed limited with certain regions becoming quite congested in recent years.

Whether or not anyone commonly thinks about them, space systems have tremendous impacts on the daily lives of almost everyone within the developed world and many within the developing parts of the world. The economic impact of space-related activity is enormous. It is estimated that space systems and related services contributed slightly in excess of $304B of economic benefit for calendar year 2012[1]. At the present time, there are approximately 1,000 active satellites on orbit ranging in complexity from simple cube satellites (CubeSats) to multibillion dollar remote sensing satellites. If one assumes an approximate average replacement cost of $200M each, this represents a capitalization of $200B for the spacecraft alone and another $75B for the launch costs[2]. Over the next decade, 1,000 new satellites are expected to be launched, with most operating in low earth orbit (LEO) or GEO[3]. In addition to the economic value of space, the capabilities derived from military space systems have transformed warfare. Many nations, to varying degrees, rely on space systems for communications, intelligence, and indications and warnings of attacks. Virtually all nations rely on weather data from satellites for both military and civilian activities.

All of the 1,000 active satellites need to be tracked. In addition to active systems, the orbital environment includes on the order of 7,000 inactive satellites and related larger pieces of space junk. Presently, most pieces of the space debris are too small to be tracked. It is thought that upwards of 20,000 pieces of debris are present in the size range of 1 cm to 10 cm along with approximately 200,000 pieces smaller than 1 cm[4]. Debris as small as 1 cm can cause catastrophic damage to an active satellite. It is possible that in the near future, objects as small as 1 cm will be tracked routinely, however, at present, objects of approximately 10-cm size are rarely tracked.

The Five Pillars of Space Situational Awareness

SSA involves more than the simple tracking of satellites. The US Air Force has categorized the various activities and established five pillars (or core activities) within the larger area of SSA. These pillars are:

- Detect, Track, and Identify
- Characterization
- Tactical Warning and Attack Assessment
- Data Integration and Exploitation
- Spacecraft Protection and Resiliency

Detect, Track, and Identify

The first requirement for effective SSA is to find and then track resident space objects (RSOs) or orbiting artificial satellites. This task is normally accomplished by radar for satellites in LEO and by optical systems for satellites in higher orbits such as GEO. Following detection and tracking, it is useful to identify the RSO and classify the object as to owner and function. Identification is not as straightforward as detection and tracking and often requires the incorporation of other information such as published space launch information.

Characterization

Following detection and tracking, characterization of the RSO can help with identification and is also useful for establishing operational patterns for the satellite. These patterns of life are used for change detection which is often an indication of some anomaly with the satellite, or an intentional change in posture, orbit, or some other characteristic. Characterization activities can include optical imaging, polarimetric imaging, photometry, polarization dependent photometry, and spectrometry. In addition to change detection, characterization data help to identify new foreign launches by comparing signatures with archived signatures for known space systems.

Tactical Warning and Attack Assessment

It is an unfortunate fact that space is slowly becoming militarized. While there is no evidence of space-based weapons at present, there are examples of nations building weapons that fly through space for the purpose of disrupting or destroying satellites. The 2007 Chinese test of a direct ascent to LEO antisatellite (ASAT) weapon is an excellent example[5-6]. This egregious act resulted in a massive debris cloud with which all spacefaring nations must now contend. Even without the threat of debris from ASAT tests, predicted orbital conjunctions are a daily occurrence. Fortunately, actual on-orbit collisions remain rare occurrences, but the result of such an event is a significant increase in the debris population, much like an ASAT test. The 2009 collision of Iridium-33 with Cosmos-2251 produced a plume of debris similar to that of the 2007 Chinese test[7].

SSA is necessary to know if the situation on orbit has changed. Changes in the behavior of foreign satellites can be an indication of imminent hostile action. This forms the basis of tactical warning. Additional situational awareness is necessary to reassess the state of affairs once initial indications of unfriendly activity have been detected. Both tactical warning and attack assessment require detailed and persistent surveillance of the space environment and observations of individual satellites.

Data Integration and Exploitation

Data integration and exploitation are critical and often overlooked aspects of SSA. Sensors produce data. The ones and zeros are of no use until they are processed and turned into actionable information. Information results from data processing, data reduction, data fusion and, ultimately, exploitation of the data to derive knowledge. All too often, when faced with a lack of effective SSA, the tendency is to build additional sensors or sensor platforms. It is likely that substantial gains in SSA can result from more effective integration and exploitation of existing data. This, however, represents a difficult challenge as data processing is necessarily a software exercise and software engineering is less predictable than building hardware.

Spacecraft Protection and Resiliency

It is interesting that spacecraft protection and resiliency are included as a pillar of SSA. In general, these activities would be consumers of SSA information rather than producers. Spacecraft protection can result from features built into a satellite to make it more durable or more maneuverable. The satellite might also include on-board sensors for short-range SSA to detect threats within its local volume of space[8]. Resiliency is the ability to react to and overcome some form of adversity without complete loss of function and capability. Individual spacecraft can be made partially resilient through the use of redundant systems. Similarly, a constellation of spacecraft can be resilient if the network reacts to and partially compensates for the loss of or degradation of one or more elements of the network.

Space Surveillance

Space surveillance is a subset of SSA. Space surveillance is primarily concerned with the hardware and techniques used to detect and track RSOs. The result of space surveillance is data that are used to feed the processes and algorithms used to produce information. Space surveillance also includes the systems and processes used to collect signature data on specific spacecraft for the purpose of characterization and change detection. Similar to detection and tracking, these surveillance activities collect signature data that feed into identification and change detection activities. For the purposes of this paper, space surveillance is limited specifically to collection. This may include processing as necessary for continued and follow-on observations, but does not include other exploitation of the data.

In most cases, it is efficient to process the data at the sensor location, thereby enabling operators to quickly determine the need for follow-on observations and queue sensors for immediate observations. There are also examples where the raw collection data are transmitted to distant facilities for processing. This is thought to be less efficient. The Ground-Based Electro-Optical Deep Space Surveillance (GEODSS)[9] system processes the raw sensor data on site and only transmits limited track information to the Joint Space Operations Center (JSpOC). The Space Surveillance Telescope (SST)[10] is an example of a sensor where the data are linked to a distant facility for processing before information is forwarded to the JSpOC. For this paper, the main focus is the space surveillance systems and not the processing of the data or actions resulting from the information derived from these data.

Current SSA Systems

GEODSS

The active backbone of the US ground-based SSA capability for GEO satellites is the GEODSS network, consisting of three active sites, one developmental site, and one experimental test site. Active sites are located on the islands of Diego Garcia and Maui and near Socorro, New Mexico. Each active site includes three optical telescopes with supporting computer systems for image processing and data reduction. Each GEODSS telescope features a 1 m aperture with a 2.15 m focal length and an image area of approximately 2 square degrees. The image is formed on a back-illuminated charge coupled device (CCD) photon detector with 1960 x 2560 pixels on a 24 μm pitch. The optical system is described as a member of the Ritchey-Chrétien design family, but is unusual in that the secondary mirror is of spherical figure with very low optical power. A system of four lenses improves the image prior to the sensor.

While the GEODSS system is somewhat old, having entered into operations during the 1980s, it has an extremely well-designed optical train and a very rugged mount. Through upgrades and service life extension programs, the telescopes have maintained their position as first-rate instruments with near state-of-the-art sensitivities. A major weakness of the GEODSS architecture is that it does not provide world-wide coverage; the present network has a wide gap in coverage over Western Europe and a narrow gap in coverage over East Asia. As the great 40 inch refractor at the Yerkes Observatory, Williams Bay, Wisconsin, is still in operation after more than 115 years, there is no reason the GEODSS network cannot remain effective for many more decades.

SST

The SST was funded by the Defense Advanced Research Projects Agency (DARPA) as the prototype for a new generation of ground-based optical SSA instruments. As a prototype, the SST was not built as a military system and therefore is lacking many of the features normally associated with military hardware. Nonetheless, the SST is an impressive optical instrument and will prove to be an effective SSA system, once it is relocated to Western Australia and enters routine operations as part of the US Space Surveillance Network (SSN).

The SST has a 3.5-m aperture and can image a field of nearly 6 square degrees. Its telescope has a focal length of 3.5-m giving it an overall focal ratio of f/1. Such a short focal ratio on an instrument this large represents a significant design and fabrication challenge and a huge accomplishment for the development team. SST was initially assembled and tested in New Mexico but is now being relocated to Western Australia. Deploying a prototype instrument for operational use introduces a multitude of challenges and concerns regarding reliability and maintainability. One problem with the relocation effort is that it was necessary to forgo a mirror recoating facility in order to reduce the overall relocation costs. However, it will be necessary to either build such a facility in the future or endure the expense and downtime to occasionally send the mirrors elsewhere for recoating. Another problem is that the data processing concept has the raw images transmitted to a northeastern US location for processing before tracks are forwarded to the JSpOC. The enormous volume of digital data necessitated the telescope be located near existing wide-bandwidth communications as another cost-saving measure. As a result, the SST will be located at the Harold E. Holt Naval Communications Station in Western Australia, on a site that is approximately 150 feet above sea level. This low elevation is unfortunate and will result in reduced performance stemming from the need to look through additional atmosphere. The last major telescope to be located at such a low elevation was the 40 inch refractor installed at the Yerkes Observatory in 1897. In the intervening 118 years, astronomers have learned a great deal about the proper siting of telescopes.

SBSS

SBSS is the Space-Based Space Surveillance satellite, a purpose-built space-based SSA system[11]. SBSS was developed in response to the success of the Space-Based Visible (SBV)[12] sensor that was carried as a demonstration payload aboard the Midcourse Space Experiment (MSX) satellite launched in 1996. Where SBV was a relatively small payload hosted on a large satellite, SBSS was designed from the outset to be an operational SSA sensor. SBSS flies in a sun synchronous orbit (SSO) at an altitude of 630 km. The orbit is oriented so that ascending and descending nodes approximately align with the solar illumination terminator line. The sensor resides in a two-axis articulated mount with a field of regard of 3π steradians, thereby allowing the satellite bus to maintain a near constant attitude with the solar panels always pointed toward the sun.

The SBSS sensor is mated to an optical telescope of 30-cm aperture. The optical design is an unobscured, off-axis three-mirror anastigmat, and the camera is known to have a 2-megapixel CCD sensor. As the instrument was built by Ball Aerospace, the CCD is likely to be similar to those used for the Kepler mission, also built by Ball Aerospace. Those CCDs feature 2200 x 1044 pixels on a 27 μm pitch[13]. With this CCD, SBSS would have an approximate field of view of 2 degrees by 4 degrees.

The SBSS system can detect and track satellites in two different modes. One mode, known as rate-track mode, has the sensor following a satellite, holding the image spot on a single pixel. This results in the background stars forming streaks which yields high sensitivity but requires the operator to know where the target satellite is and where it is going. The other mode is known as sidereal-rate mode. When performing this operation, the stars are tracked, which means satellites will form streaks on the focal plane. This mode has lower sensitivity but provides greater astrometric accuracy which is useful for determining the satellites' orbital parameters. Each method has its advantages. The telescope for the SBV system had an aperture of 15 cm. Published data indicate the sensitivity was limited to a visible magnitude of 15. Given that SBSS has four times the collecting area as SBV, simple aperture scaling suggests that SBSS can sense targets as faint as magnitude 16.5.

Sapphire

Sapphire is a Canadian satellite that performs a space surveillance mission, providing data for the US SSN[14]. Unlike SBSS, Sapphire is a small satellite with only a 15 cm aperture and a 1.4 x 1.4 degree field of view. Similar to SBSS, Sapphire is in a dusk-dawn SSO but at an altitude of 786 km. SSA operations are performed in either rate-track or sidereal track mode. With its smaller aperture, Sapphire has a limiting magnitude of 15. Where Sapphire differs significantly from SBSS is that it uses spacecraft body pointing to orient the sensor. SBSS has a two-axis gimbal mount. As a result, Sapphire is capable of approximately 1600 observations per day, resulting in 400 satellite tracks, whereas SBSS can perform as many as 12,000 observations per day. The other big difference is cost. SBSS cost in excess of $850M; the cost for Sapphire with launch and ground station was only $96M.

GeOST/ORS-5

ORS-5 will be an SSA demonstration satellite and gap filler built for the DoD Operationally Responsive Space (ORS)[15] Office by the MIT Lincoln Laboratory (MIT/LL). The satellite will take advantage of the novel Geometry Optimized Space Telescope (GeOST) concept that was developed by MIT/LL[16] and more recently referenced in US Patent 8,511,614[17]. The GeOST concept places the sensor in LEO along the equatorial plane. Rather than have the sensor point directly toward the GEO belt, it points at a portion of the GEO belt well ahead of its own position. The location is selected such that the sensor velocity perpendicular to its line of sight exactly matches the target satellite velocity perpendicular to the vector joining the sensor and target satellites. This geometry results in the image of the target satellite remaining momentarily motionless on the sensor focal plane[18]. The end result is greater integration time and higher sensitivity, thus giving GeOST a sensitivity approximately equal to that of sensor with ten times the collecting area. This would allow a sensitivity similar to SBSS from only a 10 cm aperture. For our analysis, we assume the GeOST system sensitivity will be identical to that of SBSS at 16.5 visual magnitudes.

Like Sapphire, GeOST will use body pointing to orient the sensor, but once in the proper orientation, the sensor will not move. Rather, the satellite's orbital motion will sweep around the GEO belt, being interrupted only by the solar exclusion region. GeOST should make significantly more observations each day than SBSS or Sapphire. Presently, ORS-5 is in development with a budget of $60M, which does not include the cost of launch or operations. If the system is developed within budget, ORS-5 will demonstrate space-based SSA at a cost similar to that of Sapphire, but with a collection volume and sensitivity similar to the SBSS satellite. ORS-5 may prove to be an SSA game changer.

Challenges

The overall business of SSA faces a number of challenges, both large and small. Specific challenge areas are discussed below. The greatest challenge for SSA is that we have insufficient knowledge of what is happening on orbit to appropriately manage and operate our space resources under circumstances other than ideal. Any significant deviation from the nominal operating environment, such as a collision, disrupting solar flare, close approaching near earth object, ASAT test, or other nefarious act, results in both confusion and stress. Understanding the event and making appropriate responsive adjustments can require hours to days before the situation returns to normal.

Persistent Surveillance

At present, world-wide space surveillance activities would most appropriately be described as reconnaissance. We obtain a momentary look at a region of space and then move on to look at other areas. True surveillance would require watching objects or regions over some extended period of time. Alternatively, since most RSOs that change on orbit, change slowly, we could watch an object intermittently with short revisit times. True persistent surveillance would be best but would be difficult to resource, and the simple laws of physics interfere from time to time. Another issue related to persistent surveillance is weather. One of the arguments for going to space-based sensors is to rise above the weather. Typical ground-based observation sites have weather restricted viewing more than half the time with some sites being clear no more than 25% of the time.

Looking Into the Sun

Almost without exception, objects are extremely difficult to monitor as they pass between the earth and the sun. Daylight observations, in general, pose a significant challenge for ground-based optical sensors. Space-based sensors can provide observations much closer to the sun, but all space-based sensors are still limited when the target is positioned between the sensor and the sun.

Latency

Timely detection and tracking of events in space is critical to effective operation of space systems during any crisis situation. Given clear skies, a single ground-based telescope might require 14 to 16 hours before it can observe a target satellite, provided the satellite is available in the sky above the observation site. Space-based sensors have their own latency issues resulting from earth blockage, target satellites passing into the earth's shadow, and target satellites being located between the sensor and the sun. For many space-based sensor concepts, latency lasts no more than a few hours, but for a single near-GEO sensor, latency can be more than seven days.

Sensitivity

Satellites range in size from the diminutive CubeSats, having a characteristic dimension of roughly 10 cm, to the International Space Station, having solar arrays that would cover most of a football field. When illuminated by the sun against an infinite black background, they exhibit a brightness that can span many orders of magnitude. Large satellites are easy to track as they are bright when illuminated. Small satellites can be difficult to impossible to detect or track, even with large telescopes.

Space debris is a growing concern for the SSA community. At present, objects as small as about 10 cm are tracked in LEO, but items much smaller than about 50 cm are difficult to track at GEO. Debris objects come in all shapes and sizes, but objects smaller than 10 cm are much more numerous and, currently, are all but impossible to detect or track. In most cases, our SSA systems do not have the required sensitivity. Increasing sensitivity requires the collection of more photons, or the better use of the photons already collected. Traditionally, gains in sensitivity result from increases in telescope size, or increases in integration time. It is also possible to make smaller gains through improved image processing and reduced sensor noise. No matter the approach followed, sensitivity remains a significant challenge.

Sky Coverage

Sky coverage is more easily thought of as search rate, but since current US SSA systems perform mostly tasked (tracking) observations, we do not often talk about search rate. What is important is how much sky can be covered for either search or tracking operations and how quickly it can be covered. One advantage of the SST over GEODSS is that it can image an area three times greater than a single GEODSS telescope, thereby giving it a greater search rate. High search rate requires wide-field systems, but as mentioned above, sensitivity is also a challenge. Sensitivity results mostly from larger systems. Building systems that have both wider fields of view and larger apertures quickly becomes both difficult and expensive.

Basing, Survivability, Resiliency and Replenishment

The ideal place to locate ground-based optical observation sites is along the equator at high altitude sites, well away from large population centers. Since GEO satellites are high in the sky, basing along the equator is not essential and reasonable viewing can be obtained from locations within +/- 30 degrees of the equator. Going much farther from the equator begins to introduce shorter nights during summer months, but winter months have longer nights. It is unfortunate that there are not a multitude of useful observing sites. There are however enough suitable sites to provide global coverage.

Survivability of SSA assets is important during any conflict. It is not clear which assets would be more at risk. Ground-based systems can easily be attacked, but they are often located in third countries. There might be some reluctance for one country to attack facilities in a non-belligerent country for risk of widening a conflict. Space-based assets appear in the sky over most countries and could be engaged with ASAT systems, but few countries have such capabilities at present. A more likely scenario would be laser illumination which may or may not interfere with satellite operation. Many countries operate satellite laser ranging facilities that could be used to at least dazzle optical sensors, provided energy can be coupled into the sensor aperture.

Resiliency is the ability of a system or network to adapt to adversity and maintain some, or most of its function, either immediately, or to quickly recover following an event. Replenishment is the ability to push new assets into the field to compensate for losses. Ground-based systems can be quite resilient, particularly if they are equipped with commercial off-the-shelf hardware. Larger ground-based sites with unique instruments, such as the SST, would be more difficult to reconstitute. Space-based systems can be replenished, but unless spares are on hand and launch vehicles immediately available, replenishment might require years.

Cost

Cost is an issue for SSA, both for civilian and military purposes. There are approaches that provide useful data for routine space surveillance at extremely low cost, but low-latency global coverage quickly becomes expensive. Space-based systems tend to produce more data than ground-based systems as they can collect for most of a 24-hour period. Ground-based systems are frequently sitting idle 15 or more hours per day. Recent efforts to develop optical techniques that push operations into daylight hours for bright targets will improve the utility of ground-based systems, but individual units will never be as productive as an individual space-based asset.

Competing Approaches to SSA

Ground-Based vs Space-Based

The obvious trade most people quickly identify is that between ground-based systems and space-based systems. Each approach has its advantages, making it difficult to pick a preferred approach. Ground-based systems are generally built larger and are therefore more sensitive, but they suffer from weather constraints, they must be distributed around the globe, and they are generally not useful in daylight. Space-based systems are expensive, vulnerable to ASATs and generally have smaller apertures, making them less sensitive. Space-based sensors still have problems with solar exclusion but the restrictions are much less than for ground-based telescopes. Depending upon the architecture, space-based sensors often have quick revisit times. Larger aperture sensors can be flown, but they increase cost and complexity.

Ground-Based: Small vs Medium vs Large

When considering only ground-based optical telescopes, the trade space ranges from large networks of small telescopes to small networks (or single copies) of large telescopes. The Russian International Scientific Optical Network (ISON)[19] network represents an excellent example of a large network of what are mostly smaller telescopes. ISON has a very interesting mix of telescopes and optical designs, but most of their assets are in the 50 cm and smaller aperture class. What makes ISON interesting is that they have observation locations distributed around the globe. One obvious weakness in their network is the limited coverage over the central to eastern Pacific Ocean. While this is a limitation, it is important to point out that the GEO belt above this region is also the least populated with satellites. Given that the ISON telescopes are generally smaller in aperture, they are limited to observing GEO satellites in the 15th to 16th magnitude range. Small telescopes are extremely inexpensive and can easily be deployed to remote locations, provided power and communications are available. Small telescopes often have very wide fields of view allowing them to rapidly scan the entire visible GEO belt several times each night.

The GEODSS network represents an example of a small number of medium aperture telescopes. With an aperture of 1 m the telescopes are more sensitive than most in ISON, but with only three operational locations, GEODSS leaves parts of the GEO belt without coverage. Based on optical modeling, typical sensitivity for GEODSS is on the order of 18th visual magnitude. The field of view for each GEODSS telescope is modest at 2 square degrees. A single GEODSS telescope can scan a large part of the sky each night, while three telescopes at each site can easily scan the entire sky with excess observing capacity used for follow up observations.

The SST is an example of a small network composed of large-aperture telescopes. In the case of SST, there is only one. The telescope is capable of scanning the entire sky several times each night and recording GEO objects to magnitudes as faint as 19.5. The system cost, however, is extremely high, almost to the point of being too expensive.

Space-Based: LEO vs Near-GEO

When building space-based SSA assets, the first choice is between deploying them in LEO or some higher orbit, close to, but not specifically in GEO. Basing in LEO is less expensive and the radiation environment is more benign, but one must also contend with substantial earth blockage. The earth blockage is only a short-time problem as the satellites' orbital periods are on the order of 90 minutes. LEO SSA assets quickly have access to nearly the entire GEO belt. Another advantage of LEO is that all GEO target satellites are at a similar range; thus, there is very little variation in visual magnitude due to variations in range to target. Most of the signature variation results from changes in solar illumination angle.

For near-GEO basing, we have the advantage of being very close to some GEO assets for short periods of time. As the satellite drifts across the GEO belt, virtually all GEO satellites are encountered with a relatively short range viewing opportunity. The problem is in searching; being very close to things that are still scattered across a large area results in a substantial angular volume that must be searched. Also, being very close to some satellites means that you are simultaneously very far from others. At any point in time, the close satellites are bright but difficult to see due to field of view issues, while many distant satellites can fit within a single field of view, but are very dim due to range. GEO basing has its utility, but the choice between LEO and GEO is not clear. For search and monitoring, LEO basing appears to be the better choice, while for close inspection, near-GEO would be the better choice.

Space-Based: LEO SSO vs LEO Equatorial

If one has made the choice to base SSA satellites in LEO, the two basic approaches are an SSO, or an orbit within the equatorial plane. Once again, each approach has its advantages. Satellites in SSO always have their solar cells pointed at the sun and never experience thermal variations resulting from movement into and out of earth's shadow. The GEO target satellites on the side of the earth away from the sun are mostly visible. An exception is when the observer satellite passes through the equatorial plane and visibility of GEO satellites 180 degrees away is blocked by the earth. There are also complications that arise due to changes in relative motion between observer and target satellites throughout the orbit. The biggest disadvantage to the SSO is that a large portion of the satellites are located somewhere between the observer and the sun, or at least close to such a viewing orientation. This results in significant latency of some observations.

For a satellite in an equatorial LEO configuration, there are again choices. One option is to use the satellite for tasked observations and the other is to use it for sweeping out the GEO belt during each orbit. At any instant in time, half of the GEO satellites are not visible, but over the course of one orbit, most, except for those at a viewing angle which includes the sun, become visible.

Performance of Existing Systems

To help identify the optimum approach to SSA, it is useful to examine the performance of existing systems. Presented below are approximate performance data for GEODSS, SST, SBSS, Sapphire, and GeOST. We also include performance for the ISON as it provides a useful data point on distributed, small-aperture, ground-based optical telescopes.

One figure of merit that will be used to examine performance is the inherent sensitivity of the instrument. This is defined as the sensitivity the optical sensor would have if it were mounted on the earth, tracking the stars and observing GEO satellites as they streak across the focal plane. We will also consider the sensitivity as published by the designers or reported by operators when the sensor is used as designed and in its proper environment. This approach allows us to directly compare theoretical performance between systems, and also compare actual performance for dissimilar systems.

Maximum latency is another performance indicator of interest. This number gives the maximum number of hours one should have to wait to reacquire a GEO target that could be observed by the system. Latency considers only geometric effects (such as earth blockage) and lighting effects (such as looking into the sun or the target satellite being in the earth's shadow). Latency is an important indicator of how useful the system would be for indications and warnings.

Various plots are provided below for each system. While some contour plots look similar, there is a significant difference between those for space-based sensors and ground-based sensors; these will be discussed individually with each system. The ground-based sensors are fixed relative to the GEO satellites and only the sun moves with respect to the observing location. For space-based sensors, the GEO target satellites, the sensor satellite, and the sun all move relative to one another with time, thereby necessitating the plots for each system to be somewhat different.

For sensitivity calculations, the target is assumed to be an aluminum sphere with a reflectance of 18%, composed of a diffuse fraction of 95%, and a specular fraction of 5%. Two different types of sensitivity calculations are presented. For the first sensitivity calculation, we assumed a fixed target size of 200 cm diameter and calculated the expected visual magnitude resulting from range, look angle, and solar phase angle. The results of this calculation are independent of the particular sensor and are only determined by the location of the sensor relative to the location of the target and the sun. The other sensitivity calculation starts with the limiting magnitude for the sensor and then determines the smallest target that would be visible for a given combination of sensor location and target location. While some subject matter experts are quick to point out that real satellites are not accurately modeled as simple spherical objects, the spherical targets prove useful as the signatures for real satellites are very complex functions of satellite orientation, solar phase angle, range, and sensor look angle. It is simply not practical to summarize all the variations of real signatures in a paper of this nature.

GEODSS

Performance data for the GEODSS network is summarized in table 1. We assume ground-based optical telescopes can view as far down as 70 degrees from the zenith and we assume the sun must be 22.5 degrees or more below the horizon for the sky to be sufficiently dark for observations.

Table 1. GEODSS Performance Data

Aperture	1.00	m
Focal Length	2.15	m
Focal Ratio	2.15	
Field of View	2.05	deg
Inherent Sensitivity	18	magnitude
Typical Sensitivity	18	magnitude
Typical Latency	13	hours
Maximum Latency	17	hours
Sky Coverage Efficiency	30	percent

The first section in this table summarizes previously discussed physical parameters for the sensor; sensor sensitivity is summarized in the second section; and latency calculations are in the third section. The typical latency is the approximate average maximum number of hours one would need to wait between the last observation on one night, and the first observation of the next night, assuming both nights presented clear observing conditions. Maximum latency is the maximum number of hours one would need to wait for such an observation opportunity. Due to seasonal variations in lighting conditions, maximum latency is greater than the typical latency. Note that these latency values are only valid for portions of the GEO belt visible from any GEODSS site. There are portions of the GEO belt that cannot be observed by any GEODSS sensor and therefore have an infinite latency.

The sky coverage efficiency reported in table 1 provides an indication of the fraction of time that satellites in each GEO position are visible to any sensor in the GEODSS network, averaged over all orbital positions. This quantity is determined solely from the geometry and orbital mechanics of the GEODDS and target satellite configuration; weather effects are not considered for this calculation. Higher values indicate greater coverage.

Figure 1 shows a plot of the latency expected for each longitude position within the GEO belt, when observed by the GEODSS network. A latency of 24 hours means that satellites in those longitude positions are never observed. The three traces represent the minimum latency, average latency, and maximum latency experienced over the course of 12 months. The changes are due to the latitude of the respective GEODSS sites and variation in sun position with the seasons.

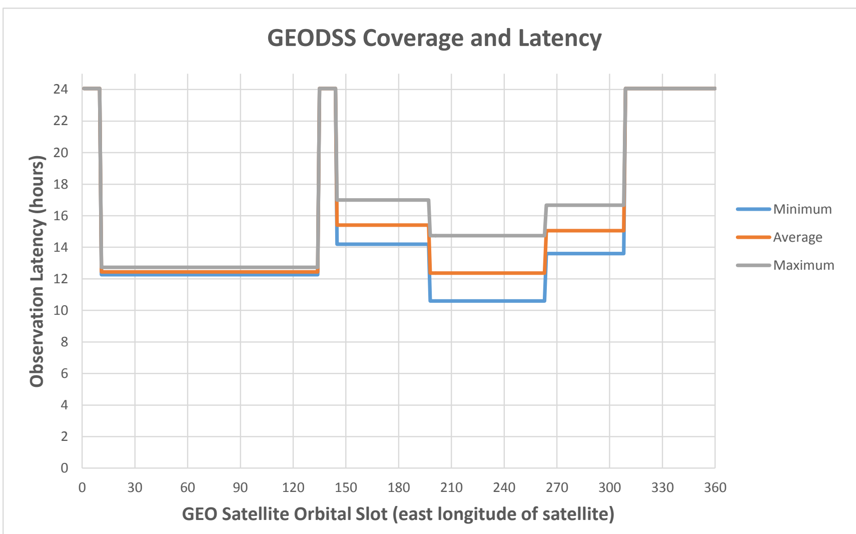

Fig. 1. Latency calculations for GEODSS.

In figure 2, we present a plot of the visual magnitude of a 200 cm target sphere as observed by the various GEODSS sites over the course of a 24 hour day. For the horizontal axis (Sun Location), 0 corresponds to 12:00 noon on the Greenwich Meridian, and every 15 units (degrees) is 1 hour later. As the sun moves east to west, we present the sun location as degrees of west longitude. On the vertical axis (Target Location), each unit specifies the standard earth longitude for a GEO satellite location as described previously, but again presented as degrees of west longitude. West longitude is unusual, but provides commonality with the sun location. This particular plot is for the month of March which includes the Vernal Equinox. The equinox results in GEO satellites briefly passing through the earth's shadow. A plot for each month would have small variations due to the seasonal variations in solar illumination.

The white space seen in figure 2 represents combinations of times given by sun position and target location where it is not possible for any GEODSS site to observe the target satellite. The ratio of this white space to the total number of observing opportunities gives a percentage which is the compliment of the sky coverage efficiency as presented in table 1 above. Note that from the GEODSS sites, a 200 cm diameter sphere has optical signatures in the range of 13th to 17th magnitude, making this size target easily visible by any GEODSS telescope.

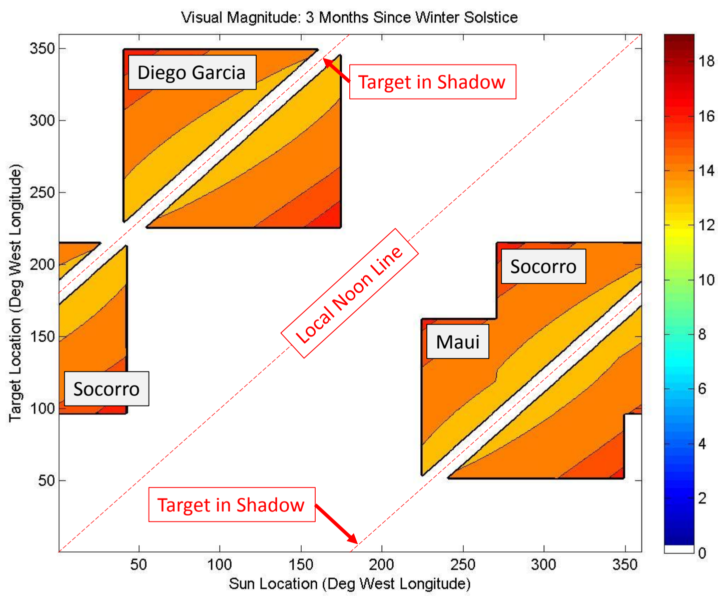

Fig. 2. 200 cm target visual magnitude as viewed from GEODSS sites.

Another way to look at the performance of the GEODSS system is to use its limiting magnitude, 18, to calculate the smallest object that would be visible. This information is shown in figure 3 below, but this time for the month of December. Since the Winter Solstice occurs during December, GEO satellites do not enter the earth's shadow so we see that targets are visible during the night without interruption. These targets are again aluminum spheres with the reflectance characteristics as discussed above, but with diameters adjusted to give 18th magnitude. This plot indicates that GEODSS telescopes are mostly able to see targets smaller than 50 cm diameter, with a few excursions where the smallest targets are closer to 150 cm diameter.

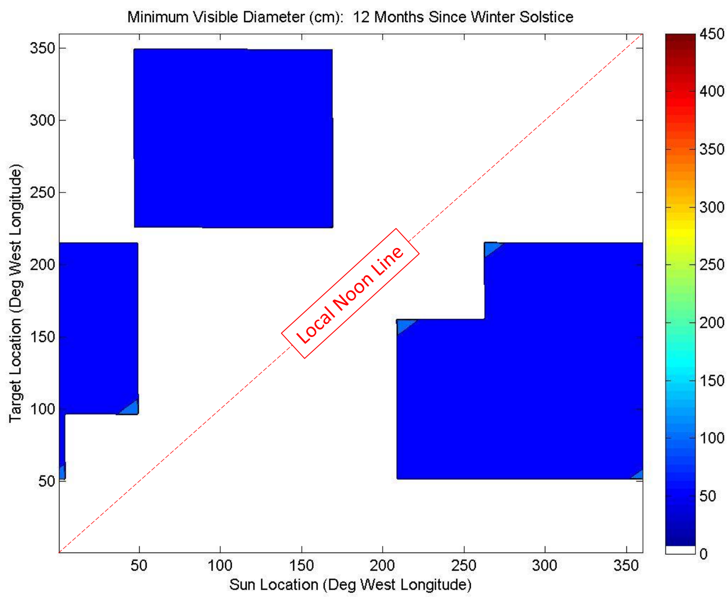

Fig. 3. Minimum detectable diameter target for GEODSS.

SST

In this section, we present data for the SST, similar to that presented above for GEODSS. Performance data are shown in table 2. These data have some numbers that, at first glance, might appear surprising, but are, in fact, as one should expect. For latency, during the summer months in Australia, SST can wait as long as 16 hours before it can begin observing again. This value is shorter during winter months. While this seems like excessive latency, this value is for SST working alone. In practice, SST will never work alone as it will be part of an integrated network of ground and space-based sensors. The sky coverage efficiency value also appears to be extremely low. This again is as should be expected for a single telescope working alone.

Table 2. SST Performance Data

Aperture	3.5	m
Focal Length	3.5	m
Focal Ratio	1.0	
Field of View	3.5	deg
Inherent Sensitivity	19.5	magnitude
Achieved Sensitivity	19.5	magnitude
Typical Latency	15	hours
Maximum Latency	16	hours
Sky Coverage Efficiency	11.5	percent

Figure 4 shows the expected sky coverage and latency durations for SST operating alone. During local winter months, latency can be as short as 14 hours, while during local summer, it extends to 16 hours.

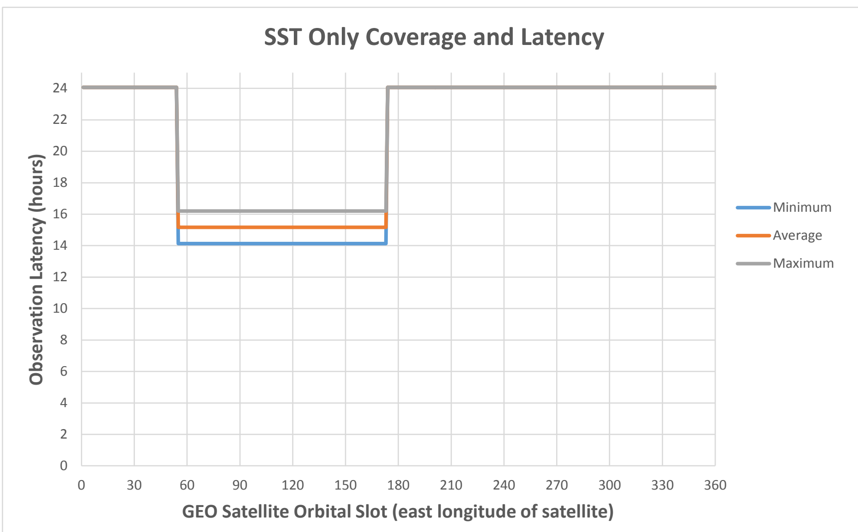

Fig. 4. Latency calculations for SST working alone.

The visual magnitude of a 200 cm diameter target sphere as viewed from the SST site during the month of June is shown in figure 5. Note that this calculation is for the site only and really has nothing to do with the SST itself. Figure 6, on the other hand, presents data from calculations showing the minimum visible target diameter, based on SST's limiting magnitude of

19.5. The results shown in figure 6 are for the month of December. One should note that SST can routinely detect targets smaller than about 30 cm diameter.

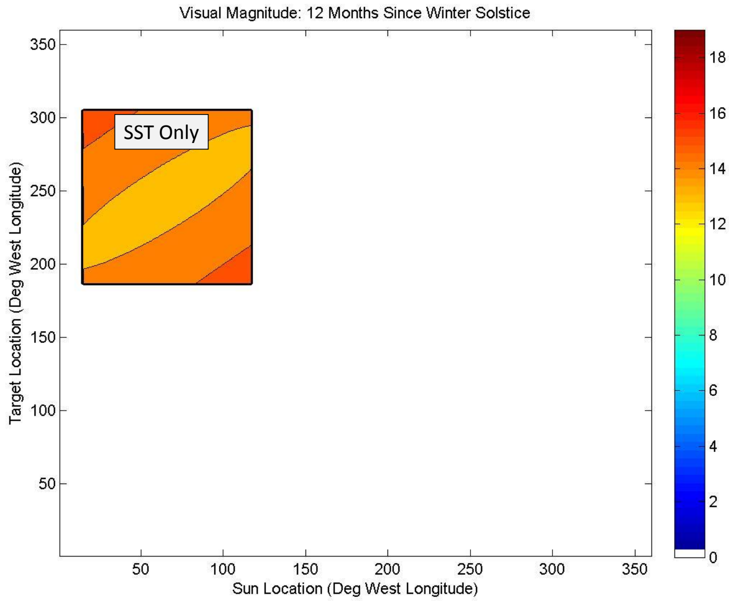

Fig. 5. 200 cm target visual magnitude as viewed from the SST site.

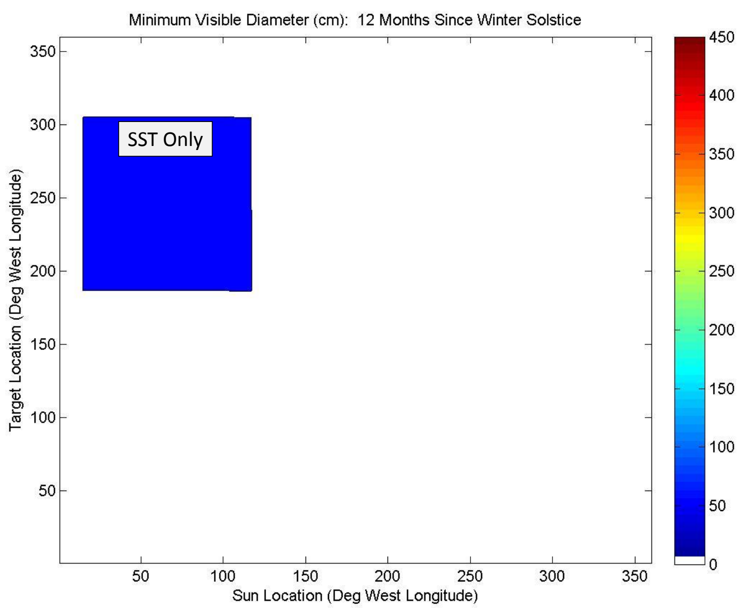

Fig. 6. Minimum detectable diameter target for SST.

GEODSS + SST

Since GEODSS and SST are designed to work together, it is useful to examine the latency and minimum detectable target plots for the combined network. This presentation shows how

SST integrates with GEODSS and significantly boosts overall SSA capabilities. The latency calculation is shown in figure 7. The minimum detectable target plot is shown in figure 8.

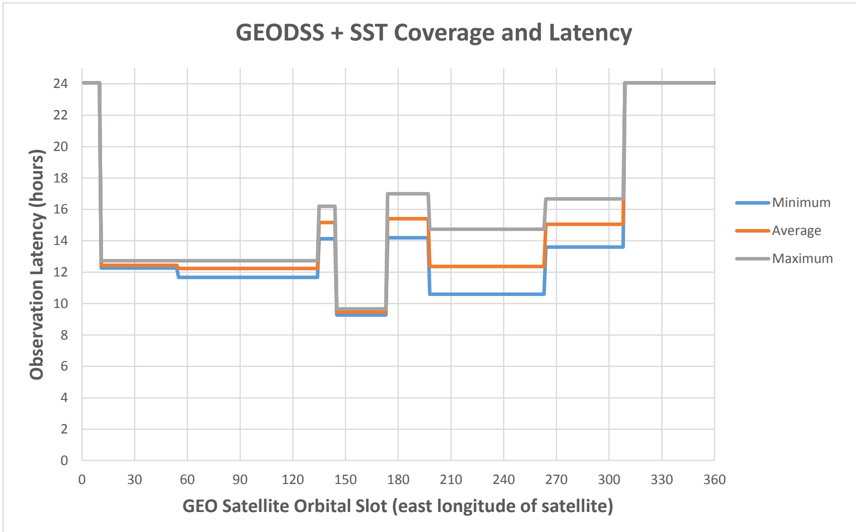

Fig. 7. Latency calculations for GEODSS + SST.

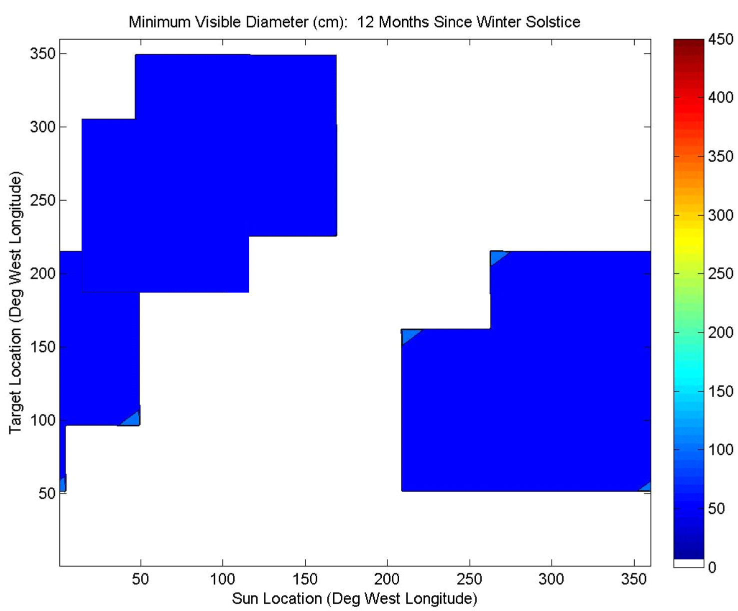

Fig. 8. Minimum detectable diameter target for GEODSS + SST.

Hypothetical Global Ground-Based Coverage

To better understand the information in the figures above, we consider a hypothetical global network of 360 ground-based telescopes, positioned around the world at the equator, and evenly spaced one degree apart in longitude. Figure 9 shows the signature of our 200 cm diameter target as viewed from these locations. It is clear that 360 telescopes greatly increase overall performance as the sky coverage efficiency for this network is 65%. The only white spaces are centered about the local noon line seen in the upper left and lower right corners and the large diagonal from lower left to upper right. Comparing figure 9 to the GEODSS network in figure 2, one can clearly see the impacts of a sparse network.

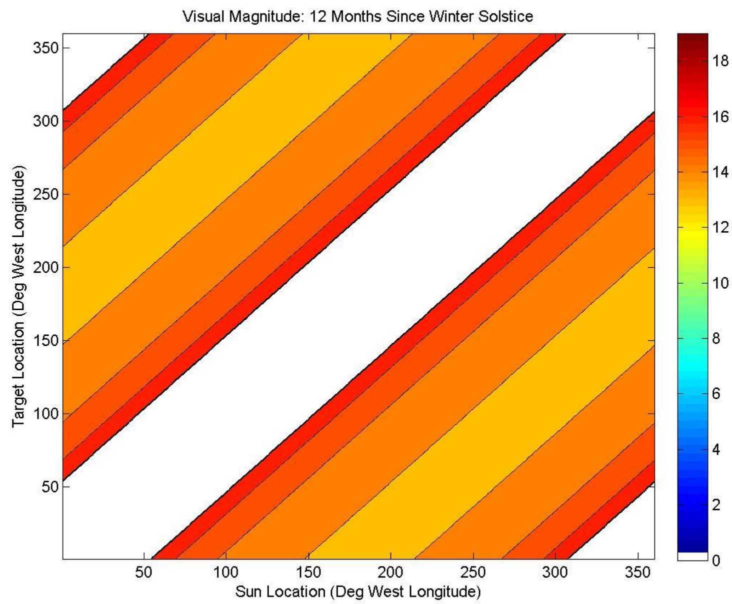

Fig. 9. 200 cm target visual magnitude as viewed from 360 equatorial sites.

ISON

Calculations for ISON are presented only for comparison. ISON is not a dense, continuous network similar to the hypothetical ground-based coverage discussed previously and illustrated in figure 9, but still has significantly more telescopes and observing sites than GEODSS or even GEODSS plus SST. Figure 10 shows the calculated latency for the ISON network based on published observing sites. With a dense network, latency decreases significantly; however, the figure clearly reveals the impact of the many ISON sites at high northern latitudes. The great variation in latency results from seasonal changes in daylight duration. Figure 11 shows the visibility of a 200 cm target from the various ISON sites. Comparing figure 11 with figure 9 shows the difference between a dense network and a true continuous (hypothetical) network. The ISON collection of telescopes achieves an impressive sky coverage efficiency of 51%.

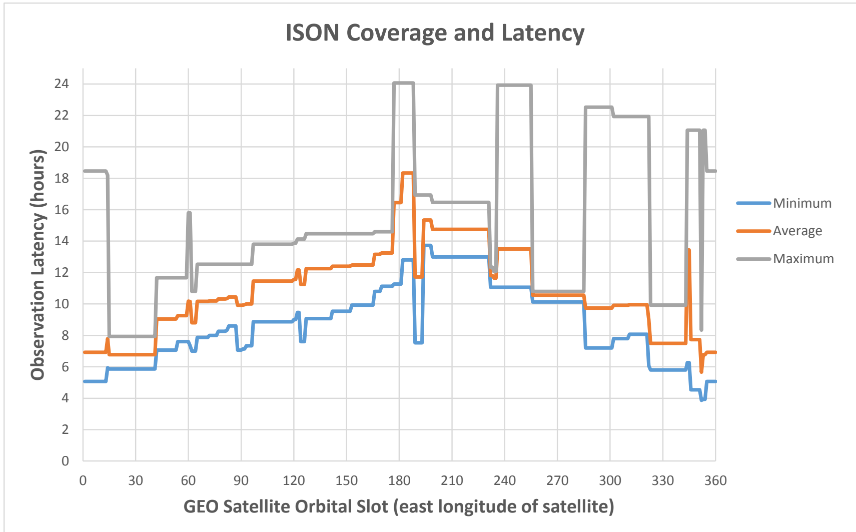

Fig. 10. Latency calculations for ISON.

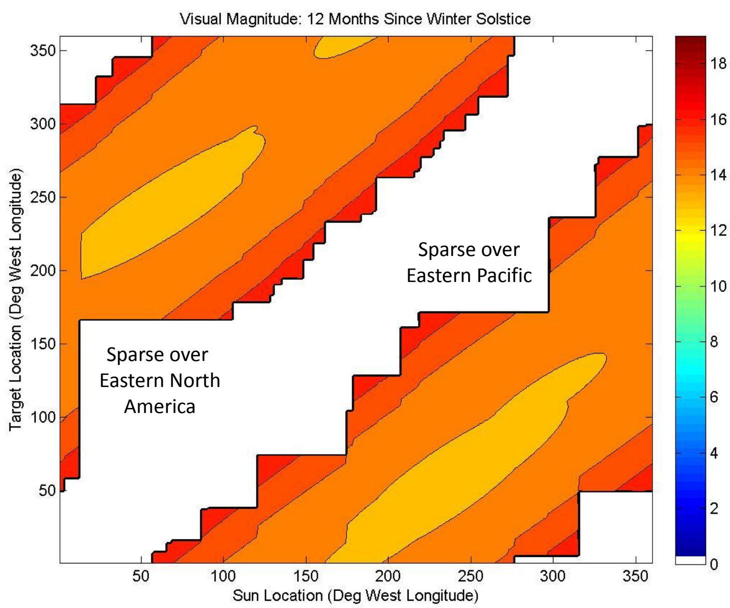

Fig. 11. 200 cm target visual magnitude as viewed from ISON sites.

SBSS

The presentation of performance data for space-based SSA collectors will necessarily be different from that of ground-based collectors as the space-based sensors are not fixed to a single geographic location. The SBSS performance data are shown in table 3, but some explanation is required. The focal length, focal ratio, and field of view were all estimates based an assumption that SBSS used the same CCD as was flown on the Kepler spacecraft. We believe this to be a reasonable assumption as Ball Aerospace built Kepler prior to SBSS and had experience with that particular CCD. The inherent sensitivity is calculated for the system based on these assumed parameters. The sensitivity achieved on orbit has not been published, but can be approximated by scaling the published sensitivity for Sapphire (or SBV) to the larger aperture of SBSS. That scaled value comes out to be 16.5 visual magnitudes. Since SBSS flies in a polar, sun synchronous orbit, the apparent velocity of target satellites is a complex function of the position of each satellite in its respective orbit. These relative angular velocities range from 5 to 65 arc seconds per second. For reference, a GEO satellite viewed from the ground has an apparent angular velocity of 15 arc seconds per second relative to the stars. This range of angular velocities gives SBSS a band of sensitivity ranging from approximately 15.7 to 17.8 visual magnitudes.

The latency value reported in table 3 results from an assumed solar exclusion angle of 45 degrees. This value is probably too small as SBSS is claimed to have a field of regard equal to 3π steradians, but 45 degrees should be close and is the value used for these analyses. The sky coverage efficiency value results from the nature of the SSO. SBSS is in LEO and therefore has periods where regions of the GEO belt are blocked by the earth. Solar exclusion further limits which portions of the GEO belt can be seen at any instant in time. Ultimately, SBSS can see the entire GEO belt, given enough time allocated for collection.

Table 3. SBSS Performance Data

Aperture	0.30	m
Focal Length	0.85	m
Focal Ratio	2.83	
Field of View	2 x 4	deg
Inherent Sensitivity	17.0	magnitude
Assumed Sensitivity	16.5	magnitude
Typical Latency	5.7	hours
Maximum Latency	6.3	hours
Sky Coverage Efficiency	49	percent

Figure 12 shows a plot for the visual magnitude of a 200 cm diameter aluminum sphere in GEO as viewed from various locations along the SBSS orbit. While this plot appears similar to those for ground-based systems, it has a significant difference. The horizontal axis is now the position of the observer satellite, SBSS in this case. Since SBSS is in a highly inclined orbit, the zero position corresponds to being over the earth's South Pole. The 90 and 270 positions correspond to passing through the equatorial plane and the 180 position corresponds to being over the North Pole. Along the vertical axis, we find the position of the GEO target satellite relative to the sun. This is not the longitude of the satellite itself.

The white areas in figure 12 are regions where no observation of a target in a specific location is possible from the SBSS sensor in a specific position. The large white bands along the top and bottom result from solar exclusion and the inability of SBSS to see behind itself. The white band across the center shows where the GEO target satellite has moved into the earth's shadow and is therefore not illuminated. The results presented in figure 12 are for the month of March which includes the Vernal Equinox. The two large white blobs, roughly circular, show where SBSS is passing through the equatorial plane on the ascending or descending side of the its polar orbit and, as a result, cannot view GEO satellites on the opposite side of the earth. The visual magnitude contours are for a 200 cm diameter target satellite. They depend only upon geometry and are not providing any indication of SBSS sensitivity. The contours only show how sensitive SBSS would need to be to see a 200 cm diameter aluminum sphere in GEO.

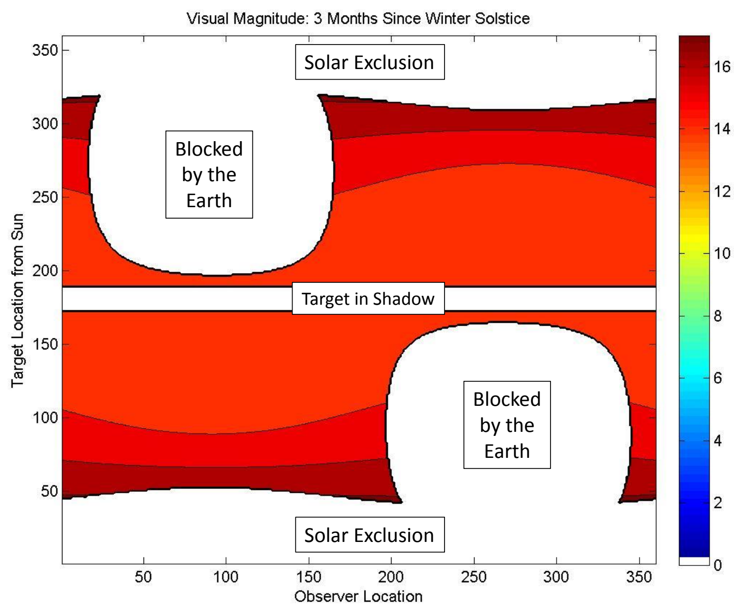

Fig. 12. Visual magnitude of 200 cm target in GEO as viewed from SBSS.

As originally envisioned, SBSS was to be a constellation of four satellites, all in the same SSO but separated 90 degrees from one another. Such a constellation would eliminate the earth blockage problem but would not reduce the solar exclusion region appreciably. Even with a constellation of only two satellites, the sky coverage efficiency increases to 74% as the earth blockages are eliminated. In figure 13, we present a plot of the maximum visual magnitude for a 200 cm sphere as viewed from two SBSS satellites in the same SSO, but at opposed positions. This plot is again for the month of March. It is interesting that even with a two satellite constellation, maximum latency remains essentially unchanged as both SBSS satellites would be in the same orbital plane. Increasing the constellation size improves coverage but latency remains unchanged.

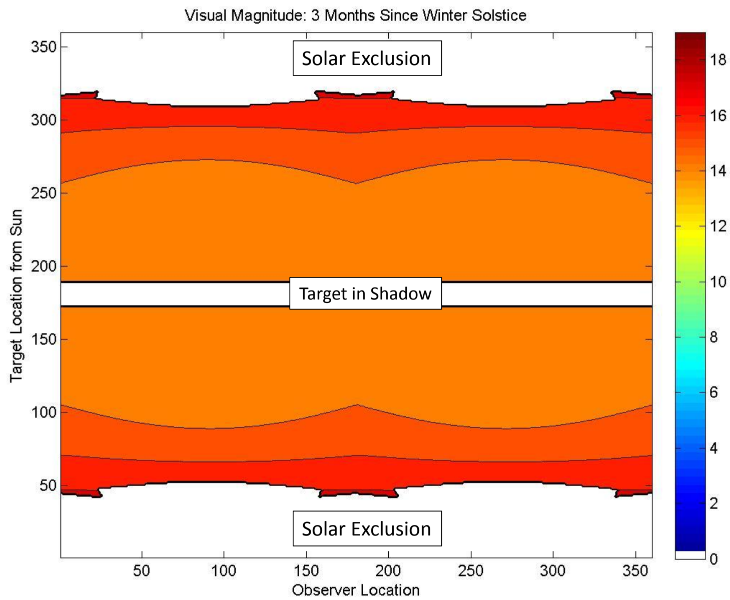

Fig. 13. Visual magnitude of 200 cm target in GEO as viewed from a 2-satellite SBSS constellation.

Figure 14 presents a plot showing what target size SBSS can actually see. This plot presents the minimum diameter for an aluminum sphere that could be sensed by SBSS as a function of target position and SBSS position. The data in this plot are approximate, as a constant limiting magnitude of 16.5 was assumed for SBSS and no attempt was made to account for the differences in relative angular velocity. As can be seen in figure 14, SBSS can view targets smaller than 100 cm diameter under favorable conditions with the minimum detectable size increasing to approximately 200 cm diameter under less favorable conditions.

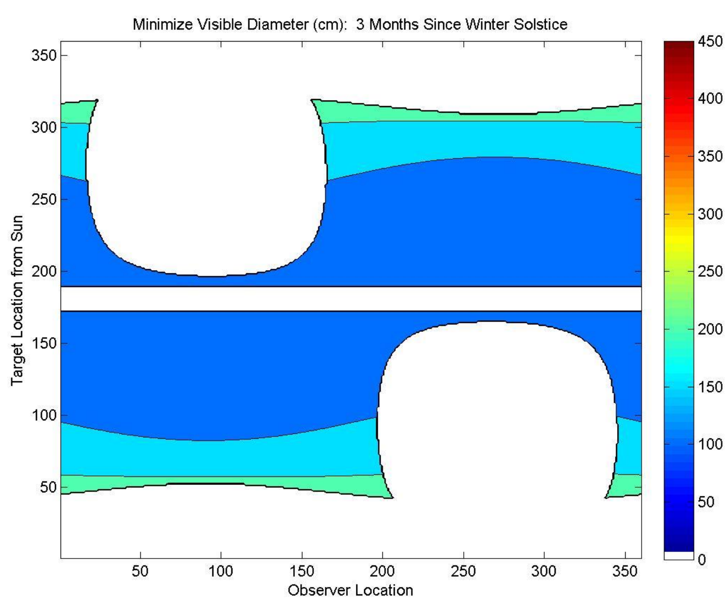

Fig. 14. Minimum detectable diameter target for SBSS.

Sapphire

While Sapphire is a smaller satellite, with a smaller aperture and an operational concept that differs from that of SBSS, Sapphire is in a similar SSO and as a result, suffers from some of the same limitations as SBSS. On the other hand, it offers many of the same advantages as SBSS. The limitations are more a matter of physics than limitations of the hardware. The performance data for Sapphire are shown in table 4. The value for achieved sensitivity is as reported by the Sapphire program. Like SBSS, Sapphire will engage targets that have a range of relative angular rates, thereby giving it a wide range of detection thresholds as was discussed above for SBSS. The solar exclusion angle for Sapphire was assumed to be similar to that of SBSS. Even though Sapphire uses body pointing, it will need to keep the sensor out of the sun. Since the majority of targets will be viewed away from the sun, we simply used a 45 degree solar exclusion angle for calculations of Sapphire performance.

Table 4. Sapphire Performance Data.

Aperture	0.15	m
Focal Length	0.55	m
Focal Ratio	3.63	
Field of View	1.40	deg
Inherent Sensitivity	15.8	magnitude
Assumed Sensitivity	15.0	magnitude
Typical Latency	5.7	hours
Maximum Latency	6.3	hours
Sky Coverage Efficiency	49	percent

Figure 15 shows a plot of the minimum detectable target size for Sapphire. This plot is similar to that seen in figure 14 for SBSS with the differences resulting from the smaller aperture telescope. Sapphire can generally sense targets that are aluminum spheres in the diameter range of 150 to 300 cm.

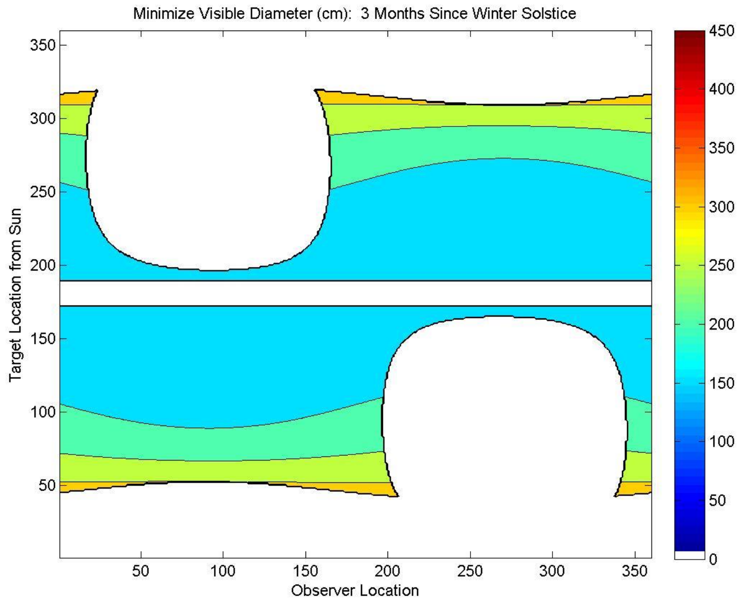

Fig. 15. Minimum detectable diameter target for Sapphire.

GeOST

Unlike SBSS and Sapphire, GeOST is a completely different concept in space-based SSA. Orbiting in the equatorial plane and using a time delay and integration (TDI) CCD sensor, GeOST will sweep out large portions of the GEO belt every 90 minutes. Due to the greater integration time resulting from the TDI operation, GeOST can achieve sensitivity similar to that of SBSS with one third the aperture and at an order of magnitude lower cost. Estimated performance data for the ORS-5 implementation of the GeOST concept are presented in table 5.

The data in table 5 are incomplete and require some explanation. The inherent sensitivity is calculated assuming the sensor was mounted on the ground. The achieved sensitivity is based on SBSS and the aperture is estimated from literature on the GeOST concept suggesting it is ten times more efficient than conventional SSA approaches. This results in an aperture roughly one third that of SBSS. To be useful, GeOST would require a substantial field of view and one might expect it to be greater than the field of view for SBSS. As SBSS has a field diameter of approximately 4.5 degrees, we will assume the field of view to be greater than 5 degrees, but this is only an assumption. Table 5 contains no data for the system focal length or focal ratio. No data are available for these parameters so these entries are left blank. The maximum latency and sky coverage efficiency are based on an assumed solar exclusion angle of 30 degrees. Some GeOST concepts have a more ambitious solar exclusion angle and would thus have lower values for maximum latency and higher values for sky coverage efficiency. We chose to use the more conservative value of 30 degrees for the solar exclusion angle.

Table 5. Performance Data for GeOST.

Aperture	0.10	m
Focal Length		m
Focal Ratio		
Field of View	>5.00	deg
Inherent Sensitivity	15.4	magnitude
Assumed Sensitivity	16.5	magnitude
Typical Latency	3.4	hours
Maximum Latency	4.3	hours
Sky Coverage Efficiency	50	percent

Figure 16 shows the expected visual magnitude for a 200 cm diameter spherical target in GEO as viewed from the GeOST orbit. For the horizontal axis, the zero position corresponds to the GeOST satellite/sensor being on a line from the center of the earth to the center of the sun. The calculations supporting figure 16 were performed assuming that GeOST could be tasked to point at any GEO object without restrictions other than earth blockage and solar exclusion. This is believed to be possible for GeOST, even though the primary mode of operation is intended to be TDI sweeping of GEO and as such, only part of the data in figure 16 is relevant. Like SBSS and Sapphire, GeOST is in LEO and suffers from having the earth block part of its view. The solar exclusion depicted is for a 30 degree keep out angle.

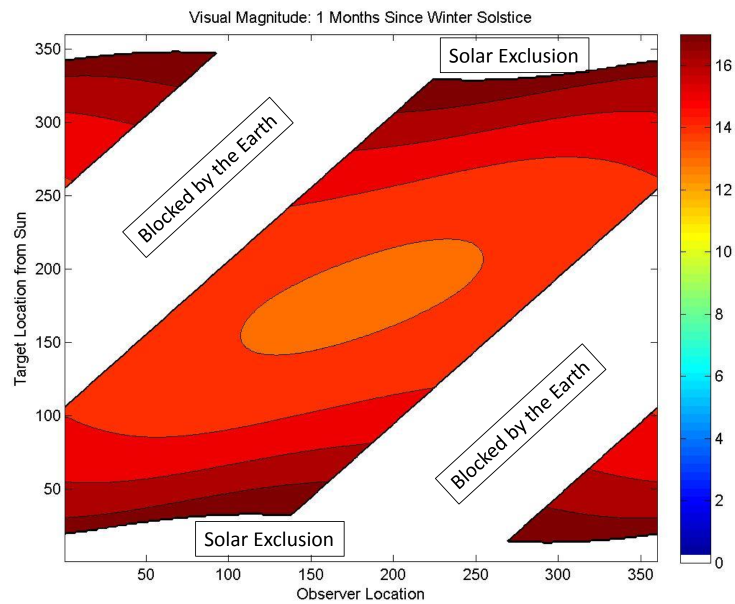

Fig. 16. Visual magnitude of 200 cm target in GEO as viewed from GeOST.

Figure 17 presents data for the minimum size target that would be visible by GeOST as a function of position in its equatorial orbit. The calculation is similar to that presented for other satellites. The data show that GeOST should be able to see targets slightly smaller than 100 cm diameter, but at times will be limited to targets as large as 275 cm diameter. Most of the variation in detectable target size is due to geometry and the solar phase angle. A larger aperture sensor would significantly improve GeOST sensitivity.

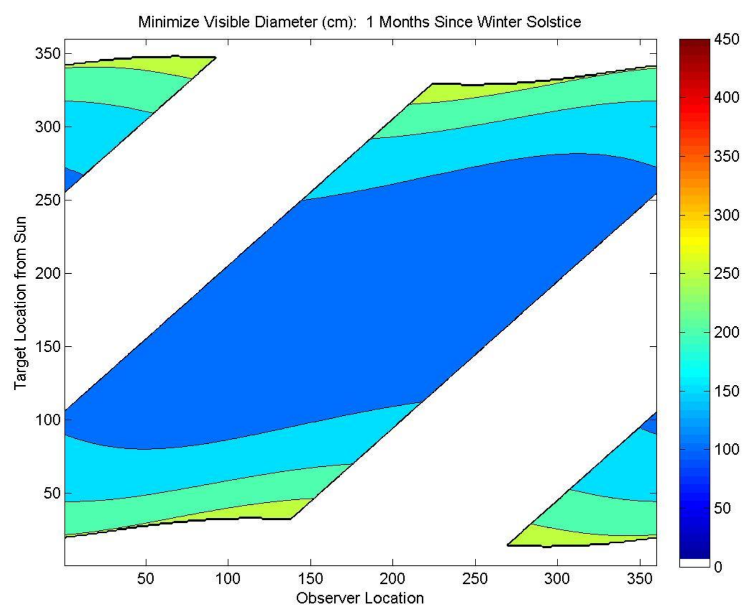

Fig. 17. Minimum detectable diameter target for GeOST.

GSSAP

Very little information on the Geosynchronous Space Situational Awareness Program (GSSAP) satellite is publically available[20]. While designed to enhance SSA at GEO, it is not clear that GSSAP is intended for broad area search. One SSA concept suggests that putting a search satellite in GEO is the ideal solution to maximize sensitivity, however, such a deployment introduces problems that do not exist for lower altitude platforms. Being in GEO or near GEO significantly reduces the range to many satellites which decreases visual magnitude and makes detection of unknown objects easier. However, searching for RSOs from up close is another matter entirely. Regardless of the altitude for the sensor satellite, the area of space that needs to be searched remains constant, but at close range, the relative angles and projected area become much larger than when viewed from a distance.

Figures 18 and 19 demonstrate this effect. Consider an observer satellite at the zero degree position, 500 km below the GEO belt, with a two square degree field of view. The number of image frames required at each position along the GEO belt as viewed by this observer is shown in figure 18. Getting up close greatly increases the angular volume that needs to be searched. Figure 19 presents the total number of frames required to cover the GEO belt as a function of observer satellite altitude. Note how the observing workload greatly increases as the observer approaches the GEO altitude.

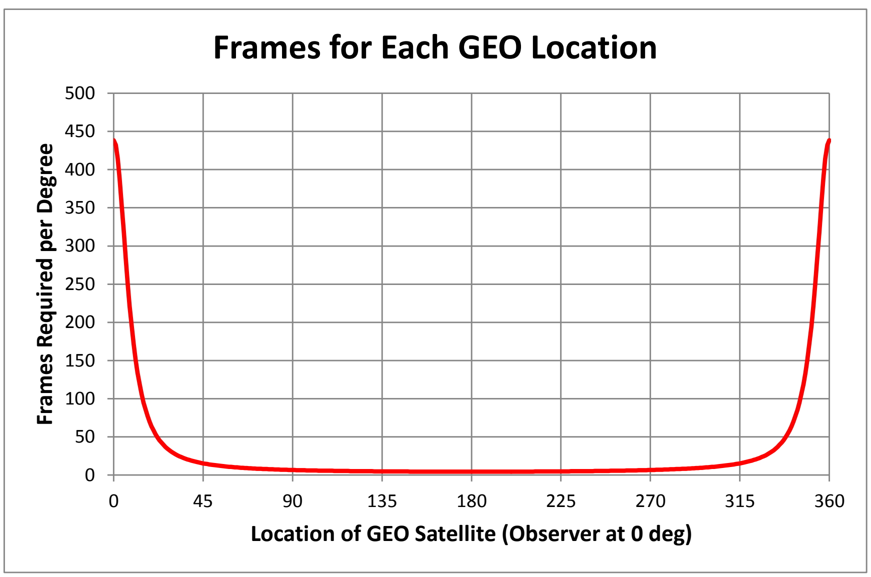

Fig. 18. Number of frames required per degree along the GEO belt for an observer 500 km below GEO.

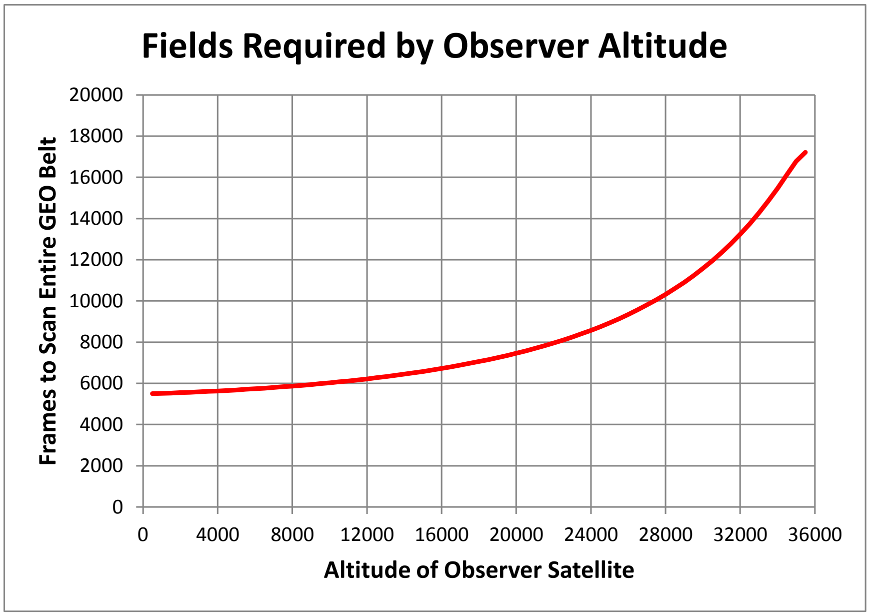

Fig. 19. Total frames required to scan the GEO belt as a function of observer satellite altitude.

According to official USAF press releases, the GSSAP satellites will be able to characterize space objects and not just observe them[21]. They are described as adding a new capability and not simply duplicating capabilities derived from other space-based SSA platforms. Given the geometric difficulties of performing a GEO search from a near-GEO vantage point, it is unlikely that GSSAP includes a true, broad area search capability. As such, we will not consider GSSAP further.

Comparing Cost and Performance

An often overlooked question for SSA systems is that of relative value. Some information is deemed so important that it will be acquired regardless of cost. For most situations, however, the cost to collect the data is important. Infinite resources are not available and there are competing needs and requirements. To help make the large potential SSA trade space easier to understand, we propose comparing the three most important characteristics: cost, sensitivity, and latency. Cost seems easiest to understand, but what is most important is the cost per observation since thousands of observations are required. This must include the expenses for acquisition, operations, and maintenance. Sensitivity is rather straight forward and has been discussed at some length in the paper. Some might be surprised to find latency listed as a key parameter rather than search rate, field of view, or sky coverage. The answer is simple, however. What is most important is keeping track of what is happening in space and discovering changes as quickly as possible. This necessarily means latency, which itself requires systems with enough field of view and agility to guarantee a low latency time.

Pertinent data for the various systems are provided in table 6. The most difficult numbers to find are system acquisition, operations, and maintenance costs. As a very rough general rule, on an annual basis, satellite operations and ground-station maintenance costs fall within the range of

5% to 10% of the acquisition cost. Certainly, commercial systems come closer to the low end of this estimate where military systems tend to be towards the higher end. Ground-based telescopes seem to have a similar cost for maintenance and operations, but tend to be closer to about 5% of the acquisition cost. Where possible, real data were used to develop the values presented in table 6. When real data were unavailable, representative values for surrogate systems were used. The important figure is cost per observation and this itself requires knowledge of how many observations each system is capable of performing during a given day. For ground-based systems, estimates had to be included for cloud cover, while for space systems, there is some reduction in availability for software updates, calibration, and vehicle maintenance operations.

Table 6. Cost, Latency and Sensitivity Comparison Data.

System	Cost per Observation	Observations per Day	Availability	Average Latency	Maximum Latency	Inherent Sensitivity	Sensitivity in Use
Single GEODSS	$0.76	12,600	0.247	13	17	18.5	17.5
GEODSS Network	$0.76	113,400	0.247	13	17	18.5	18.0
SST	$1.59	25,200	0.329	15	16	19.5	19.5
SBSS	$23.05	12,000	0.868	5.7	6.3	17.0	16.5
Sapphire - 360 Tracks	$24.35	1,440	0.870	5.7	6.3	15.8	15.0
Sapphire - 400 Tracks	$21.92	1,600	0.870	5.7	6.3	15.8	15.0
GeOST/ORS-5	$3.07	15,840	0.870	3.4	4.3	15.4	16.5

For ground-based telescopes, we used the conservative assumption that clear skies are available only one night out of four for GEODSS sites and one night out of three for the SST. The availability data for SBSS was derived from published values. The availability value for Sapphire and GeOST were simply replicated from SBSS. While some will certainly argue with the values presented here, we are confident they are within a factor of two of actual values and probably no more than 30% from the true values. Since all values were derived with similar assumptions, they remain useful for comparing one system to another. For overall cost, ground-based systems are much less expensive than even the cheapest space-based system. For latency, space-based systems are the clear winner. For sensitivity, ground-based systems easily exceed the performance of space-based systems.

Looking only at ground-based systems, we find the GEODSS network is much less expensive than the single SST on a cost per observation basis, but to be fair, SST will likely make three times the number of observations in each frame as a GEODSS telescope. The data in table 6 assume only a single observation per frame. If this adjustment is made, SST observations would actually be slightly less expensive than GEODSS. On the other hand, the maintenance and operations costs are known for GEODSS but not for SST. As SST was built as a prototype, it will likely be much more expensive to maintain and operate than GEODSS. This will tend to increase the cost of SST observations, so the data in table 6 are probably still valid.

Looking only at space-based systems, GeOST is the clear winner, having a significantly lower cost per observation, the lowest maximum latency value, and sensitivity that equals the largest system currently on orbit. It is interesting to note that SBSS and Sapphire have approximately the same cost per observation. Sapphire was much less expensive to acquire, but due to its operational concept of body pointing, it is less productive. SBSS has an articulated telescope allowing for much more rapid target acquisition, but at a much higher acquisition price.

Given the choice between a single SBSS and ten Sapphire-type satellites, the Sapphire approach would win based on resiliency, survivability, and sustainability.

Recommendation for a Future SSA Architecture

The data in table 6 present a rather clear picture of what is required for a future SSA architecture. A global network of ground-based telescopes is required to search broad areas of the sky for dim RSOs. Space-based sensors in equatorial LEO are required for their low latency and respectable sensitivity. The big hole that remains is looking close to the sun. Solving this problem will require future sensor and architecture studies. One solution that appears attractive is to have three satellites in orbits that are about 500 km below GEO. They can be used for general SSA observations, but their primary reason for existing is that between the three of them, they can easily observe the small percentage of satellites that are solar excluded for the equatorial LEO sensors. The near-GEO satellites would have solar exclusion problems of their own, but with three on orbit, spaced 120 degrees apart, the satellites that would be solar excluded for them would be different from those in the solar exclusion region for the LEO sensors.

While GEODSS is an excellent SSA system, it eventually needs to be replaced with more modern hardware with greater numbers and geographic diversity. Fortunately, given that GEODSS has experienced frequent updates, it does not need to be replaced soon, but does need to be globally dispersed and be augmented with additional telescopes. The SST is essentially new and is a state-of-the-art telescope but could easily be replaced by systems that are smaller, substantially less expensive with less complex optical designs, all with the same sensitivity[22].

A Future Architecture

Ground-Based Network of Affordable Telescopes

The first recommendation is for a global network of ground-based optical telescopes. After considerable modeling and analyses, we recommend a network of 26 telescopes located at 13 sites around the world. Ground-based telescopes are preferred for their high sensitivity and relatively low cost per observation. The proposed network should consist of a 16 telescopes of 1 m aperture located in pairs at 8 sites around the world. Pairs of telescopes are preferred as they provide natural redundancy for one another when one is not operational, and provide greater sky coverage when both are in operation. Telescopes of 1 m aperture will largely duplicate the capabilities of the current GEODSS network but with 8 sites, there will be no gaps in coverage and overall latency will be reduced. Telescopes of this size are useful for most of the routine SSA work.

The proposed network also includes 10 telescopes of 2 m aperture located in pairs at 5 sites around the world. The 2 m telescopes were selected as they can replicate the capabilities of the SST in terms of both sensitivity and search rate, simultaneously. They were designed to be optically more efficient, and when combined with advanced target detection algorithms, they easily equal SST performance, but at a significantly reduced cost resulting from their smaller size and more simple design.

The proposed locations are shown in figure 20. The green square markers represent the eight locations for 1 m telescopes, while the red diamonds are the proposed locations for the 2 m telescopes. Details of each location for the 1 m telescopes are provided in table 7. Details of each location for the 2 m telescopes are provided in table 8.

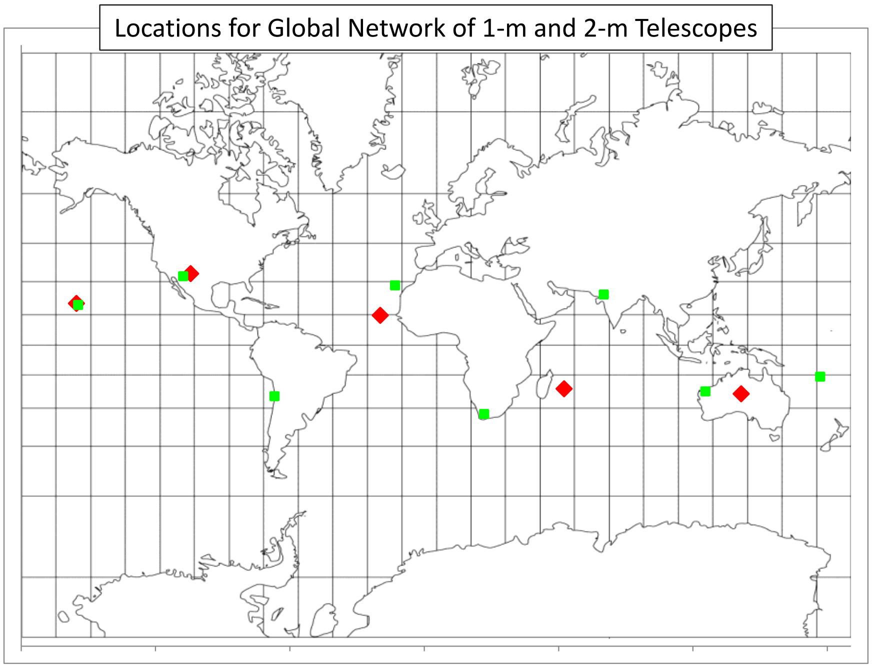

Fig. 20. Proposed locations for network of 1 m and 2 m SSA telescopes.

Table 7. Possible Locations for 1 m Telescopes.

Small SSA Telescope Sites		
Latitude	**Longitude**	**Location**
19.82	-155.47	Mauna Kea, Hawaii
-15.36	166.76	Mount Tabwemasana, Vanuatu
-22.34	116.87	Mount Farquhar, Australia
24.65	72.78	Mount Abu, India
-32.38	20.81	SAAO, South Africa
28.76	-17.89	Isla de la Palma, Canary Islands
-24.59	-70.19	Cerro Paranal, Chile
32.70	-109.89	Mount Graham, Arizona

Table 8. Possible Locations for 2 m Telescopes.

Large SSA Telescope Sites		
Latitude	**Longitude**	**Location**
-23.40	132.39	Mount Zeil Australia
-21.10	55.48	Pinton des Neiges, Reunion Island
14.98	-24.38	Fogo Island, Cape Verde
33.82	-106.66	Socorro, NM, GEODSS Site
20.58	-156.26	Haleakala GEODSS Site, Maui

Note that there are no locations that host both 1 m and 2 m telescopes. The sites were specifically separated to provide geographic diversity with the hopes of, to the greatest extent possible, avoiding similar weather patterns. There are two locations where 1 m sites are close to 2 m sites but are still separated by more than 100 km. For example, in Hawaii, Haleakala hosts a 2 m telescope site while Mauna Kea hosts a 1 m site. These could easily be interchanged. Both locations have high elevation and substantial infrastructure with existing astronomical observatories. In the Southwest United States, there are two sites separated by a few hundred kilometers. The existing GEODSS site was selected to host 2 m telescopes, while Mount Graham in Arizona was selected to host 1 m telescopes.

The proposed locations are not absolute as nearby locations can easily be considered as substitutes. For example, in New Mexico, the development site used for the SST could be used rather than the current GEODSS site. In southern Arizona, there are several mountains with observatories that could substitute for the proposed Mount Graham.

In general, sites were selected for their proximity to the equator, for high-elevations and for existing, or near-by infrastructure. The two sites selected in Australia both require some development, although there are existing sites with good infrastructure on both the east and west coast as well as in central Australia that could substitute for the proposed locations.

With the proposed network of 13 sites, expected observation latency will be reduced from that provided by our current network. The calculated latency values for the combined network of 1 m and 2 m telescopes is shown in figure 21. The calculations supporting this figure do not account for weather related interruptions in observing. Typical latency is on the order of 10 hours or less and the maximum latency never exceeds 15 hours.

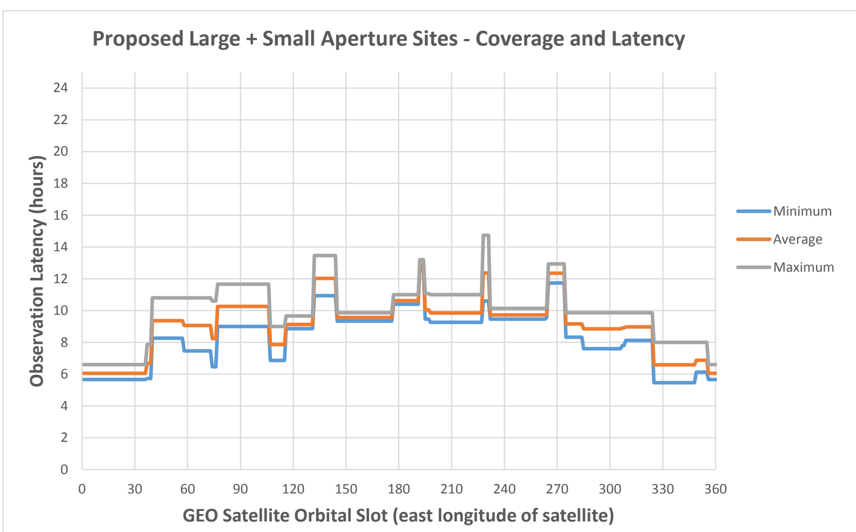

Fig. 21. Latency calculations for combined network of 1 m and 2 m telescopes

Ground-Based Network of 1 m Telescopes

Performance data for the network of 1 m telescopes is presented in table 9. The telescopes are proposed to have the same aperture as GEODSS but with a field of view five degrees in diameter. This will result in a system with sensitivity that equals or slightly exceeds the current GEODSS, but has a much wider field of view for more rapid search and detection.

Table 9. Performance Data for 1 m Telescope Network.

Aperture	1.00	m
Focal Length	1.55	m
Focal Ratio	1.55	
Field of View	5.00	deg
Inherent Sensitivity	18	magnitude
Expected Sensitivity	18	magnitude
Typical Latency	10	hours
Maximum Latency	15	hours
Sky Coverage Efficiency	54	percent

Figure 22 presents the calculated geographic coverage and latency for the 1 m network, given ideal weather conditions. As can be seen in this figure, the network has true global coverage and typical latency values are on the order of 10 hours.

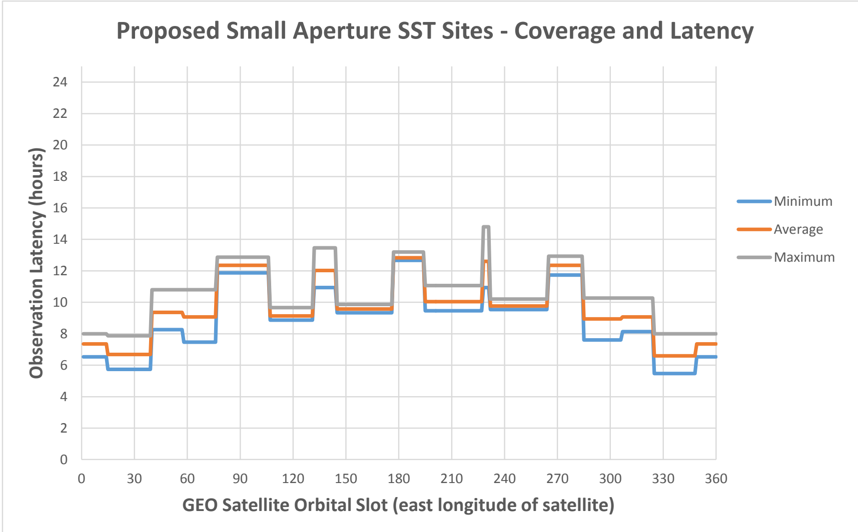

Fig. 22. Latency calculations for 1 m telescope network.

Figure 23 presents the visual magnitude for a 200 cm aluminum sphere target in GEO as viewed from the eight locations for small aperture telescopes. This figure shows some regions where coverage is reduced during certain hours, but in general, this arrangement gives true global coverage of the GEO region. Figure 24 presents the minimum detectable diameter for an aluminum sphere as viewed by this network of telescopes. The calculations clearly show that the proposed network can routinely see targets on the order of 125 cm diameter and smaller.

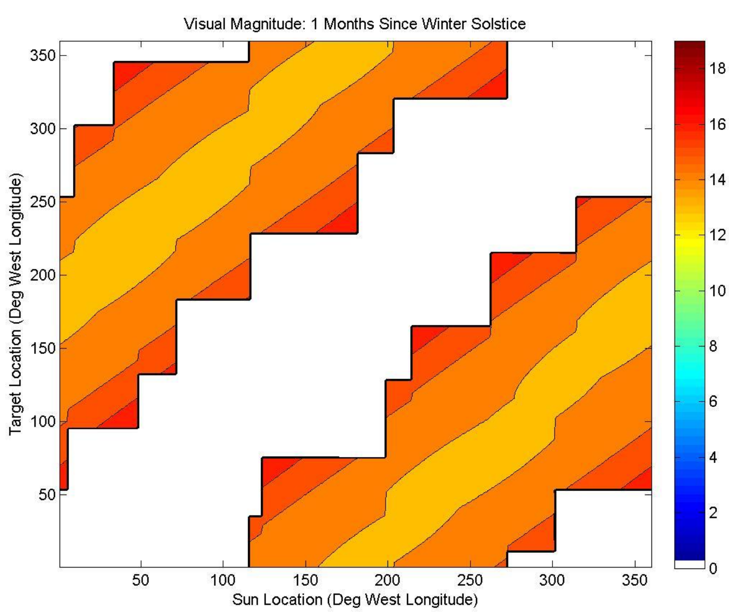

Fig. 23. 200 cm target visual magnitude as viewed from 1 m sites.

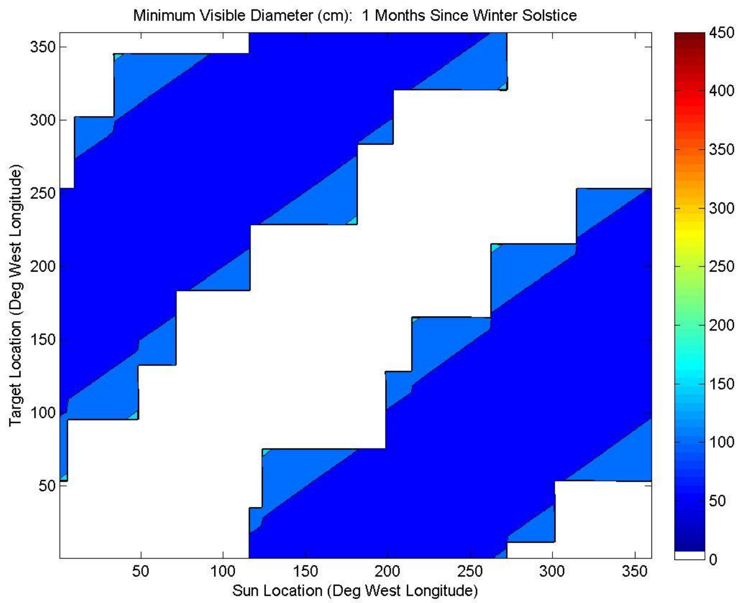

Fig. 24. Minimum detectable diameter target for 1 m network.

Ground-Based Network of 2 m Telescopes

To complement the network of 1 m telescopes, we also propose a network of ten 2 m aperture telescopes located at five sites around the world. For the same reasons as described for the network of 1 m telescopes, we believe two telescopes per site are warranted. These will be the main ground-based observing telescopes with the network of smaller systems used for follow-on observation and during periods of weather outages at the main sites. The performance data for this network is shown in table 10.

Figures 25, 26 and 27 present the latency calculations, visible magnitude calculations, and minimum detectable target size calculations for this network of telescopes. As there are only five sites, the coverage is a bit more sparse than for the supporting network with eight sites, but the proposed five-site network is sufficiently dispersed that it still provides excellent global coverage.

Table 10. Performance Data for 2 m Telescope Network.

Aperture	2.00	m
Focal Length	3.20	m
Focal Ratio	1.50	
Field of View	3.50	deg
Inherent Sensitivity	19.5	magnitude
Expected Sensitivity	19.5	magnitude
Typical Latency	12	hours
Maximum Latency	17	hours
Sky Coverage Efficiency	47	percent

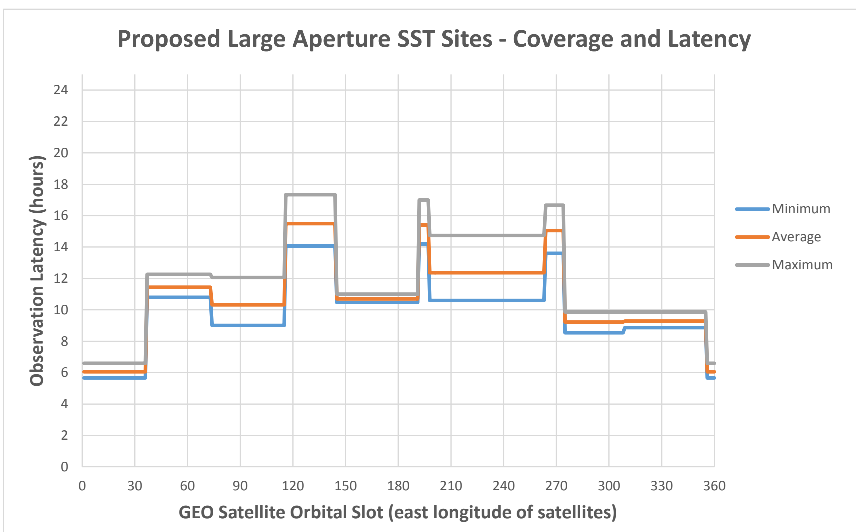

Fig. 25. Latency calculations for 2 m telescope network.

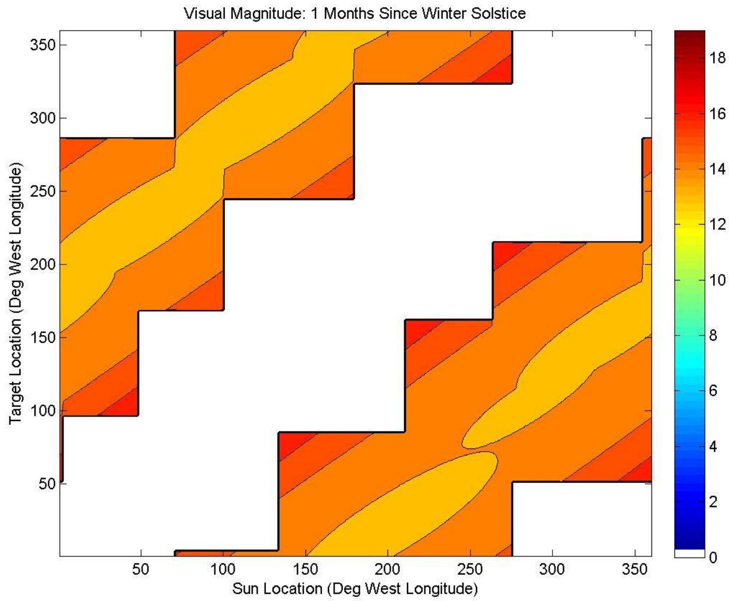

Fig. 26. 200 cm target visual magnitude as viewed from 2 m sites.

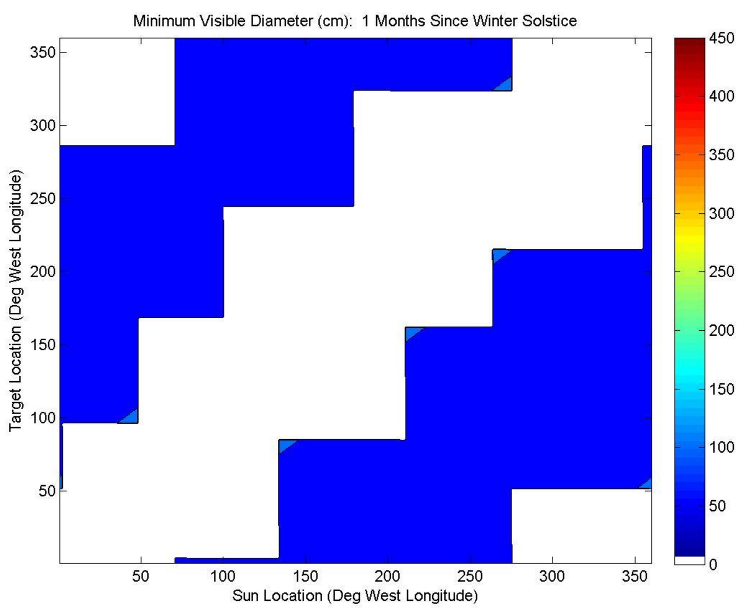

Fig. 27. Minimum detectable diameter target for 2 m network.

Space-Based Network of Equatorial LEO Satellites

To augment the proposed network of ground-based telescopes and reduce observational latencies, we propose an orbiting constellation of two GeOST satellites in equatorial LEO and positioned opposite one another. System parameters similar to those discussed above for GeOST/ORS-5 are deemed sufficient with the addition of a 0.40 m focal length and a focal ratio of 4. For the combined network of two satellites, maximum latency drops slightly to 3.4 hours with a typical latency of about 2.6 hours, entirely due to solar exclusion. The big gain in performance is seen in sky coverage efficiency, improving from a value of 50% for a single satellite to 87% for the two satellite configuration. Constellation performance data are provided in table 11.

Table 11. Performance Data for Two-Satellite GeOST Constellation.

Aperture	0.10	m
Focal Length	0.40	m
Focal Ratio	4.00	
Field of View	>5.00	deg
Inherent Sensitivity	15.4	magnitude
Expected Sensitivity	16.5	magnitude
Typical Latency	2.6	hours
Maximum Latency	3.4	hours
Sky Coverage Efficiency	87	percent

Figure 28 presents the visibility of a 200 cm diameter target for the two satellite GeOST constellation. This plot is for the month of March as we see the effect of satellites being in the earth's shadow. The white spaces at the top and bottom of the plot show regions of solar exclusion. The two satellite constellation does not significantly improve outages due to solar exclusion.

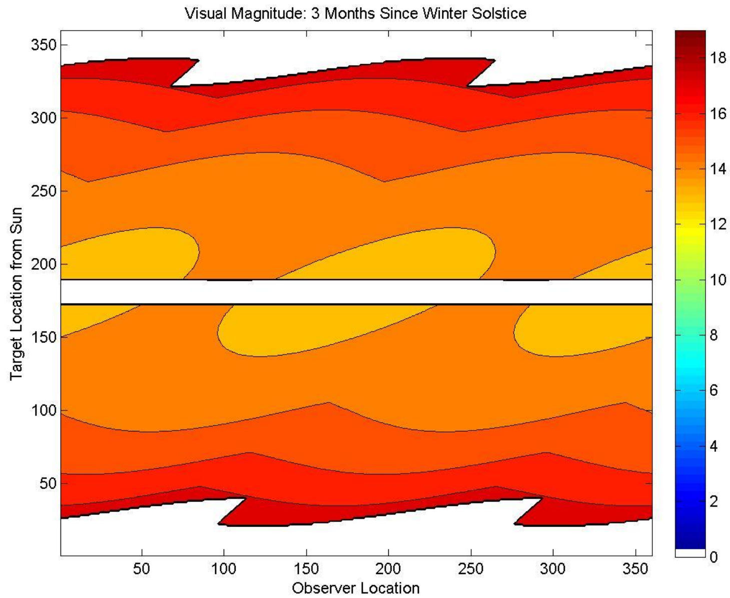

Fig. 28. 200 cm target visual magnitude as viewed from GeOST constellation.

Space-Based Network of Near-GEO Satellites

To combat the problems of the solar exclusion angle with other sensors, we propose a three-satellite constellation of Sapphire-like sensors located in an orbit about 500 km below the GEO belt. The three satellites should be oriented 120 degrees apart in orbit. The sole requirement for these sensors is to observe satellites that are within the solar exclusion region for the GeOST constellation, but these satellites can contribute to the overall SSA collection as well. It is envisioned that GeOST will pick up most of the observation duties as its sensor will have higher inherent and practical sensitivity. The satellites in low-GEO need to be kept simple and inexpensive. Table 12 presents performance data for our low-GEO SSA satellite (LGSSA). The maximum latency value is due entirely to satellites passing through the earth's shadow on the equinoxes. Latency during the rest of the year is negligible. The sky coverage efficiency is 99% with most of the remaining 1% being due to effects of the earth's shadow. Figure 29 shows the visibility of GEO targets from the LGSSA orbit as the expected visual magnitude for our 200 cm aluminum sphere target.

Table 12. Performance Data for Three-Satellite LGSSA Constellation.

Aperture	0.15	m
Focal Length	0.55	m
Focal Ratio	3.63	
Field of View	1.40	deg
Inherent Sensitivity	15.8	magnitude
Expected Sensitivity	15.0	magnitude
Typical Latency	0	hours
Maximum Latency	1.2	hours
Sky Coverage Efficiency	99	percent

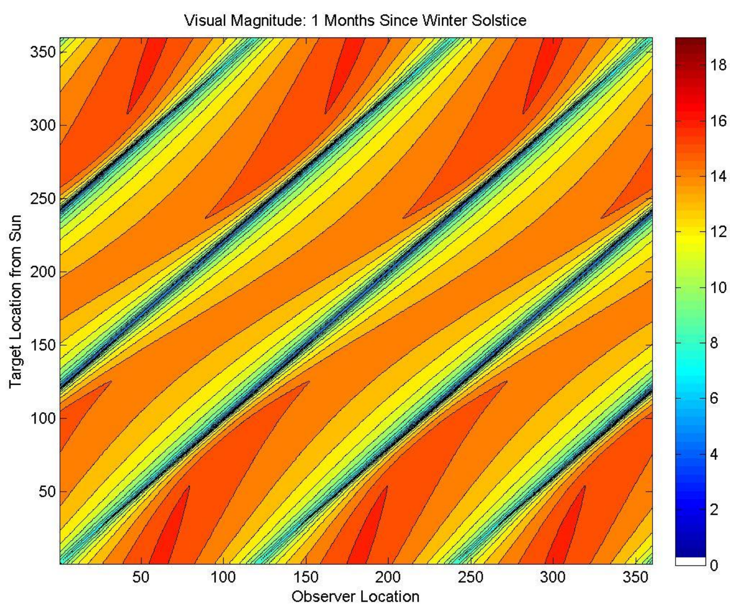

Fig. 29. 200 cm target visual magnitude as viewed from LGSSA constellation.

Figure 29 shows that almost the entire GEO belt is continuously visible from the three-satellite LGSSA constellation. A natural question to ask is why one needs the GeOST constellation when the LGSSA system performs so well. This question has several answers. First, examining figures 18 and 19, we see that sensors near the GEO altitude are not terribly efficient at searching for objects in their local vicinity. Any satellite within 30 degrees of longitude of a sensor is easy to see because it is close, but very difficult to search for as the number of search frames would become difficult for a body-pointed sensor to accommodate. Second, upon examining the data in table 6, we find that two GeOST-like satellites will be capable of more than 31,000 observations each day while three LGSSA satellites would make less than 5,000 observations per day. Simply put, LGSSA as an inexpensive body pointed sensor cannot handle the workload required of it to replace GeOST. Finally, there is the issue of sensitivity. While some satellites will be closer to an LGSSA than GeOST, many satellites will be farther away from an LGSSA and therefore more difficult to see. GeOST is more sensitive than the envisioned LGSSA. While LGSSA could be made larger and more sensitive, GeOST could also be made larger and more sensitive. Simply put, LGSSA is not a search system. It is intended for targeted observations of specific regions that are temporarily not observed by GeOST due to solar exclusion. While LGSSA is not envisioned as a search asset, it might be used for limited imaging of GEO targets, thereby picking up much of the hypothesized GSSAP mission.

Combined Future SSA Architecture

To summarize what has been proposed, we believe a future integrated SSA architecture might consist of the following systems:

a) 16 each, 1 m telescopes located at 8 sites distributed around the globe;
b) 10 each, 2 m telescopes located at 5 sites distributed around the globe;
c) 2 each, GeOST/ORS-5 like satellites in equatorial LEO, located 180 degrees apart; and
d) 3 each, LGSSA satellites located 500 km below GEO, spaced 120 degrees apart.

The cost for such an overall architecture can at best be approximated using available data for similar individual components. These data are presented in table 13. Many estimates are especially conservative to account for cost growth. The approximate initial capital cost is $1.079B with an annual operations and maintenance cost of $64M. It should be noted that this architecture will require several years to assemble so the entire cost is not incurred within a single fiscal year. Also, the data for system capital cost in table 13 do not account for economies of scale. It is highly likely that purchasing 16 identical 1 m telescopes will significantly reduce the cost per unit. Similar economies might be realized for the 2 m telescopes and both satellite systems.

Table 13. Estimated Cost for Future SSA Architecture.

	Per Unit Cost ($M)	Number of Units	Total Cost ($M)	Life Expectancy (years)	Cost per Year ($M)	Observations per unit per Day	Overall System Availability	Observations per unit per Year	Total Observations per Year	Cost per Observation ($)
1 m Telescope	$4	16	$64	40		12,000	0.30	1,314,000	21,024,000	
1 m Site Development	$5	8	$40							
1 m Site Ops & Maint	$3	8	$24							
1 m Telescope Network Amortized Annual Cost					$26.60					$1.27
2 m Telescope	$25	10	$250	40		12,000	0.30	1,314,000	13,140,000	
2 m Site Development	$5	5	$25							
2 m Site Ops & Maint	$3	5	$15							
2 m Telescope Network Amortized Annual Cost					$21.88					$1.66
GeOST Satellite	$100	2	$200	7		15,000	0.85	4,653,750	9,307,500	
GeOST Launch	$50	1	$50							
GeOST Operations	$5	2	$10							
GeOST Constellation Amortized Annual Cost					$45.71					$4.91
LGSSA Satellite	$100	3	$300	10		5,000	0.85	1,551,250	4,653,750	
LGSSA Launch	$150	1	$150							
LGSSA Operations	$5	3	$15							
LGSSA Constellation Amortized Annual Cost					$60.00					$12.89

Ground-based telescopes provide deep coverage at an affordable price and provide some resiliency should a space-based asset fail. The proposed GeOST constellation provides rapid search capability and greatly reduces latency of the ground-based observations for most objects. Satellites making up the LGSSA constellation provide coverage of GEO targets that would be within the solar exclusion region for the GeOST constellation and also can perform a secondary duty of characterizing GEO satellites as they drift by. The proposed integrated solution should provide affordable observations that reduce typical latency values to near zero and maximum latency periods to no more than 1.2 hours, occurring only near the spring and fall equinox periods. Further, this architecture should eliminate solar outages while still allowing for very deep surveys of the GEO region to search for debris and small, dim, CubeSat-like objects.

Summary

We have attempted a systematic evaluation of the overall problem of SSA and considered the various systems available to provide observations. The limitations of the current SSA architecture include insufficient global coverage, inadequate sensitivity, significant latency for ground-based observations, and expensive space-based assets with reduced, but still significant latency as compared to ground-based assets. The SST will improve sensitivity and fill a gap in current GEODSS coverage but it is too expensive and complex to be replicated as part of a world-wide network. Space-based systems such as SBSS provide significant capability but are themselves quite expensive and only reduce deficiencies with the ground-based network, they do not eliminate the issues. The GeOST/ORS-5 satellite currently in development appears to be a game changer. It promises to significantly reduce the cost of space-based SSA, but still has limitations that neither it nor the supporting ground-based observatories can solve.

For the future, we have proposed a new integrated architecture that takes advantage of the best parts of the current systems and those under development and augments them with new, larger ground-based telescopes along with a new space-based system located below the GEO belt. The new architecture appears to provide low-cost observations, high sensitivity, and near-zero latency while completely eliminating the problem of solar exclusion regions.

References

[1] The Space Report 2013, Space Foundation, Colorado Springs, CO (2013).

[2] Result calculated from published data: SATELLITES TO BE BUILT & LAUNCHED BY 2022, WORLD MARKET SURVEY, Forecasts to 2022, 2013 Brochure, Euroconsult (2013).

[3] SATELLITES TO BE BUILT & LAUNCHED BY 2022, WORLD MARKET SURVEY, Forecasts to 2022, 2013 Brochure, Euroconsult (2013).

[4] https://directory.eoportal.org/web/eoportal/satellite-missions/s/sbss, accessed February 2015.

[5] T.S. Kelso, Analysis of the Iridium 33-Cosmos 2251 Collision, AMOS Technical Conference (2009).

[6] A.J. Tellis, China's Counterspace Programs-Only More Bad News, Testimony to the House Armed Services Subcommittee, 28 January 2014, http://carnegieendowment.org/files/Ashley_J_Tellis_HASC_Counterspace_Testimony_Jan_28_2014.pdf, accessed March 2015.

[7] T.S. Kelso, Analysis of the Iridium 33-Cosmos 2251 Collision, AMOS Technical Conference (2009).

[8] J.R. Shell, Commercially-Hosted Payloads for Debris Monitoring and Mission Assurance in GEO, AMOS Technical Conference (2011).

[9] W.C. Jeas, Military Electronics/Countermeasures, November 1981.

[10] Space Surveillance Telescope (SST) Data Sheet, Version 1.0, DARPA, September 2011.

[11] Space-Based Space Surveillance (SBSS) Fact Sheet, http://www.afspc.af.mil/library/factsheets/factsheet.asp?id=20523, accessed February 2015.

[12] G.H. Stokes, The Space-Based Visible Program, Lincoln Laboratory Journal, Vol. 11, no. 2, pp. 205-238 (1998).

[13] Kepler: NASA's First Mission Capable of Finding Earth-Size Planets, NASA Press Kit, February 2009.

[14] A. Scott, On-Orbit Results for Canada's Sapphire Optical Payload, AMOS Technical Conference (2013).

[15] New Mission Selected for Operationally Responsive Space Office, Los Angeles Air Force Base Press Release, July 30, 2014. http://www.losangeles.af.mil/news/story.asp?id=123419604, accessed March 2015.

[16] A.A. Grometstein (editor), MIT Lincoln Laboratory, Technology in Support of National Security, MIT Lincoln Laboratory (2011).

[17] I. Robinson, SATELLITE SYSTEM PROVIDING OPTIMAL SPACE SITUATIONAL AWARENESS, US Patent 8,511,614 (2013).

[18] A.K. Stimac, GeOST & SensorSat Concepts, MIT Lincoln Laboratory (2013).

[19] I.E. Molotov, Pulkovo cooperation of optical observers-the first two years of the project PulKon, International Scientific Conference "Earth Observation space objects," Zvenigorod (2007).

[20] GEOSYNCHRONOUS SPACE SITUATIONAL AWARENESS PROGRAM (GSSAP) Fact Sheet, http://www.afspc.af.mil/library/factsheets/factsheet.asp?id=21389, accessed March 2015.

[21] K. Williams, 1st Space Ops Assumes Space Surveillance Mission, AeroTechNews, 11 June 2014, http://www.aerotechnews.com/news/2014/06/11/1st-space-ops-assumes-space-surveillance-mission/, accessed January 2015.

[22] M.R. Ackermann, Alternatives for Ground-Based, Large-Aperture Optical Space Surveillance Systems, AMOS Technical Conference (2013).