GLOBAL SPACE SITUATIONAL AWARENESS SENSORS

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1. ABSTRACT

Space situational awareness (SSA) is an essential and integral piece of space operations. Although the U.S. military's Space Surveillance Network (SSN) is currently the single best source of SSA in the world, it does not provide the level of SSA currently needed to support space operations. The lack of geographical sensor distribution and coverage outside of the continental U.S., particularly in the Southern Hemisphere, is a significant limitation of the SSN. There exist a large number of individual sensors across the globe and smaller sensor networks which already provide some level of SSA data to various users, and could also provide data to support the U.S. need for SSA. These sensors are being developed for a variety of missions, including space surveillance, missile warning, missile defense and testing, and scientific applications.

This paper summarizes the work currently underway as a joint project by the Secure World Foundation and the Center for International and Security Studies at Maryland (CISSM), University of Maryland, to document these global sensors including networks from Europe, Russia, and China. This information will be collated in a publicly-accessible database which will serve as the foundation for future analyses to assess the utility of these sensors as complements to the existing plans by the U.S. military to acquire new sensors to enhance SSA. It is also part of a broader project which includes development of an open source software suite for SSA analysis.

2. THE RATIONALE AND SCOPE FOR THIS PROJECT

The launch of Sputnik in 1957 created the need for space surveillance, the ability to track human-created objects in Earth orbit, calculate their orbital position and velocity, and be able to predict their location in the future (known as metric data). During the Cold War, the advent of intercontinental ballistic missiles (ICBMs), which could deliver their nuclear payloads on ballistic arcs through space, and their deployment in massive numbers prompted both the United States and Soviet Union to develop networks of phased array warning radars. The development of space-based capabilities using deep space orbits, primarily for intelligence gathering and communications, added incentives for the deployment of optical telescopes to augment the space track capabilities of the phased arrays. More exotic and specialized sensors were added to the inventory to collect technical intelligence on missile testing.

This initial collection of space surveillance sensors was largely under military control, and many of them had a primary mission other than tracking satellites. However, over time space surveillance gradually became their primary day-to-day activity. Using this data, both the U.S. and U.S.S.R developed catalogs of human-created objects in Earth orbit, primarily for intelligence and battle planning. In recent years, the term space surveillance has been subsumed by the broader term space situational awareness, which adds additional types of information to metric data with the goal of characterizing objects in space and the space environment.

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Today, the world has changed significantly. Instead of two superpowers conducting and controlling much of the activity in space, an increasing number of nations are using space for civil, commercial, and military benefits. Ten nations have developed the capability to place objects into Earth orbit. More than seventy nations and international organizations currently operate satellites [1]. The number of human-created objects in Earth orbit has gone from zero in 1956 to more than 21,000 larger than 10 centimeters in diameter currently being tracked. Several hundred thousand additional pieces between 1 and 10 centimeters are largely untracked [2]. Approximately 1,000 of these objects are functioning satellites, which represent hundreds of billions of dollars in investment and revenue [3].

Space Situational Awareness (SSA) capabilities have not kept pace with these changes. The national SSA capabilities operated by the U.S. and Russia still have by far the most capability, but they are struggling to meet today's demands. The huge leaps in computer hardware performance, drops in cost, and modern software techniques are largely unutilized. More importantly, both the U.S. and Russian systems are still controlled by their respective militaries and rely largely on the premise that national security is their only customer.

The vast majority of satellite owner-operators conduct their activities in orbit without knowledge of the objects around them or the space environment. Although space is by definition vast, certain regions of Earth orbit provide unique utility, and those regions are becoming increasingly congested. This combination of congestion and lack of information can lead to incidents in space, such as the February 2009 collision between the American Iridium 33 and Russian COSMOS 2251 [4]. The thousands of pieces of debris created by this event increased the risk of collision for other satellites in the same region. A similar catastrophic collision in geostationary Earth orbit (GEO) that generates a large amount of debris is one of the worst-case scenarios for the long-term sustainability of Earth orbit.

This paper outlines a project initiated and funded by Secure World Foundation to develop a publicly-accessible database of global SSA sensors based on open source information. This paper discusses the efforts to date and outlines futures plans for the project. In addition to fostering awareness of non-traditional SSA capabilities, the goal of the project is to establish a crowd-sourced data set which can be used for future analysis of combinations of various sensor and architectures for shared or collaborative SSA.

This paper is part of set of papers which have the overall goals of fostering SSA capabilities to support civil and commercial spaceflight safety and promote the long-term sustainability of the space environment. The authors believe that providing all space actors basic SSA data and analytical tools is essential to accomplishing these goals. The authors' approach to developing these analytical tools is summarized in two other papers, “Computer Systems and Algorithms for Space Situational Awareness: History and Future Development” [5], and “Open Source Software Suite for Space Situational Awareness and Space Object Catalog Work” [6].

3. SSA TO SUPPORT CIVIL AND COMMERCIAL SAFETY

SSA can broadly be defined as characterizing the space environment and its effects on activities in space. This paper and project specifically focuses on SSA to enhance the safety of civil and commercial activities in space. The primary consideration is ensuring that all space actors have the basic SSA information and analytical tools necessary to operate in a safe and efficient manner, including avoiding catastrophic collisions with other space objects.

Under this definition and within these requirements, SSA for civil and commercial safety requires fusing at least three data sets: positional data on space debris, positional data on active satellites, and space weather. Building a catalog of accurate positional data for space debris requires a network of radar, optical, and other sensors that are geographically distributed around the Earth and in orbit. Observations from these sensors need to be combined using a mathematical process which incorporates accurate models for perturbations. A continuous feedback loop of observation, data association, propagation, tasking, and observing is required to maintain an accurate catalog. This process in general is called catalog maintenance [7].

Active satellites can also be tracked using the same sensors and procedures. However, in most cases a satellite owner-operator is able to determine the location of their own satellite much more precisely than anyone else. Satellite owner-operators can use a variety of techniques, including satellite laser ranging (SLR) to on-board global positioning system (GPS) receivers that report the satellite's position and velocity vectors via telemetry. Active satellites also present an additional complication in that they maneuver, and doing so disrupts the catalog maintenance process. Using a periodic track-and-revisit approach could result in a satellite which has maneuvered being untracked for a period of time, particularly if it is conducting a series of significant maneuvers such as transitioning from a GEO transfer orbit to its final slot in the operational GEO belt. Thus, positional data from satellite owner-operators is complementary to that collected by sensor networks.

Although it is feasible for one state to build the network of sensors required to accomplish this SSA task, the economic cost of doing so is prohibitive. Such a network would also be constrained to geographic locations owned by that state or by states that are amenable to entering into basing or other agreements. It is likely that the political issues stemming from these basing requirements would result in a set of suboptimal choices for sensor locations. Operations at geographically remote sites require complicated logistics, imposing additional costs and complexities.

Characterizing space weather, and in particular its effects on satellites, is a relatively new and still emerging field. Space weather can have a variety of effects on satellites and the space environment from subtle to catastrophic. The interplay between the Earth's magnetosphere and particle and field emissions from the Sun are the source of much of these effects. Periodic variations in the Sun's output causes changes in the density of the Earth's upper atmosphere, which in turn changes the amount of drag the upper atmosphere imparts on satellites in low Earth orbit (LEO). Coronal mass ejections (CMEs) and Solar flares release massive amounts of charged particles and electromagnetic (EM) energy that can damage or disrupt spacecraft operations.

Successful monitoring and prediction of space weather requires instruments to be placed where they can monitor the Sun. The L1 Lagrangian point between the Earth and the Sun is a prime location for this, as satellites in this location can continuously observe the Sun without being occluded by the Earth or the Moon. NASA's Solar Heliospheric Observatory (SOHO) and Advanced Composition Explorer (ACE) satellites are already at the Earth-Sun L1 point monitoring space weather, and there are plans for other nations to send additional spacecraft.

Taken in aggregate, the preceding requirements of a geographically distributed sensor network, owner-operator data, and space weather monitoring necessary for effective SSA lead strongly to the conclusion that international cooperation and data sharing among all space actors is beneficial, if not required. Combining or sharing data from existing sensors could alleviate the need to build new ones. Two-way data sharing between governments that operate sensors and satellite owner-operators provides both parties with a much more complete data set. And international cooperation on space weather detection and prediction can make more efficient use of limited budgets and long spacecraft design times.

4. GLOBAL RADAR SSA SENSORS

Radars form the backbone of an SSA system. Radar consists of at least one transmitter and receiver; the transmitter emits radio waves at a specific frequency. Some of these waves reflect off the target and are measured by the receiver, which is then able to calculate location of the target in relation to the radar. The primary advantages of radars are that they can actively measure the range and range rate to a target, and that some types of radars can accurately track many objects at once. The main disadvantages of radars are their cost, in initial construction and operations and maintenance, size, and complexity.

At the beginning of the space era, two radar concepts were available for space object tracking. The first is an interferometer-based system, also known as a bi-static or multi-static system, where the receiver and transmitter(s) were separated by a specific distance. Bistatic radar systems are especially well suited to so-called "fence" applications, where a continuous amount of energy is emitted in a certain direction. All objects passing through this "radar fence" will thus be tracked. The bistatic concept is illustrated in Fig. 1.

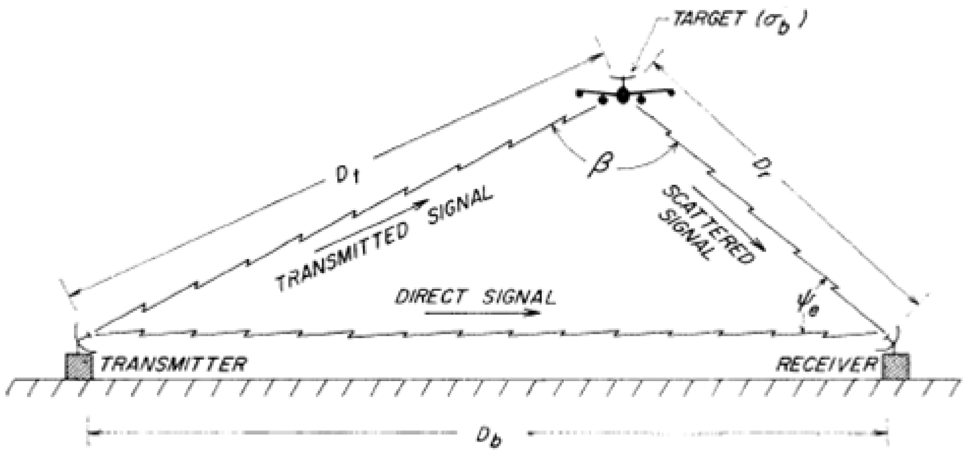

Fig. 1: Bistatic Radar [8]

The second initial radar concept was a monostatic radar which had collocated transmitting and receiving antennas, usually mounted on a parabolic dish that could be rotated and elevated. Monostatic radars mounted in this fashion are also known as mechanical trackers and are especially well suited to precision tracking of one or a few objects. With enough power, monostatic radars can also be used to track space objects in the GEO belt at more than 36,000 kilometers away. In regions with inclement weather, mechanical tracking radars are usually mounted inside domes which are made of a material that is transparent to EM radiation at their operating frequency. Fig. 2 demonstrates the monostatic radar concept.

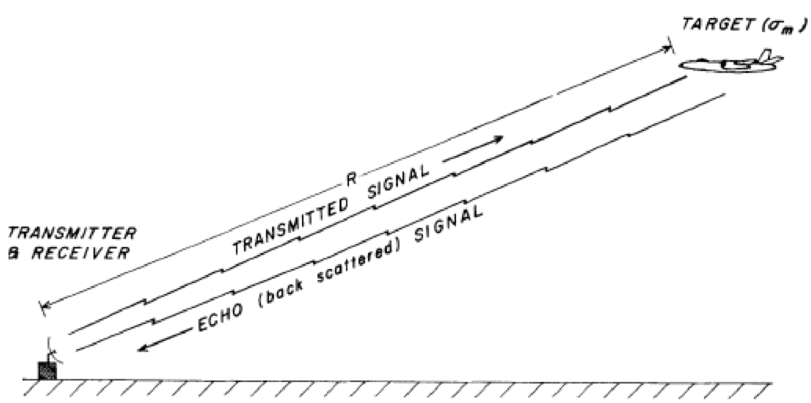

Fig. 2: Monostatic radar [8]

During the space era, two additional radar paradigms have evolved: monostatic and bi-static radars employing phased array antennas. A phased array is a collection of small, identical antennas, usually mounted on a fixed "face", which can vary the phases of their respective signals. By doing so, the effective radiated energy can be "steered" or focused in a specific direction, and in many cases multiple independent "beams" of energy can be individually steered to multiple targets at once. Phased arrays tend to have more complicated supporting systems than mechanical radars [9]. Fig. 3 shows an example of a monostatic phased array with two separate faces operated by the U.S. military.

Fig. 3: PAVE PAWS phased array at Clear AFS, Alaska

United States

The United States military operates the most capable set of radars for SSA as part of its Space Surveillance Network (SSN), and it is also the most documented system with many technical details in the open literature. The SSN utilizes phased arrays, dish-type mechanical trackers, and multistatic fences. Most of the phased array radars were originally built for the missile warning mission and thus were built on the periphery of the United States and the Northern Polar Region. Although some of the original sites have been shut down, several still remain active and today perform both space surveillance and missile warning missions.

These radars provide excellent overall coverage in LEO and good coverage in GEO, and allow the U.S. to maintain the most accurate and complete catalog of objects in LEO. However, their concentration in the Northern Hemisphere and the lack of any radars sensors in the Southern Hemisphere, Africa, South America, and Asia creates significant gaps in coverage. In particular, objects in highly eccentric, rapidly decaying orbit present a difficult problem. When their perigee is in the Northern Hemisphere, these objects are easily tracked by the radars. However, when perigee rotates south, the SSN must rely on attempts by optical telescopes to track the object at or near apogee. The rapid decay means that the altitude of apogee is changing significantly with every orbit.

The United States operates a host of other radars that are not part of the traditional SSN but could provide SSA data. The Missile Defense Agency operates a number of radars, including the Sea-Based X-Band Radar, which are currently dedicated to missile defense operations and testing but could provide SSA data. The U.S. Navy also operates 56 Arleigh Burke-class destroyers, which are equipped with the AN/SPY-1radar system. Primarily designed for tracking airborne threats, the AN/SPY-1 system is also part of the Aegis Ballistic Missile Defense System and has been used to successfully track space objects [11]. Other potential assets include the USNS *Observation Island*, which carries an AN/SPQ-11 phased array radar and is used for collecting technical intelligence on missile launches.

Russia (Commonwealth of Independent States)

Russia currently operates the second most capable network of SSA radars, after the U.S. As with the U.S., the Russian system is based largely on missile warning systems. Several of the original systems are no longer functional or were dismantled, and the remaining radars are spread out across the former Soviet Union; approximately half are located outside of Russian territory [12]. Russia has a series of bilateral agreements with the host countries to continue to operate these facilities [12].

Russia operates two Daryal-type bistatic phased array radars in Pechora, Russia, and Gabala, Azerbaijan, although the Azerbaijan system's receiver and transmitter are closely related [12]. Each site consists of a receiver and transmitter operating in the VHF range. The Volga-type radar in Baranovichi, Belarus, is another bistatic phased array operating near 3 GHz. The Don-2N radar, known in the West as Pill Box, is a four-face phased array which is part of the ABM system protecting Moscow. Russia also maintains older Dnestr-M/Dnepr radars at Olenegork, Balkhash (Kazakhstan), and Mishelevka. Fig. 4 shows the location and coverage of the Russian early warning radar network.

Fig. 4: Russian early warning radars [12]

Europe

Europe does not currently possess an SSA sensor network, although individual states operate a handful of significant radar installations. The French military owns the Grande Reseau Adapte a la Veille Spatiale (GRAVES) radar, which is a continuous wave bistatic fence. While bistatic radars have not been favored in recent years [10], GRAVES uses a radar concept which joins the bistatic and phased-array concepts in a useful way [13]. The GRAVES concept involves a compromise concept which covering a "volume" rather than the very thin "envelops" distributed according to the optimal observation elevations. Instead, azimuths sweep with a beam which is wide in elevation and relatively narrow in azimuth. The GRAVES concept increases the frequency of observations and improves the responsiveness of the orbit determination process.

Another significant European radar is the German Tracking and Imaging Radar (TIRA) system operated FGAN Research Institute for High Frequency Physics and Radar Techniques. TIRA is a monostatic mechanical tracker that can track objects as small as 2cm at 1,000 kilometers altitude [14]. TIRA can also be used in a bistatic mode with the 100m receiver antenna of the Effelsberg radio telescope, which can increase its sensitivity to 1 cm. TIRA also has the capability to image objects in LEO using a higher frequency of 16.7 GHz imaging radar, with a resolution of 15 cm [14].

Norway also maintains the GLOBUS II tracking radar in cooperation with the U.S. government. GLOBUS II is a deep space mechanical tracking radar that can both track and image objects in the GEO belt. Norway is also home for part of the European Incoherent Scatter (EISCAT) radar system which is used primarily for scientific research on the interaction between the Sun and the Earth through disturbances in the magnetosphere [15]. EISCAT radars used for space debris research consist of UHF and VHF mechanical trackers located in Tromsø, Norway and two more mechanical trackers in Longyearbyen, Svalbard. The EISCAT radars are typically used for beam park experiments, which track all the objects passing through a particular region of orbit over a fixed time period [16].

People's Republic of China (PRC)

It is assumed by many observers that China possesses radars that are used for SSA, although this is not officially acknowledged by the PRC and little information is available publicly. The same physics and strategic, political, and geographic considerations that govern the location of U.S., Russian, and European SSA sensors will govern the location of Chinese SSA sensors and the technology used. China is believed to have a network of phased array radars, each likely to have 3,000 km range and 120 degree of azimuth coverage. Some of the possible locations and capabilities for Chinese phased array radars are discussed in Ref. **Error! Reference source not found.** and Ref. 17

and summarized in Table 1. Additionally, there is evidence that China has a long-range precision mechanical tracking radar [19].

Table 1: Postulated Chinese phased array radar network for LEO space object tracking

Location	***Coordinates***	***Maximum Range***	***Sector in Azimuth***
NW China	87.5 E, 43.0 N	3000 km	-60 to + 60 deg
Kashi	76.02 E, 39.54 N	3000 km	180 to 359 deg
Kunming	102.74 E, 24.99 N	3000 km	200 to 320 deg
Hainan	109.4 E, 19.0 N	3000 km	120 to 240 deg
Jiangxi	114.93 E, 26.8 N	3000 km	60 to 180 deg
Changchun	125.69 E, 44.0 N	3000 km	0 to 120 deg
Xuanhua,Hebei Prov.	115.04 E, 40.61 N	3000 km	-60 to +60 deg
Henan, Province	112.97 E, 34.76 N	2500 km	30 to 150 deg

China does not possess radars outside of its borders and thus lacks radar coverage outside of eastern Asia. However, China also operates two Yuanwang tracking ships which can be deployed to broaden its coverage [20]. These ships are primarily used to support China's human spaceflight activities, and could be deployed to provide SSA for other activities.

5. GLOBAL OPTICAL SSA SENSORS

Optical telescopes form the second major type of sensor used to track space objects. They operate in the same fashion as telescopes used for astronomy applications: electromagnetic radiation emitted by an object is gathered and focused to form an image. Refracting telescopes use lenses, while reflecting telescopes use mirrors. Catadioptric telescopes used a combination of mirrors and lenses. Although telescopes can be designed for many different parts of the EM spectrum, the visible portion is most often used for SSA. Fig. 5 shows the European Space Agency's (ESA) Space Debris Telescope, located on the island of Tenerife, Spain.

Fig. 5: ESA Space Debris Telescope, Tenerife, Spain [14]

The capabilities of optical telescopes are usually measured by the size of their aperture and field of view (FOV). The size of the aperture determines the amount of light that is collected and the depth of field over which the telescope can focus. The FOV determines how much area can be seen by the telescope any given moment. Traditionally, there is an engineering tradeoff between the ability for a telescope to quickly search a wide area and the ability to detect very faint objects.

An increasing number of optical telescopes are being developed with adaptive optics (AO) for SSA applications. AO systems work by measuring distortions in a wavefront and compensating for them in the light detection system. In SSA applications, this typically involves using a laser to create a temporary guide star near the object being imaged. The laser's distortion due to the Earth's atmosphere is measured and used to correct the image of the target object.

The main advantage of optical telescopes for SSA is their range. Above 5,000 km altitude, it becomes very time consuming and difficult for radars to search for objects. Optical telescopes can perform this function much faster and easier. The main disadvantage of optical telescopes is that they can only operate under certain conditions. Those that rely on the Sun to illuminate their targets can only work when the target is illuminated and the telescope is in darkness. Clouds and light pollution from cities and human activities are also an issue. The best locations for telescopes are where the air is thin, dry, and free from contaminants, and these locations are usually only found at high elevations or in remote desert areas.

United States

The U.S. SSN has fewer optical telescopes than radars, but the telescopes have better geographical distribution. The main U.S. optical system is the Ground Based Electro-Optical Deep Space Surveillance (GEODSS) system. It consists of three separate sensors sites: Socorro, New Mexico, Maui, Hawaii, and Diego Garcia in the Indian Ocean. Each site operates a cluster of three telescopes, each of which can be operated independently from the others. An additional mobile site with one telescope is located at Morón, Spain. Several other optical instruments located on Maui are also used, for both tracking and imaging of space objects. Together, the GEODSS system provides global coverage of the GEO belt, although weather can cause gaps in the coverage.

Russia (Commonwealth of Independent States)

The Russian military operates a significant optical tracking facility in northern Tajikistan. Known as Okno or "window", the facility includes a number of optical telescopes that can track objects in all orbital regimes, including LEO. The Okno facility provides the Russian military with coverage of the GEO belt over Russia only.

Fig. 6: Russian Okno facility[21]

The Russian Academy of Sciences manages a network of optical telescopes around the world known as the International Scientific Optical Network (ISON) which does provide global coverage of the GEO belt. ISON is a partnership of between many academic and scientific institutions, currently including 30 telescopes in 20 observatories in 10 countries [22]. Most of these facilities are located in Europe and Asia, with one being located in South America and off the coast of Africa. ISON is a heterogeneous mix of telescopes of various sizes and capabilities, but as a network it can track a wide range of object sizes throughout deep space and provide a significant number of observations.

People's Republic of China (PRC)
More information is known about China's optical telescope capabilities for SSA that radars, in part because of China's participation in the Inter-Agency Debris Coordination Committee (IADC). China's main optical SSA capabilities are operated by the Purple Mountain Observatory, which operates multiple telescopes in four separate locations that can track satellites throughout all orbital regimes. However, like Russia, China lacks coverage outside of its borders and thus does not have global coverage of the GEO belt.

Space-Based
Space-based optical telescopes provide a number of advantages over ground-based, primarily the absence of weather and an atmosphere, and are increasingly being seen as an important part of an SSA system. The U.S. military launched the Midcourse Space Experiment (MSX) satellite in 1996 which became the first dedicated space-based optical telescope for SSA. Until its end-of-life in 2006, MSX used its optical sensors to contribute to the SSN, primarily by finding lost objects in the GEO belt. MSX is due to be replaced by a more advanced constellation of dedicated SSA sensors known as the Space-Based Space Surveillance System (SBSS).

Canada is also planning on launching space-based optical satellites to support SSA. It's Near Earth Object Surveillance Satellite (NEOSSat) will have the mission to detect and track both asteroids in orbit around the Sun and objects in high altitude orbits around the Earth. NEOSSat will be followed by Sapphire, an autonomous, dedicated satellite for SSA that will contribute to the U.S. SSN [23].

6. CONCLUSIONS

The initial research done for this project indicates that the world does not suffer from a lack of SSA sensors. Rather, there is a global deficit in knowledge about the sensors that are currently available and their capabilities for SSA, and more importantly a lack of capability to share or combine data between sensors and networks. Such sharing or collaboration is not a trivial matter – there are significant technical obstacles to overcome in dealing with data formats, tasking, calibration, authentication, and data validity. Significant policy obstacles also surround data sharing policy and ensuring security and privacy concerns are met.

However, none of these obstacles are insurmountable, and the value of improving SSA globally for all space actors likely outweighs the political and economic cost of overcoming these issues. Enhancing global SSA capabilities through collaboration and sharing will improve the long-term sustainability of the space environment by providing all space actors with the information necessary to act safety, efficiently, and responsibly. Global SSA can also act as a transparency and confidence building measure (TCBM) to reduce mistrust and misperceptions in space, thereby reducing the risk of conflict and degradation of the space environment.

7. FUTURE WORK

The future work on this project can be divided up into three phases. The first is to compile a database of global SSA sensors using existing sources and information. The primary information in this database will be name, location, type, and capabilities. Phase two will create an Internet-accessible version of that database. Once online, the information will be publicly accessible. Members of the global SSA community will be able to add or correct information, and it is hoped that states will use the database to showcase the SSA resources they can offer. Consideration is being given for the creation of a Google Earth layer from this database. This will allow linking of actual satellite imagery of locations with the sensor characteristics and visualizations of sensor coverage within Google Earth. This database will then be available for anyone to access and retrieve information. Phase three will include analysis based on this data set of global SSA capabilities, and in particular the advantages and disadvantages of various sensor combinations. Consideration is also being given to offering of a prize to the best analysis.

Additional research is needed in a number of areas, including quantifying the types of data and accuracy needed to support civil SSA, as separate from the requirements for military SSA, and in quantifying the operational capabilities of global SSA sensors.

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