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ANALYSIS OF THE TECHNICAL FEASIBILITY OF BUILDING AN INTERNATIONAL CIVIL SPACE SITUATIONAL AWARENESS SYSTEM

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ABSTRACT

There is a demonstrated need to provide the multitude of space actors a certain level of information about all the objects in orbit and the space environment to operate in a safe and sustainable manner. The collection of this information, called space situational awareness (SSA), is currently almost entirely the domain of a few national militaries and much of the data is kept from broad public dissemination. One approach to solving this problem would be to create an International Civil SSA (ICSSA) system where data from multiple actors, States, and commercial providers is voluntarily shared. Technical hurdles such as different propagators, data formats, sensor calibration and tasking, and data security pose significant challenges but are solvable. Mitigation strategies, such as deciding whether to base the ICSSA system on sharing of sensor observations or element sets, can be effective in surmounting these hurdles. Tradeoffs between technical capability and political viability can also play a significant role in the over system feasibility.

I. PROBLEM STATEMENT

The past decade has seen an extraordinary growth in the number of man-made objects in Earth orbit and the number of actors placing and operating satellites in Earth orbit. The first-ever collision between two satellites in February 2009 highlighted the existing gaps in data needed by all space actors to operate their satellites in a safe and secure manner [1]. In a non-military application, this data, known as space situational awareness (SSA), consists of positional data on objects in Earth orbit and information on space weather. Currently, many States have space surveillance sensors capable of tracking objects in Earth orbit. Some private or university actors also maintain a tracking capability. Out of these, only a handful have networks of several sensors, and only one—the United States—has close to global coverage. The two main limitations are the economic cost of building and maintaining the sensors and finding politically viable locations that could host the sensors. Some States also have existing capabilities to monitor, predict, and warn about space weather events that could damage or destroy satellites, but few actively share this data. In addition to the data, analytical tools and trained personnel are required to enable sound decision-making.

The concept of an international civil space situational awareness network has been proposed as a possible solution to this issue. The network would consist of a voluntary sharing of data from SSA sensors by participating States and private actors towards a central data clearing house. This data would then be shared with all participants, enabling each to perform their own analysis and decision-making. For those actors without indigenous analytical capabilities, the data clearing house would also offer analytical services. This paper analyzes the technical issues involved with pooling data from international participants, including centralized tasking, sensor calibration, data security, data format standards, and analytical tools. Finally, this paper highlights areas where further technical research and analysis are needed.

II. SPACE SITUATIONAL AWARENESS

A. Historical Context

Since the start of the Space Age in the 1950s, space situational awareness has been performed almost entirely by the militaries of space-faring nations. The United States and Russia both built large networks of ground-based tracking facilities that could collect data on objects in Earth orbit. Consisting primarily of large tracking radars and optical telescopes, these facilities were often dual-purposed with other military missions, such as ballistic missile warning and tracking during the Cold War [2].

As an object in orbit passes over these tracking sites, data is collected on the object's precise position at each moment in time. This metric data, called observations, is commonly passed to a central analysis center where it is combined with observations from all the other tracking sites which collected data on the same object, although in some cases each sensor can operate independently.

Multiple tracks of observations on each object are combined through a process called track association. Orbit determination is then applied to these tracks to produce an element set, which can be used for predicting where an object is in orbit at a given time [3]. These elements sets, along with tasking instructions for the next time period, are passed back to the tracking sites to collect further information. An iterative process is established to continually track and update the element sets for all objects in Earth orbit. These element sets are then stored in a satellite catalog which is continuously updated and corrected through a process known as catalog maintenance.

This collection and maintenance of metric (i.e., positional) data on objects in orbit is known as space surveillance. In recent years, this metric data has been combined with other types of data and re-named space situational awareness, due to its ability to describe more than just locations. By adding information on space weather, planned spacecraft maneuvers, and imagery of satellites, it is possible to characterize space objects and in some cases determine intent of space actors. Known as space object identification (SOI), this is of significant value to military SSA but of limited value for civil uses.

B. Current Capabilities and Gaps

The United States military currently operates the largest satellite tracking network and maintains the most complete catalog of objects in Earth orbit in the world. It maintains a globally distributed network of more than twenty tracking sites across a significant portion of the globe. These tracking sites feed data to the Joint Space Operations Center (JSpOC) located at Vandenberg Air Force Base in California. The JSpOC maintains two satellite catalogs, one in which the element sets are kept in a Two-Line Element (TLE) format and another in which they are stored as state vectors with corresponding covariance matrices.

The main drawback of the US military's SSA capabilities lie in the location and distribution of the tracking sites. Many of their tracking radar locations are optimized for their original missile warning functions and not space surveillance. This means the system has excellent coverage in the Northern Hemisphere. However, as of 2009 there are no US military tracking sites located in South America, Africa, Asia, Australia, or Antarctica. As satellites in every orbit, aside from geostationary, are continually moving over the Earth's surface, this presents large gaps in the tracking coverage and poor temporal resolution between tracks.

A second drawback is the age of the tracking sensors and the systems use to analyze the data. Many of the tracking sensors date back to the 1950s and use outdated technology such as vacuum tubes and lack modern computer controls. These create limitations in both the quantity of data that can be collected and the size of the object that can be tracked. Likewise, much of the computer hardware and software located in the JSpOC which is used to maintain the satellite catalog is outdated. It contains hard-coded limitations such as the total size of the catalog and atmospheric and gravity modeling. Recent attempts to get around these restrictions have resulted in systems which have been designed and built outside the formal military acquisition channels. While functional, these systems are a temporary stop-gap measure at best.

The third major deficiency in the US military's SSA system is the lack of data from other actors. Entities which own or operate satellites are able to determine the satellite's location with greater precision than is normally possible by third-party tracking. Satellite owner-operators also have data on upcoming maneuvers and orbit changes for their satellites. Very few of these owner-operators share their data with the JSpOC, mostly due to the lack of a trusted relationship between the US military and these potentially international partners. Lacking this pre-maneuver data, the US military is forced to react to maneuvers and task sensors to find and re-acquire satellites, which leads to gaps in coverage and potentially losing track of an object.

Russia maintains the second most capable tracking network and satellite catalog. However, it has many of the same limitations as the United States, with the problem of geographic sensor distribution being even more pronounced. All of the Russian tracking sites are located in Asia or Europe and, as such, Russia has no real ability to track satellites when they are not overhead Russian territory. This leads to degraded accuracy of low-Earth orbit objects and a very limited catalog of objects in geostationary orbit as those stationary over the Western Hemisphere are essentially untrackable.

Several other States have SSA capabilities, but all are limited to one or, at best, a few sensors. This list includes, but is not limited to, France, Germany, the United Kingdom, Japan, China, South Africa, and Canada. In addition, there are significant scientific and academic networks of sensors, such as the International Scientific Optical Network (ISON). Managed out of the Keldysh Institute for Applied Mathematics in Moscow, ISON coordinates over 25 optical instruments around the world for space debris research and tracking.

C. International Civil Space Situational Awareness

There are differences in requirements between traditional military SSA and the proposed international civil SSA systems. Primarily, this is a difference in what types of data are needed to support analytical missions.

The US Air Force defines SSA in its official doctrine as "characterizing, as completely as possible, the space capabilities operating within the terrestrial and space environments" [4]. It defines the components of SSA as intelligence, surveillance, reconnaissance, environmental monitoring, and command and control [4].

International civil SSA has a subset of these requirements. The primary goal is to provide all space actors with the basic information necessary to operate in a safe and sustainable manner. To accomplish this goal, only the components of surveillance, environmental monitoring, and command and control are needed.

An international civil SSA system has the potential to fill in the gaps in the existing military SSA systems. The primary gap previously identified, geographic distribution of sensors, is perhaps the easiest to fill. An international data sharing system can utilize the many existing sensors located around the world that are used for scientific research and not part of existing SSA networks, in addition to those existing networks. Since so many of these sensors already exist, the economic costs of such a system are greatly reduced.

One potential model for an international civil SSA system is one where States, commercial companies, and other entities choose to participate. In return for voluntary contributions of data to a central database, participants get access to all the contributed data. This allows for each participant to perform their own analysis and create their own data products. A centralized analysis center would also provide analysis and support to those participants who lack indigenous capabilities.

III. TECHNICAL HURDLES TO ICSSA

A. Astrodynamic Techniques and Propagators

At the core of SSA is the process described earlier where multiple sensor observations are combined into tracks to produce an element set. This process is critical in that the resulting element set provides data which can be used to propagate the location of the reference object forward or backward in time.

There are three main categories of techniques to accomplish this task: analytic, semi-analytic, and numerical. Each category makes a tradeoff between speed of calculation and precision. Within each category there are multiple mathematical models. Depending on the requirements, different entities may choose to use astrodynamic techniques from one or multiple categories. Additionally, there are differences in the way models calculate orbital perturbations. General Perturbation (GP) models remove the periodic variations within an orbit to produce a so-called “smooth” result. The same model must be used with the element set to add these periodic variations back in. Special Perturbations (SP) provide for higher-order perturbations effects at multiple points along the orbit, allowing for more accurate predictions.

As an example, the US Air Force currently uses an analytic technique called Simplified General Perturbations 4 (SGP4) to produce the low accuracy satellite catalog which is used for most day-to-day operations and parts of which are publicly available on the Internet [5]. They also use a numerical technique to produce a second, high accuracy catalog of SP element sets. Additionally, the US Navy uses a GP analytical model called Position and Partials and functions of Time (PPT) to generate the orbital element sets to legacy Navy users.

Additional complexity in this process derives from the use of various models for the Earth’s gravity and atmospheric density, both of which play significant roles in determining satellite perturbations.

The heterogeneity of astrodynamic models and techniques currently in use presents a significant challenge to any SSA data sharing system, as the participants are likely to use several different models. While it is possible to convert between models, it can result in a lower accuracy product and increased errors. Incomplete or incorrect information about which gravitational or atmospheric model was used can lead to disastrous consequences. If participants use propagators to create ephemerides over a certain time period, those can be easily shared as long as they are mapped to a common coordinate frame. However, these ephemerides constitute a significant amount of data that needs to be transferred.

B. Reference Frames and Data Formats

The element sets created by the various astrodynamic techniques can use different frames of reference. These reference frames can have the center of the Earth at the origin, the center of the satellite, or even a specific point on the Earth. A reference frame such as Earth Centered Inertial (ECI) is useful for determining position in orbit as it does not change as the Earth rotates. A reference frame that does rotate, such as Earth Centered Fixed (ECF), is useful for storing the projected flight path of a launch vehicle so that the resulting initial orbit does not have to be re-calculated, should the launch time slip.

These element sets can also be stored in various formats. The element sets produced by the aforementioned SGP4 technique are called NORAD TLEs, while those produced by the SP theory are stored as state vectors with accompanying covariance matrices.

The observations taken from space surveillance sensors also exist in various formats. Those from radar installations are commonly in a format using the azimuth, elevation, and range to a target object from the sensor along with the time of observation. The exact latitude, longitude, and height above mean sea level of the sensor site, along with the reference point for the azimuth, must be known to accurately use these observations. Observations collected by optical telescopes are usually in a format that includes right ascension and declination angles and are thus sometimes referred to as “angles only,” as they do not have any range data.

As with the astrodynamic techniques, the wide variation in reference frames and data formats can pose a significant obstacle to SSA data sharing, even within the same organization. And as with astrodynamic techniques, conversion between the various forms can be done if complete and accurate information about the reference frame and data format is known.

C. Sensor Calibration and Tasking

As with any measurement system, the accuracy of the individual data collections is a major factor in the overall end product. Determining the accuracy of the multitude of sensors used in a space surveillance system in a quantitatively meaningful way can be a daunting task. As an example, radar sensors are commonly tasked to track a reference object in orbit. These are usually special satellites with reflective coatings or devices whose position is determined extremely accurately using laser ranging. The sensor site being analyzed will track one of these calibration satellites and the data will be compared to the laser reference. In this way the accuracy of the senor can be established and calibrated if necessary.

Systematic calibration of all the sensors in a system will allow for determining which sensors are on average more accurate than others. These “trusted sensors” can then have their data weighted more heavily when used for orbit determination and the data from less accurate sensors can be de-weighted. Sensors which consistently show significant errors in a certain aspect of measurement can have a bias applied to their data to correct these errors.

In addition to systematic calibrations, space surveillance systems also use centralized tasking methods to optimize their sensor capacity and capabilities. An algorithm known as a tasker is used to manage the process. This generally starts with an analysis of the number and frequency of observations needed to maintain the accuracy of a particular orbit type over the desired time range. Objects in an orbit with a high energy dissipation rate (EDR), such as those in terminal atmospheric decay, experience a high rate of change and thus need more frequent sensor tracks and updates [6]. Those in orbits with a low EDR, such as Medium Earth Orbit (MEO) need fewer observations and updates.

The tasker should also take into account the spread of observations around an orbit. An orbit determination based on multiple tracks of observations from the same sensor will result in an orbit which is accurate over the sensor but inaccurate on the other side of the Earth. Tracks from multiple sensors spaced in true latitude around an orbit are ideal for accurate orbit determination.

To determine which sensors can track an object, the tasker uses the existing element set for the object to determine which sensor sites it will pass over. It then does a geometric “look angles” calculation to see if the object passes within the range, elevation, and azimuth limits of the sensor. Additionally, use of an object’s radar cross section (or visual magnitude for optical sensors) can be used to calculate a probability of detection for that pass. The tasker can then intelligently determine which sensors are the best to assign to a specific object.

Finally, the tasker needs to know the capacity of each sensor and its availability. The capacity is determined by how many objects a sensor can track at any given time along with its duty cycle during the tasking period. Any schedule maintenance or other activities which can create downtime for the sensor needs to be known. All of these factors are then combined by the tasker algorithm to determine which sensors are tasked with which objects during the next tasking period.

This tasking process is complex and potentially difficult for a single system of sensors which are centrally managed by a single entity, such as the US military’s Space Surveillance Network (SSN). Developing a robust tasking process for an international SSA system which shares data from sensors from multiple networks and jurisdictions is a monumental task.

D. Analytical Tools

Along with the mathematical tools needed for orbit determination and orbit propagation, additional tools are needed to create operational and decision-making data from a satellite catalog. For the problem of civil safety and long-term space sustainability, the most essential tools are those for conjunction assessment and collision avoidance.

Conjunction Assessment (CA) is the process by which close approaches between two objects in orbit are determined [7]. For any two objects, the CA process is fairly straightforward. Their orbits are propagated forward in time over the period being screened and the distance between them is calculated. This miss distance is usually measured in all three orbital dimensions (in-track, cross-track, and radial) separately, although a single closest approach distance can be calculated. Additionally, if the error covariance matrices for the two objects are known, then the probability of collision between the two objects can be determined.

This process is greatly complicated when expanded out to include all of the more than 20,000 objects currently being tracked in Earth orbit. This "all vs. all" CA problem requires significant computing capacity, but perhaps more importantly significant human analytical capacity to sort through all the close approaches to determine prioritization, contact the appropriate satellite owner-operator, and perform additional analyses for verification. Even limiting the process to all maneuverable payloads, which are the only ones that could actually prevent a collision, versus all objects, creates a non-trivial task for both humans and computers.

Once a conjunction event has been discovered which exceeds the satellite operator's threshold for safety, a determination must be made on whether or not to perform a collision avoidance maneuver. This is a complex process, as an improperly calculated maneuver can have little effect on the conjunction or even introduce a new conjunction in the future, while wasting precious fuel and interrupting the service that satellite provides. Again, knowing the covariance matrices for the two objects can help greatly in making this calculation.

Many techniques exist for doing both conjunction analysis and collision avoidance, and part of the problem is the lack of quantitative assessments between them so that accurate comparisons can be made. Each satellite owner-operator is likely to have different thresholds for which close approaches constitute a safety issue. One central analysis center providing CA for all operators is therefore likely to need multiple thresholds, creating additional complexity and capacity. Questions over the validity of the CA technique and analysis are also likely to arise, especially in situations involving multi-hundred-million-dollar satellites.

E. Data Security

Any system which shares data faces security challenges, even if the data is not of a national security or classified nature. An ICSSA system would be no different. Corporations may have intellectual property restrictions on certain data or tools which restrict their dissemination. They may wish to obscure information about the location of their satellites from competitors for fear of them deriving intelligence about techniques or positioning that could lead to a competitive advantage.

The integrity of data which is entered into the system and distributed among the participants needs to be maintained. While digital computers do, in theory, create perfect copies of information without degradation, in practice this becomes much more difficult. Computer hardware such as hard disks and memory is prone to bit flips, bad sectors, and other glitches which can randomly change small pieces of data. Software can include bugs which can destroy or cause unintentional changes to data. Transmission systems used to communicate data can garble or drop pieces of information.

Procedures for verifying the identity of an entity that wishes to access data and their authorization for said data is extremely important. Additionally, there needs to be procedures in place to ensure that unauthorized entities cannot inject false or misleading data into the system.

F. Correlation of Observations and Cross-Tagging

In any space situational awareness system, correlating the observations collected by a sensor to an existing object in the satellite catalog is a critical process. Done properly, this allows for the new observations to be "tagged" to the appropriate objects, which then can be used to update the element set for the object. Done improperly, the data becomes tagged to the wrong object which could then corrupt the element set. At worst, the data does not tag to any objects, which prevents the correction of their element set and could lead to creation of duplicate objects in the satellite catalog.

Data collected from phased array radars is relatively easy, as it has range information. Correlation of angles only data collected from optical telescopes and radar “fences” is more difficult as it lacks range information.

The sheer volume of sensor observations can also present a challenge. The US military SSN collects on the order of 500,000 individual sensor observations each day, all of which need to be run through an observation association process, with new sensors coming online which could double that number [8]. An international system with potentially many more sensors than the SSN could have a much greater flow of observations.

A related problem to obs association is that of cross-tagging. A cross-tag occurs when an object in the satellite catalog mistakenly become misidentified as another. The most common reason for this occurs in the geostationary belt, where satellites occasionally drift past other objects when changing orbital slots. There are also several clusters of multiple satellites occupying the same orbital slot, which can be easily misidentified.

IV. MITIGATION STRATEGIES

A. Sharing element sets versus observations

There is a significant amount of difference between SSA data sharing systems based on sharing observations from sensors and sharing element sets. As discussed earlier in this paper, element sets are produced by combining multiple tracks of observations from one or more sensors. A data sharing system that allowed for participants to exchange and combine sensor observations has the potential to produce extremely accurate element sets beyond what the individual actors could achieve. This stems from the ability to combine observations from sensors outside any one State’s control optimally spread along a space object’s orbit.

However, to accomplish this effectively, intimate data is needed on each sensor’s operating procedures, calibration, bias, and weighting, along with coordinated tasking of all sensors. This requires a centralized command and control and governance structure that might be beyond current political feasibility.

Sharing data on the element set level could potentially be easier politically. If each participant combined the observations from their own tracking resources into element sets, sharing them with the group would require less intimate knowledge of the sensor operations and less centralized governance. Each actor would then be able to use the element sets shared by the others to supplement their own catalog. Additionally, sharing information about upcoming maneuvers for satellites under each participant’s control would be essential, as they serve as an “event horizon” beyond which any conjunction analysis are invalid for that object.

The downside to sharing at the element set level is that it limits which participants can provide meaningful data to the system. Those with a single or few sensors that are not geographically distributed will not be able to produce element sets of high accuracy across the entire orbit of the space object. These element sets might be useful if they were the only ones available for that particular object, but would generally only be accurate over the sensors which acquired the observations.

B. Standardized Data Formats

As discussed earlier, there are multiple formats for each type of SSA data, including observations and element sets. A common format for both of these data types that is agreed upon by all parties is essential to the operation of a data sharing system.

Work is already underway at the International Standards Organization (ISO) on developing some of these standardized formats [9]. In addition, a tool to convert between the various element set formats is also necessary. Work on such a tool is taking place at both the Center for Space Standards and Innovation (CSSI) and Intelsat.

C. Open Source Software

Critical to the success of any data sharing system is trust between the participants in both the quality of data from the other participants and in the software tools used by all to produce and analyze data.

Traditional computer software development has followed a close-source model. The underlying source code, which contains all the software instructions, is converted into an executable file. This process is generally considered to be irreversible, since having the executable file means, one cannot determine the original source code. Thus, the original source code can be maintained as intellectual property and kept hidden from competitors.

A significant downside to this closed--source process is in security. Since only the original authors can see the source code, only they can scan it for bugs which could lead to security vulnerabilities or output errors. Another significant downside is that to the end users the software is a “black box” and it can be difficult to verify the accuracy of it under all circumstances.

Open source software (OSS) development allows the source code to be viewed and potentially modified by anyone. In OSS development projects, there is usually a strict system of trust and controls that allows anyone to contribute code to the final software package. Alternatively, anyone can take the existing code and create a fork, or alternative development branch, modified to suit their own needs.

For an SSA data sharing system, OSS offers several obvious advantages. All participants can view the source code, which increases the likelihood that bugs will be found and increases transparency and confidence. All participants can contribute code to the project, allowing them to add features, algorithms, and conversion utilities which they see as important. The software can be as inclusive as necessary with a variety of astrodynamic models, techniques, and conversion utilities to allow use by a broad user base. Participants will not be forced to use the OSS software if they have their own proprietary solution, but it will be available to those who do not.

D. Public Key Encryption

For many potential participants, data security is the most important factor in any potential SSA data sharing system, although it does not pose any challenges that have not been addressed in other systems.

Authentication is the means of verifying a participant’s identity. For an SSA data sharing system, this is crucial to ensure that only authorized participants can inject data into the system and access data in it.

Encryption is a means of protecting data from unauthorized disclosure by converting it from its usable form, called clear text, into an encrypted form, called cipher text. In the best encryption systems, this is done by combining the data with random noise such that the end result is essentially random noise. Thus, the data can be shared without concern for interception.

These data security requirements are not unique to SSA data sharing—indeed; they have been tackled time and time again in a variety of regimes. Robust solutions already exist, and the challenge is to properly integrate them into the system design.

One such solution is known as public key encryption. It relies on each participant having a unique pair of keys. One of these keys is kept private and never disclosed. The other is made publicly available to all. Any data which is encrypted with one key can only be decrypted using the other. In this way, participant A can send data securely to participant B simply by encrypting it with B’s public key. Only B has the matching private key to allow decryption. Likewise, the identity of participant A can be validated by anyone if A encrypts an agreed upon string of text with their private key. Only decryption using A’s public key will return the cipher text to the original string, thus validating that A sent the message. This technology is used in many common activities, including secure Internet browsing, called Secure Sockets Layer (SSL).

Validated and mature software packages for an entire range of data security solutions are readily available in open source form, which can be modified and integrated into the SSA data sharing software and architecture.

V. CONCLUSIONS AND FUTURE WORK

The brief overview of the technical challenges posed by an ICSSA system described in this paper does not purport to be an exhaustive analysis of the problem, nor does it seek to provide robust solutions. Rather, it is intended to provide a feel for the challenges inherent to creating such a system, as well as some their potential solutions.

While some of these technical challenges are indeed difficult, none appear insurmountable. Many are simply extensions of the challenges that already exist in national SSA systems and which have largely been solved or mitigated.

Choices made in the architecture of any SSA data sharing system will almost certainly rest on a cost-benefit analysis of accuracy versus complexity and difficulty. These choices will also affect the political, legal, and diplomatic challenges faced in creating such a system. It may be the case that overall accuracy and capability of a system could be subservient to the political realities. If so, a more detailed analysis needs to be done to properly define the trade space.

Choosing between building an ISCCA system which shares at the observation level as opposed to one which shares at the element set level is potentially the key decision. While a system based on the observational level is likely to provide greater accuracy and opportunities for inclusion of partners, the technical and political challenges it imposes may not exceed the benefits. A system based sharing of element sets, which could later be expanded to the observational level, may be the most feasible choice.

Additional work is already underway on a number of issues raised in this paper. A catalog of potential SSA sensors worldwide is being compiled. This will then be used to determine the marginal benefit of adding various sensors to an ICSSA system, an analysis that will prove useful in determining which partners are essential to such a venture.

The open source software project described in this paper is the subject of a more thorough and detailed analysis slated for future publication, including project scope and feasibility.

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