OrbitOutlook: Data-centric Competition Based Space Domain Awareness (SDA)

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Abstract

While Space Domain Awareness (SDA), including all of space surveillance and characterization of all space objects and environments, is critical for national and economic security, SDA capabilities cannot be developed independent of cost. Traditional space surveillance architectures are implemented utilizing an approach in which a single government owns and operates all capabilities. New capabilities are developed through large acquisition programs, and upon completion the government is responsible for performing all system operations and maintenance. Final integrations require detailed accreditation processes, and do not fully capture sensor biases/uncertainties thus resulting in inaccuracies such as cross-tagging. OrbitOutlook's space surveillance architecture is utilizing an approach in which all space surveillance capabilities are competed in an open market-place. This approach provides a significant increase in network flexibility and cost reduction through competition. To enable this approach, DARPA is developing algorithms which enable a fundamental architecture shift from sensor-centric validation to data-centric validation. To demonstrate this architecture DARPA is arranging fee-for-service agreements to leverage civil, academic, industry, and government infrastructure to rapidly create a flexible global SDA network.

Since announcing the initiative, DARPA has been inundated with information on highly capable assets currently available for tasking with little or no modification. Several of these initiatives have begun, and the pathfinder effort SpaceView has successfully performed a preliminary demonstration. SpaceView is leveraging existing amateur astronomer infrastructure to construct a global network and is rapidly expanding in its second phase. Other efforts are underway, such as StellarView, which plans to leverage existing University infrastructure. DARPA has also solicited industry for concepts to rapidly (<12 months) deploy an un-cued Low Inclined LEO Object (LILO) detection capability. DARPA has also identified a novel dynamic database architecture to provide the flexibility to rapidly incorporate new unique data sources. At the heart of the effort are the DARPA validation algorithms which are designed to determine confidence metrics and quantify the error in each measurement. The final result envisioned by DARPA is an efficient, cost-effective, flexible, and effective global network for Space Domain Awareness.

1. INTRODUCTION

For decades, the Space Surveillance Network has been tracking orbital objects and maintaining a catalog that allows space operators to safely operate satellites for a variety of uses. Even as new advanced sensors are deployed (such as the Space Fence), orbital populations continue to grow at an ever increasing rate. Most estimates of the requirements to safely operate in this congested, potentially contentious, environment examine the raw number of objects in orbit. Over the last couple of decades, bytes have become the standard metric of progress, and massively distributed systems have demonstrated the ability to effectively collect and process information. Examples include the dominance of cluster based supercomputers, and the phenomenal success of Google. In this paper, the requirements to maintain complete Space Domain Awareness (SDA) are examined from a perspective of the data volume required to generate the information needed for SDA. This work attempts to frame the SDA challenge in this new paradigm, and examine distributed options to gather the needed information. While data volumes are naturally dominated to first order by the number of objects, this estimate also attempts to account for the additional demands of characterizing unknown objects and maintaining accurate tracking of active space objects. Traditional SDA utilizes a "detect and track" methodology. Success is determined based on the ability to maintain a catalog of two line element sets for any tracked objects. OrbitOutlook is developing an architecture, see figure 1, which focuses on the knowledge provided by the data. This fundamental shift in methodologies measures success by the ability to produce indications and warnings, and requires more diverse and evolving data types. In this paper, data types for different orbital regimes and levels of knowledge are estimated and compared to the capabilities of existing observatory assets in the academic and private sectors. The comparison shows that there are significant data needs that can be fulfilled by creatively leveraging these assets.

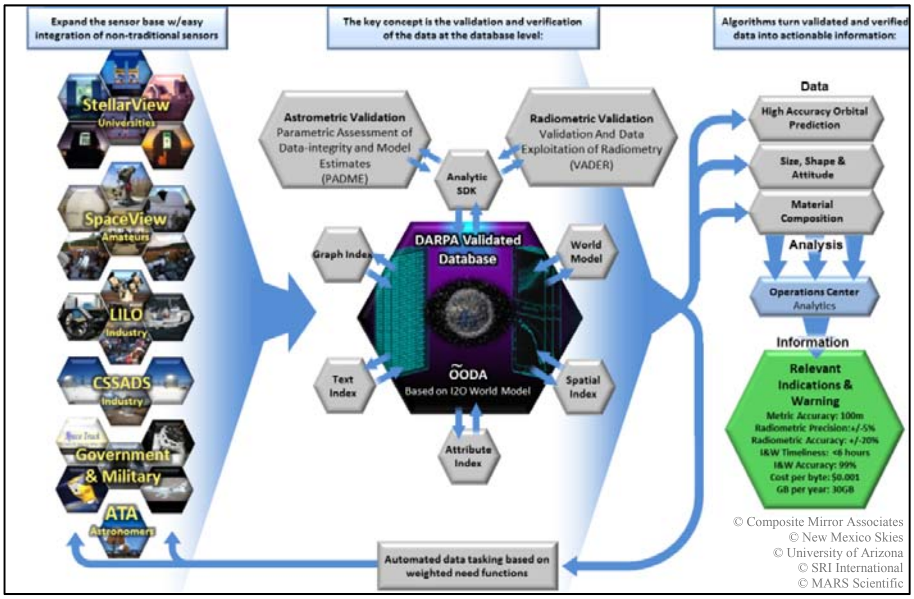

Figure 1: OrbitOutlook Architecture

2. SDA DATA NEEDS ESTIMATE

Space Domain Awareness is the ability to detect, track, and characterize passive and active space objects. Most systematic efforts to achieve this goal have focused on the detection and tracking aspects, addressing characterization in an ad-hoc fashion. The current space catalog contains over 20000 known objects, but it is widely recognized that the catalog is incomplete and many additional resident space objects exist. In addition, it is also generally accepted that the number of objects, both passive and active, is steadily increasing. Complete and true space domain awareness, then, must account for both an expansion in the size of the general catalog, as well as the capacity to routinely characterize objects of interest.

The initial step in estimating the volume of data needed to achieve these goals is to define the data size for the two basic components of SDA: tracking and characterization. For tracking, the core information needed is the orbital definition encapsulated, for example, by a two line element set. This fundamentally describes an object with a unique identifier, as well as its position, velocity and direction. This information allows the prediction forward (or backward) in time, but the accuracy degrades as the amount of propagation time increases. Thus, the need to maintain a certain average level of accuracy in the tracking catalog will also influence the number and frequency of observations required. Characterization implies a much different level of knowledge. Object characterization implies some resolution of an object's features and/or behavior. Photometric signatures of brightness vs. phase & body angle and 2-D images of an object are two notable examples which can be used to form an estimate of the amount of information required to characterize a space object.

Another key parameter to be considered is the frequency of observation. This sampling rate varies depending on the characteristic timescale with an object changes, and the tracking accuracy desired. Thus, the rate can be quite different, in general, for passive and active objects. Passive objects change position and direction only under the influence of natural events and perturbations, such as atmospheric drag, and these factors typically change orbits over timescales of days to months. In contrast, active satellites can maneuver at virtually anytime, and alter their orbital path on much shorter timescales of several hours.

These factors can be combined into a parametric sum which coarsely defines the total data needed to form a comprehensive awareness of the orbital population. The equation given below includes the dominant terms which account for the vast majority of the data volume in the estimate:

$$\mathrm{B}_{tot} = \eta N_p \left(\frac{\beta_{mo}}{\tau_{mo\_p}} \right) + \eta N_a \left(\frac{\beta_{mo}}{\tau_{mo\_a}} \right) + \frac{\eta}{\gamma} N_a \left(\frac{\beta_{img}}{\tau_{img}} \right) \tag{1}$$

Where N_a , N_p are the number of active and passive objects; β_{mo} , β_{img} are the bytes/observation for metric observations and images; τ_{mo}, τ_{img} are the time between observations; η, and γ are scale factors that account for relative orbital accuracy goals for the various components of the total, as well as normalize the sum to account for inefficiencies such as false detections, uncorrelated targets, and verifications. Note that there is no component of the total for images of passive objects (debris), as it has been assumed there is no need for detailed inspection of these objects on a regular basis.

Next it is useful to define the values of these parameters that approximate the current and future state of the space domain. The current catalog and network performance is to be compared to threshold and objective goals for Space Domain Awareness. The values are assumed are listed in table 1 and plotted in figure 2:

Table 1: Parameters used in estimating data needs for SDA

	Current	***Threshold***	***Objective***
β_{mo} , β_{img}	0.1, 10Kb	0.1, 10Kb	0.1, 10Kb
Number of Objects (N_a , N_p)	4K ,14K	5K,100K	8K, 150K
Update period (τ_{mo_p}, τ_{mo_a}, τ_{img})	3, 3, 300 days	3, 1, 45 day	3, 0.5, 30 days
η, γ	6,5	8, 5	12, 5
Size Object (near/deep)	10cm/30cm	> 3 cm/10cm	> 1 cm/5cm
Orbital Vector Accuracy	5km	500 m	100 m
GB/Year of relevant data	**~1.5**	**~12**	**~30**

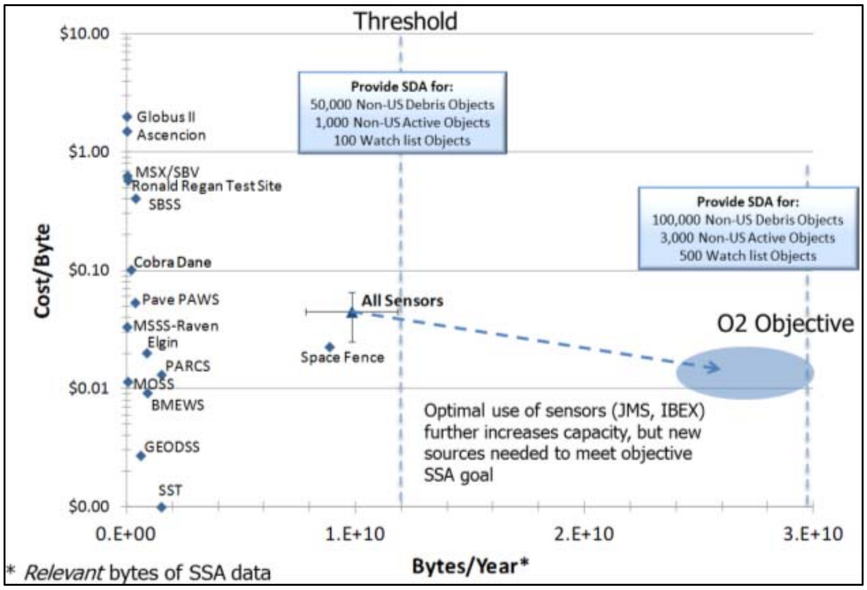

Figure 2: O2 Cost per Byte vs. Bytes per Year Threshold and Objective Values

The increasing values of the η parameter is caused by the ever tighter goals for orbital vector accuracy. Their relative values are estimated via the simplifying assumption that the propagation error over time is proportional to the square of the update period divided by the square root of the number of observations used to create the track. The absolute value of η is calibrated based on DARPA estimates of the current data generation capacity of the SSN. The value of γ is estimated based on future surveillance need scenarios, but there is no large-scale systematic effort to collect such data in place today, so the current value may be regarded as relatively uncertain.

This calculation indicates that the future need for SDA data will indeed be quite large, and an order of magnitude or greater than the data volumes being routinely captured and processed today. It is worth noting that these estimates are for reduced data only. Implicit in the estimation is elimination of redundant, stale, and/or inaccurate observations, as well as extraction of the useful information from the raw data. The raw data volumes (CCD images, for example) will greatly exceed these estimates.

When defining a data-centric metric, it is important to include relevancy. Otherwise, the system can become biased towards high data volume sensors which may not provide significant value. For example, it may be possible to collect metric information at 100 Hz, however only 1 collect every minute may be relevant. O2 defines relevant data as reduced, non-redundant, and essential information provided within a relevant timeline.

3. DATA SOURCES

The OrbitOutlook Program will demonstrate the ability to rapidly integrate capabilities owned and operated by a variety of communities through a spectrum of methodologies. In 2012 DARPA began an effort called SpaceView, figure 3, to begin collaborating with and integrating sophisticated civil owned and operated telescopes. This effort has successfully completed the first phase of demonstrations and has recently begun its second phase to demonstrate the expansion of the network globally. DARPA is beginning a second effort called StellarView, figure 4, to integrate unique University data sources from around the world. A third O2 effort called LILO, has solicited industry for concepts to rapidly deploy mature low cost solutions for providing un-cued low inclined low earth orbit object detection.

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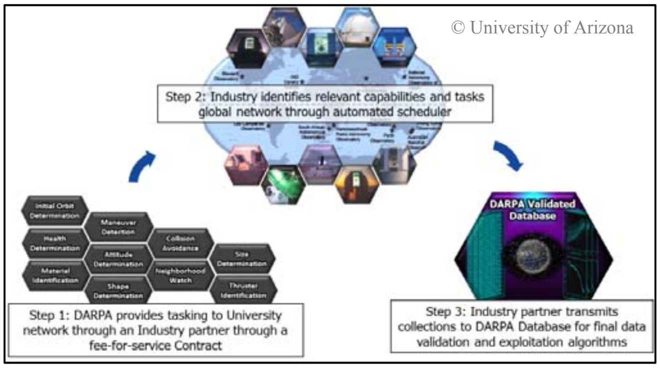
Figure 3: SpaceView



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Step 2: Industry identifies relevant capabilities and tasks global network through automated scheduler

Step 1: DARPA provides tasking to University network through an Industry partner through a fee-for-service Contract

Step 3: Industry partner transmits collections to DARPA Database for final data validation and exploitation algorithms

Figure 4: StellarView

The combination of these efforts demonstrate wide spectrum of integration methodologies:

- Sensor Development/Deployment:
    - Industry is solicited to provide a needed capability within a given timeline, which requires a new development effort or relocation of a current capability.
- Algorithm Development:
    - A capability exists which was designed for another purpose, and is upgraded with algorithms to meet an SDA need.
- Network Development:
    - The infrastructure owned by various entities exists and is upgraded with coordinated network control.
- Tasker Development:
    - A network of capabilities exists, and is upgraded with streamlined coordinated tasking to meet SDA timelines.
- Data Sharing:
    - An existing capability has not been through the formal accreditation process and is provided a mechanism to share its data with OrbitOutlook for validation and exploitation.

4. INFORMATION-CENTRIC VALIDATION & EXPLOITATION

At the heart of the OrbitOutlook Program, is the need to validate and exploit any information provided from an uncertified capability. There are two joint efforts in the program which leverage techniques developed by the Air Force Research Laboratory to validate and exploit radiometry and astrometry from non-traditional sensors. There are two phases to the validation process. First, all information which is sent to the database is initially filtered utilizing available truth information and by analyzing the provided meta-data for inconsistencies. Second, the information is exploited parametrically to identify any information which produces out of family solutions. These solutions are then flagged for further review. At the end of this process, confidence metrics are provided for any exploitation information derived. By following this process of information centric validation, decisions relevant to SDA can be made with known confidences.

5. DATABASE

The OrbitOutlook program includes several features which are challenges to conventional databases. One of the major objectives is to create a system which is flexible and expandable, to include data formats or types not currently planned or known. The database must therefore be dynamic in the sense that new data fields and relationships can be defined without requiring re-entry or update of the entire database structure. Typical databases are too rigid to satisfy this requirement, and even if automated re-organization or field expansion is possible, it is a manual and time-consuming process. A related challenge is the need to index the information contained in different ways. Most databases rely on a single type of indexing, such as relational, hierarchical, or temporal. In OrbitOutlook, incoming data may not have a well-understood relationship to other measurements, yet its correlation to other information also is expected to change over time. These relationships may also involve dynamic weighting, or confidence factors. Among the indexing types to be included is a temporal aspect, where the database allows for a searchable provenance for a particular record or object, as well as support for future hypotheses. In a typical database, such bookkeeping is unwieldy and inefficient, because the basic data structures are not created with such operations in mind. Accommodating this type of dynamic and multi-variate indexing is a discriminating feature that has spurred the investment in a non-standard database for the program. Finally, efficient scaling and access speed is an important feature of the O2 database. As with any database, data access and replication is a limiting factor in how widely a database can be used, computing resources required, and the size of the user base and overall capacity. Distributed use of very large databases can also be problematic, as either remote copies of the entire database are needed for rapid access, or suffer from high latency from remote use of centralized storage. An ideal solution for the O2 scenarios will address this issue by accommodating scaled or incomplete copies of the database to be utilized remotely without sacrificing the indexing structure(s). Though very large databases certainly exist, none were evident that also met the needs for data flexibility, highly distributed access, and dynamic indexing.

6. CONCLUSION

As the space domain grows ever more accessible and the resident space object population increases, the amount of data required to maintain adequate domain awareness and ensure safe operations will greatly increase. This data can be provided by a number of different means, and a substantial base of observatory assets exist with capabilities well-matched to the projected need. Additionally, modern cameras and computer controlled mounts enable even backyard astronomers to acquire data of potential utility and meaningfully participate. The flexibility, responsiveness, and efficiency of the Space Surveillance Network might be significantly enhanced if these data sources can be harnessed in a coordinated, systematic way. DARPA has been identified methods that support this kind of dynamic and distributed architecture within the current SSN architecture, and will continue to investigate opportunities to utilize non-traditional data sources of value to the space surveillance community.