An Australian experimental SDA system: RED STAR

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1. ABSTRACT

The Australian Defence Science and Technology Group (DSTG) has developed an experimental capability to inform and shape the acquisition of an operational Space Domain Awareness (SDA) system for Australia. The SDA research environment, known as Research and Development Space Target Awareness and Response (RED STAR), is at an initial functional stage and continues to evolve.

The RED STAR system accepts data from multiple sources, including SDA sensors and space object catalogues such as space-track.org. Data from multiple heterogeneous SDA sensors can be processed including various ground-based sensor types such as optical telescopes and radar systems. In addition to data from real sensors observing real objects in space, modelling and simulation is used in RED STAR to generate data from simulated sensors observing simulated objects or a blend of real and simulated events to support a “sim-over-live” configuration. A repository allows the collection, storage, curation and retrieval of SDA data for analysis and for evaluation of prototype algorithms to support SDA functions. Tools for performing multi-sensor orbit determination and photometric analysis may be implemented and evaluated using RED STAR, which enables processing and visualisation functions. The data management software for RED STAR uses an agile software approach to develop a cloud native, containerised application suite of cooperating services. Web-based visualisation is used with RESTful API to support information exchange. The RED STAR system supports space intelligence analytics using multiple sources to determine space object information such as size, shape, function and attitude.

This paper provides an overview of DSTG’s SDA activities for RED STAR and examples of various constituent tools to support SDA.

2. INTRODUCTION

The First Nations peoples of Australia, Aboriginal and Torres Strait Islanders, have been observing the sky for millennia. Observations of celestial objects have been used by Aboriginal and Torres Strait Islanders to inform navigation, calendars, food availability and weather. Astronomical phenomena serve as the foundation for narratives that have passed from elders to new generations through song, dance and storytelling [1, 2].

Sputnik 1, launched by the Soviet Union during the International Geophysical Year (IGY) in 1957, was the first human-made object to orbit the Earth. Australia joined international efforts with public and government monitoring activities focused on detection of Sputnik 1 using optical and radiofrequency sensors [3, 4]. Australia agreed to host two tracking stations at the Woomera Test Range in South Australia which were used to support the US program for the Vanguard 1 satellite launched in 1958 [5].

In 1967 Australia’s first satellite, the Weapons Research Establishment Satellite (WRESAT), was launched from the Woomera Test Range using a modified US Redstone rocket. The WRESAT carried upper atmospheric radiation measurement experiments designed at the University of Adelaide and successfully transmitted scientific information to tracking and research stations around the world. A network of sensors was used to track WRESAT during its 42 days in orbit [6].

Live television footage of Apollo astronaut Neil Armstrong stepping onto the surface of the moon in July 1969 was transmitted from the Apollo tracking station at Honeysuckle Creek, near Canberra ACT. Today the Canberra Deep Space Communication Complex at Tidbinbilla NSW tracks spacecraft voyaging beyond the solar system [5].

The US Space Surveillance Network (SSN) monitors space objects in space and includes two sensor systems that are currently operated in Australia: (i) C-Band Space Surveillance Radar [7] and (ii) Space Surveillance Telescope [8]. The Australian Deep-space Advanced Radar Capability (DARC) is planned for operations by 2026 [9].

Australia contributes to the US Joint Commercial Operations (JCO), which is a US Space Force-led initiative using industry providers to deliver space domain awareness capabilities [10]. The JCO operates across three regional cells: Americas, Pacific and Meridian. Sprint Advanced Concept Training (SACT) exercises have served as an environment for exploring new data, tools and concepts from the commercial sector [11].

Australia's Defence and National Security interests span multiple operating domains. Access to services that are reliant on the space domain such as satellite communications, intelligence, surveillance and reconnaissance information, and position, navigation and timing are critical for Defence and civil operations. Assurance of access to the space domain is needed to support Australia's integrated force for operations by the Australian Defence Force (ADF), whether the operations are conducted within Australia or overseas. An awareness of objects and activities in the space domain is necessary for protecting and defending space assets and services. The Australian Space Agency is also developing a civil space monitoring capability to enhance safety of space traffic [15].

Australia's Defence Science and Technology Group (DSTG) is the Australian Government's lead agency responsible for applying science and technology to safeguard Australia. DSTG today applies science and technology to provide evidence that can shape and inform space services. DSTG's small satellite Buccaneer Risk Mitigation Mission (BRMM) and Buccaneer Main Mission (BMM) build on the space legacy established by the WRESAT and other space projects [12, 13]. An operational Space Domain Awareness (SDA) system is one of many Australian Defence programs supported by DSTG evidence [14]. An experimental SDA system known as the Research and Development Space Target Awareness and Response system (RED STAR) has been developed by a DSTG-led team. RED STAR continues to evolve in response to stakeholder needs.

With a focus on technical aspects of an SDA system, RED STAR includes experimental capabilities for sensing of space objects, data integration and management, data curation, processing of data to develop orbital state estimates, modelling, simulation and analysis functions. Preliminary effort is underway to develop RED STAR capabilities in sensor management, manoeuvre detection and space intelligence including space object identification and characterisation.

This paper provides a summary of the experimental SDA system, RED STAR commencing with an outline of the functions followed by descriptions of components that comprise RED STAR.

3. RED STAR OVERVIEW

In early 2021 DSTG commenced development of the experimental SDA system, RED STAR, to inform and shape Australia's SDA capabilities. Prioritised requirements for RED STAR are developed by DSTG personnel in consultation with Defence and other stakeholders. The RED STAR team consists of DSTG personnel working with contracted personnel from Saab Australia, Lockheed Martin Australia, In Track Solutions and Swordfish Computing.

Figure 1 shows the external interactions and key functions that comprise RED STAR[i]. Research and Development needs for RED STAR are identified and prioritised based on SDA stakeholder requirements. The RED STAR system accepts data and information from many external sources, including data repositories such as the Unified Data Library (UDL), online catalogues as space-track.org, open-source information and data directly provided from SDA sensor providers.

[i] The seven-pointed star used to represent the RED STAR system alludes to the Commonwealth star featured on the flag of Australia and to the red half of the Aboriginal flag.

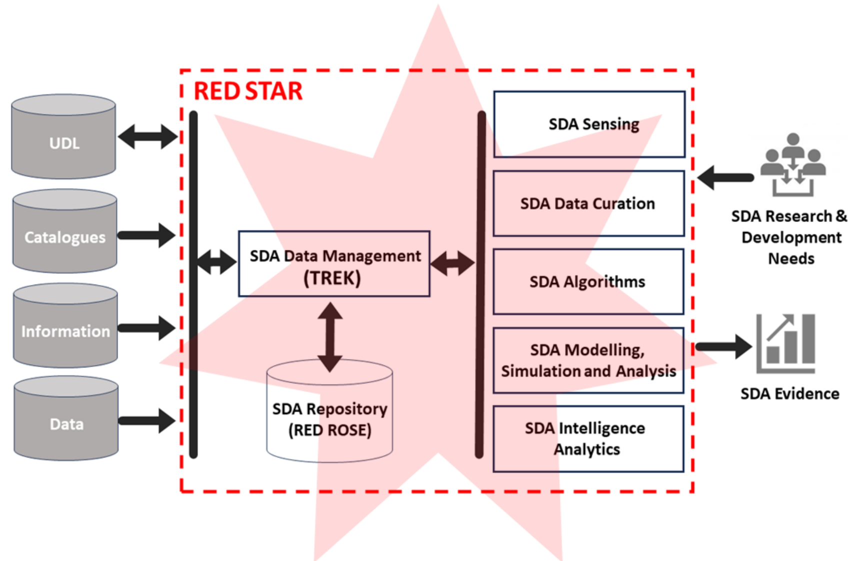

Figure 1. Conceptual relationships between key functions of DSTG's experimental SDA system, RED STAR

At the core of the RED STAR system is an SDA Data Management function which accepts data from external and DSTG sources, including research systems for SDA Sensing. An SDA Repository is used for storage of unprocessed and processed data. An SDA Data Curation function performs normalisation and monitoring of data to ensure data consistency for subsequent processing such as with SDA Algorithms including Orbit Determination. The SDA Intelligence Analytics function considers information about space entities. An SDA Modelling, Simulation and Analysis function enables modelling and simulation of space scenarios with various analysis activities applied to real and simulated data. RED STAR functions are typically developed and tested in standalone testbeds before integration with other functions.

As shown in Figure 2, the data and functions of the RED STAR system yield scientific and technical evidence to inform and shape Australia's Defence capabilities for SDA operations and concepts that (i) are currently being executed, (ii) are planned as part of Defence acquisition projects and (iii) may be implemented in the future.

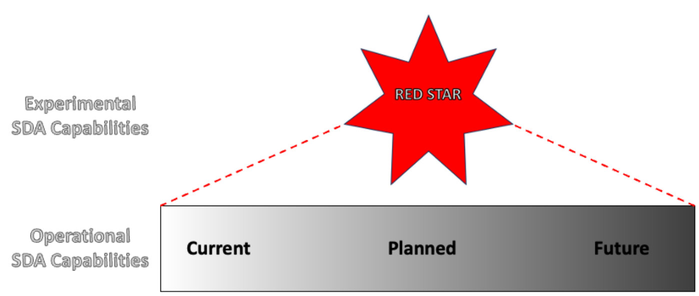

Figure 2. The experimental SDA capabilities of RED STAR inform and shape Operational SDA capabilities for Australia

4. SDA SENSING

DSTG conducts research into sensing capabilities for various applications including sensing of space objects with different phenomenology including optical sensing in the visual and Infra-Red (IR) bands, active radar in different Radio-Frequency (RF) bands and passive radar. This section provides an example of some of the SDA sensing activities that can be deployed as part of the RED STAR system.

The DSTG optical observatory is a passive, electro-optical, narrow-field sensor system shown in Figure 3 that has been developed for SDA Sensing research [16]. The observatory consists of two platforms. The first platform is a transportable trailer mounted Paramount ME II Equatorial Mount. The optical payload consists of two co-mounted 20 cm Officina Stellare RH200 Telescopes (f/3) with a Finger Lakes Instrumentation (FLI) ProLine PL4240 cooled CCD sensor on one telescope, and a FLI Kepler KL400 on the other. This provides a field-of-view of ~2.4 degrees (2048 x 2048 resolution, 4.5 arcsec per pixel). The second platform is a fixed concrete pad with a Paramount ME II Equatorial Mount. The optical payload is a 50 cm telescope Officina Stellare RiFast 500 (f/3.8) with FLI ProLine PL4240 cooled CCD providing a field-of-view of ~0.8 degrees (2048 x 2048 resolution, 1.46 arcsec per pixel).

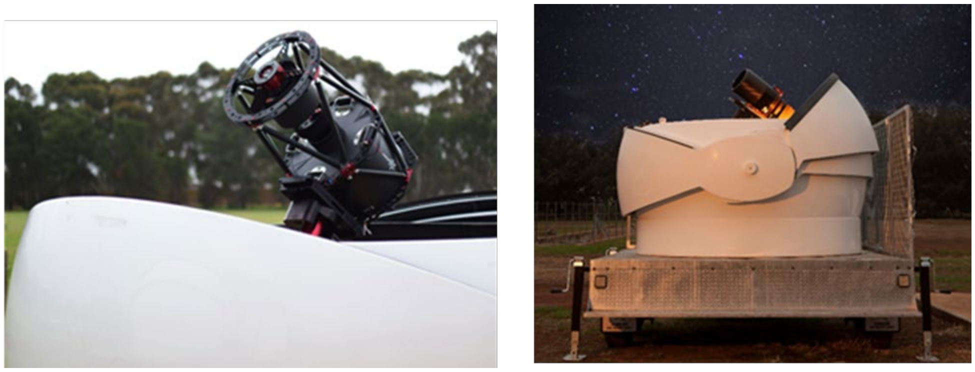

Figure 3. Fixed 50cm telescope (left) and the transportable 20cm telescope (right) of the DSTG optical observatory

The ProLine sensors are connected to a Symmetricon GPS timing card to provide accurate time stamps for the start and end of each shutter release, while the Kepler sensor uses the Kepler Image Time Stamp system directly connected to the camera. The exposure time varies depending on the orbital regime and the system is typically operated at least 10 degrees above the horizon due to geometric constraints imposed by the dome and surroundings. Objects are tracked using Two Line Element Sets (TLEs) or ephemeris as input to automated sensor scheduling software written in Matlab, together with the TheSkyX commercial package.

The processing pipeline automatically identifies 'streaks' (stars) and 'blobs' (objects) in Flexible Image Transport System (FITS) format imagery and performs plate solving using open-source Astrometry.net [15]. Objects are tracked using a Kalman filter, associating detections and filtering false alarms to provide electro-optical observations with measurement components of right ascension, declination and visual magnitude for each tracked object, corrected for annual and diurnal light aberration.

Optical observations using the DSTG observatory formed part of Australia's participation in coordinated Space Domain Awareness (SDA) experiments which were conducted by defence science and technology (S&T) organisations of the Five-Eyes (FVEY) nations: the United Kingdom, United States, Australia, Canada and New Zealand. The experiments were designed to develop and test capabilities to perform SDA under challenging conditions. These included the tracking from launch through to rendezvous and docking in Geostationary Earth Orbit (GEO) for commercial life-extension missions of (i) Mission Extension Vehicle-1 (44625) with Intelsat 901 (26824) in 2020 [27] and (ii) Mission Extension Vehicle-2 (46113) with Intelsat 10-02 (28358) in 2021 [28].

The DSTG optical observatory permits EO observations to be provided to Orbit Determination processes within the SDA Algorithms function of the RED STAR system. Visual magnitude measurements allow photometric assessments (also known as "light curve" analysis) to determine whether an object has changed its state, including its attitude, or to estimate aspects of an object's characteristics such as its attitude or rotation period. The optical sensors may be tasked as part of research into the management of multiple sensors to achieve SDA operational objectives. Figure 4 shows (i) imagery with detected objects in LEO and GEO, (ii) candidate object observations on an azimuth-elevation polar diagram, (iii) assessment of right ascension and declination observation accuracy against object ephemeris, and (iv) photometric assessment for a single object passing through the sensor field of view.

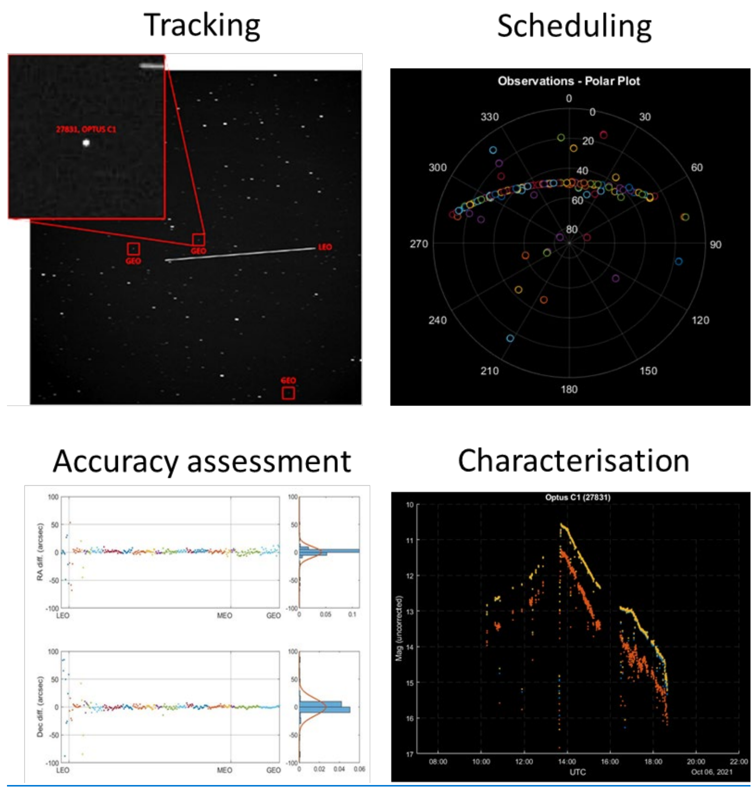

Figure 4. A sample of optical data from the DSTG optical observatory

DSTG research into various types of sensing can be leveraged by the RED STAR system; examples include decametric line-of-sight active radar [15] and passive radar using illuminators of opportunity [16]. Some of these sensor types share features such as (i) the employment of linear receiver antenna arrays which measure a coning angle to the array rather than resolving the received signal into azimuth and elevation angles and (ii) bistatic configurations where the transmitter and the receiver are at different locations. Such features pose challenges for further processing as part of SDA algorithms that perform multi-sensor orbit determination. In a similar manner to optical photometric assessments, the variation in signal strength from radar systems may reveal space object characteristics such as rotation axis and period from an analysis of the Micro-Doppler signature [17].

5. SDA DATA MANAGEMENT AND REPOSITORY

SDA data management is the core RED STAR function that ingests a large set of different data types, including observations from diverse sensors and sources, mean orbital elements in TLE format, state vectors, ephemeris data and conjunction messages. Data feeds the RED STAR ingestion pipeline for storage in the RED STAR: Repository of Space Environment (RED ROSE), for subsequent retrieval as required by other RED STAR functions.

The SDA data management system of RED STAR is known as the Technology Research Environment for Knowledge of space (TREK), which has been developed using cloud native, DevSecOps and modern agile software methodologies. TREK is implemented as a hybrid service-based architecture comprising a mixture of event-based and streaming design patterns. TREK architecture is tailored to meet the need to stream high rates of data from a variety of different sources, including remote platform and repository APIs as well as with sensor systems directly.

Data ingestion and digestion pipelines of TREK provide the basis for integrating a breadth of data sources and data types, whilst also providing the flexibility to rapidly extend into and integrate new data streams. The pipelines ingestion mechanisms are varied and include web APIs and file-based data structures which together are managed as a set of containerised software services enabling scalability and availability. The pipelines are comprised of two key components: ingestors and digestors. The ingestors are responsible for capturing data from external sources. Data items are then pushed onto a data bus such that other event-based services can be notified of new data items. The digestors pull data items from the data bus and are responsible for mapping and writing of data records to the database tables. The data mapping enables the capture and storage of disparate data schemas onto a consolidated database set of tables tailored towards research and development activities. A Push Enqueuer service is responsible for facilitating the transmission of information towards higher classification domains. As all data items are pulled from the data bus by the Push Enqueuer, Transmission Control Protocol (TCP) packets are subsequently reassembled into User Datagram Protocol (UDP) datagrams and streamed in a unidirectional manner to a Push Bridge service on the receiving network. The receiving Push Bridge reassembles all received UDP datagrams into TCP packets and sends these packets to a publishing service for writing into the variety of data type topics that can be consumed by the instance of TREK on the receiving network.

The TREK software is deployed on several Kubernetes clusters which coordinate data flows and workloads across multiple services, all making extensive use of Vert.X. Vert.X is a Java-based event driven application framework for inter-process communication, produced by the Eclipse Foundation, which enables massive parallelism inside each service.

Vert.X allows every service to be made into a pipeline. Pipelined services are made of a series of components that pass on results to the next component via the Vert.X event bus. An example of a pipelined service is the library ingestor service which captures records supplied as a library file (a compressed ZIP file, for instance). Figure 5 shows how the components cooperate for the example of the library ingestor service.

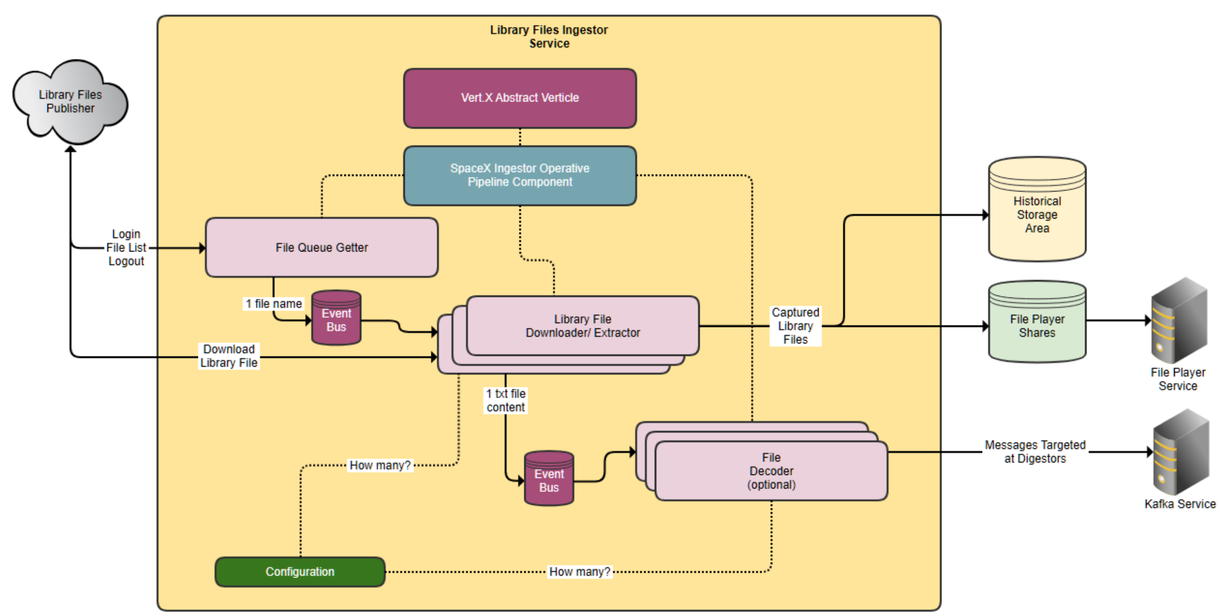

Figure 5. The Library ingestor service is an example of a TREK service

Apache Kafka is used as the messaging publish and subscribe middleware for inter service communications in TREK. The standard configuration of Kafka is implemented ensuring its intrinsic scalability, fault tolerance and resilience is realised. The TREK software runs two Kafka clusters: an internal cluster, which is intended for inter-services messages only, and the external cluster, referred to as Kafka External, to make data available, selectively, to third parties. Processes external to TREK can only see, and interact with, the latter. As background services are written in Java and the user interface is implemented in React related technologies, having data structures that are mutually intelligible by these two layers becomes important. TREK uses OpenAPI to generate structures in a way such that each is produced in the appropriate dialect, while preserving similar meaning across all layers. At the deepest level, the base of TREK service pyramid, are the database support services, currently implemented as a PostgreSQL relational database management system.

Three core tools are available in TREK to enable researchers and other authorised users to access data from RED ROSE: (i) Data Explorer, (ii) Data Extractor and (iii) Data Health.

The Data Explorer tool provides the user with an understanding of the data items associated with specific space objects. Common use cases include exploration of data available for specified objects or identification of gaps in historic database records. Figure 9 shows the Data Explorer User Interface when the user has selected a time duration of one week and a set of objects of interest, which are listed vertically in the main display. A pre-defined list of space objects is also available to users if preferred. For each object, the Data Explorer display indicates the data available and the corresponding times. The availability of ELSETs and state vectors as a function of time is depicted in red and yellow, respectively; additional data types such as sensor observations may be indicated depending on the data available in the repository. In Figure 6 the bottom three rows of the main display indicate relatively frequent updates for the selected GEO satellites during night-time viewing conditions while the upper four rows indicate approximately five updates per day for the selected LEO satellites. As shown in the top right of the menu bar, users can further refine the selection through data source and data point filters, specifying which data types are of interest, and the system mode under which the data was captured. Further options are possible including filtering by specified commercial providers, by ingestion pathways such as UDL or by type such as real vs simulated data. A similar tool to the Data Explorer of TREK has been developed as part of RED STAR for analysis of Event Ledgers, which are a record of products that are associated with a specified event such as an RPO [30]. Event Ledgers are being investigated to achieve integrated space operations through shared SDA that is consistent across multiple international agencies.

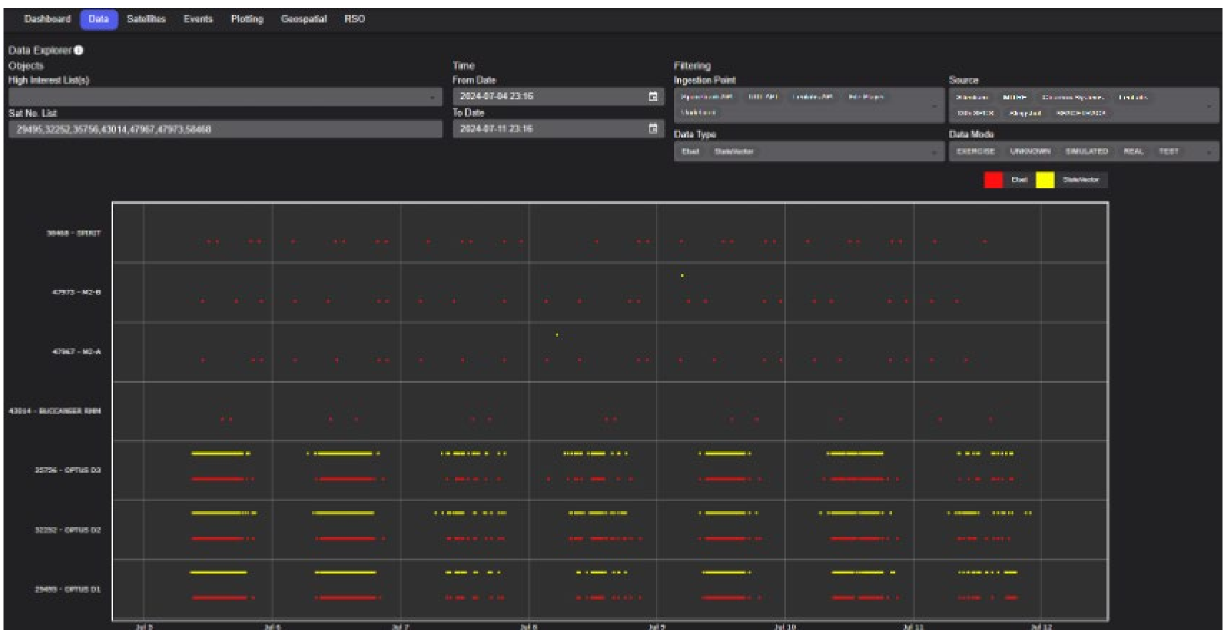

Figure 6. Data Explorer User Interface

The Data Extractor provides the user with a tool to extract specified categories of data. Users select the category of interest and apply Representation State Transfer (REST) conditional query filters relating to the data fields. Common use cases include bulk download of data for offline analysis or applying algorithms to selected data. Figure 7 shows the Data Extractor User Interface where the user has selected the ELSET data in the time range of a week and the space objects corresponding to the Optus D1, D2 and D3 satellites. The user has left the fields list as the default, which shows all available fields for this data. A subset of available fields can be selected as required. Records can be limited to facilitate a rapid response time; the Extractor provides the option to save as a file or to access the data through a URL, as shown in the bottom of the figure. These features provide the ability for both user data extraction and machine to machine data transfer.

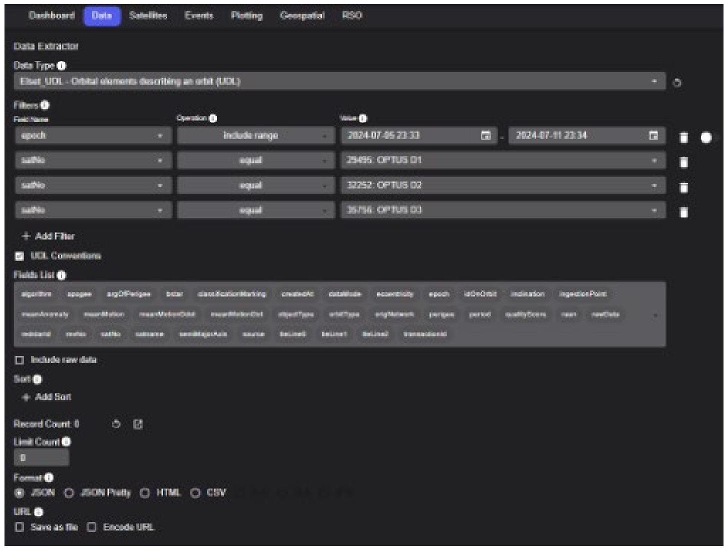

Figure 7. Data Extractor User Interface

The Data Health feature provides the user with a real time picture of data activity and data health, referenced to user determined criteria. Common use cases include the evaluation of data ingestion activity and the investigation of potential data ingestion anomalies. Figure 8 shows a list of data sources, which is defined as a unique combination of ingestion point, data type and location (for sensors); space-track.org and UDL data sources can be seen. The table displays data metrics with the age of the last data item received and a count of the data item received during the preceding 24 hours. Cells are coloured according to the health status, which is determined through criteria defined by authorised users. The orange colour flags the receipt of data from a particular source that fails to meet expected criteria, highlighting the need for further investigation. The table can be set to view each unique data source, or grouped by either ingestion point or data type. A histogram view of the data health is shown on the right side of the figure. For the user selected data source (purple row), data activity over the last 24 hours is presented in ten-minute bins. The histogram indicates low levels of data activity in the past nine hours, with much higher levels of activity prior to that time. Planned developments of the Data Health feature include enhancements to defining health status based on criteria with additional parameters.

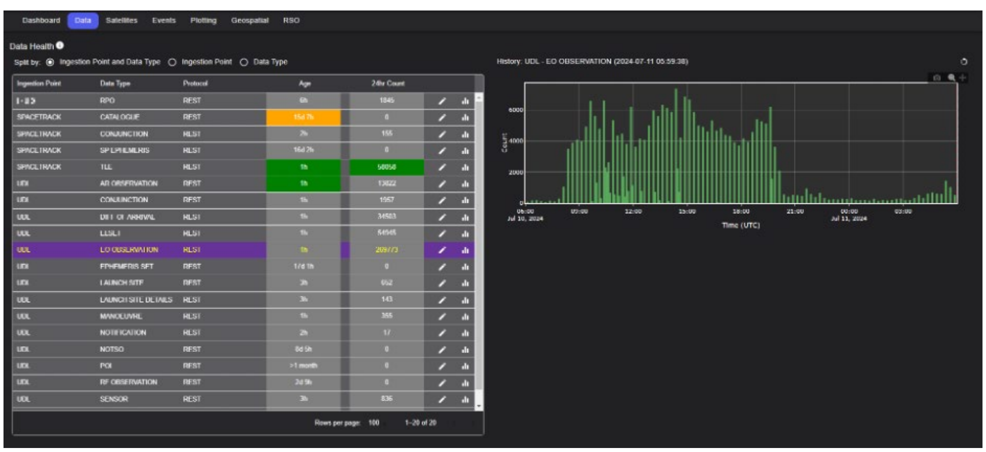

Figure 8. Data Health User Interface

One of the key challenges addressed by TREK is data access management across different user groups, use cases and accessibility groups that arise from the different data licencing arrangements. To facilitate open and collaborative use of data across the RED STAR program, a data access management approach focussing on role-based access control and record level filtering and tagging has been implemented. Each data source that is ingested into RED ROSE is associated with a data access item based on an assessment of the data source and pipeline. This enables data access to be managed based on the account's user organisation and use cases.

6. SDA DATA CURATION

As discussed in the previous section, RED STAR ingests data from many sources, ranging from UDL data in a uniform format, to individual sensors with novel observation phenomenologies and unique data formats. In RED STAR the data curation process provides two main benefits [11, 19]:

1. Building and maintaining trust in the data from each provider and sensor, and
2. Normalising the data into a common, standardised form.

Each of these is critical to ensuring that RED STAR can reliably generate products with consistent quality.

DSTG does not control the calibration or maintenance for most sensors or data sources, and the variety of RED STAR data sources introduces a variety of different data formats. The first step in data curation is an on-boarding step that compares data from a new source with ground-truth ephemeris data[ii]. This ensures that the data is being interpreted correctly and that the observations align with the expected observations as predicted from the ground-truth. It additionally ensures that all the required meta-data (such as sensor location or measurement noise standard deviation) is either collected from external sources or deduced from the observations themselves. For example, each UDL provider supplies observation data in a consistent format, but the data may need to be interpreted differently depending on the provider. Aspects such as the following need to be understood for each provider:

- Compensation for light aberration
- Reported timestamp to account for light transit time
- Provision of a track ID

The result of the on-boarding step is a set of rules for how to interpret the data from each provider (or sensor). These rules can change over time as the data providers refine their processes.

Once rules are available for a source, the data curation process can normalise the data into a consistent format that can be interpreted in a consistent way, with consistent supporting metadata. We currently use an "opinionated" subset of the UDL data format for state vectors and different observation types. Derived products, such as those generated by the Data Extractor from the previous section, but especially the SDA Algorithms of the Orbit Determination system, benefit from this consistency. Normalising data as a separate step before orbit determination allows the OD process to concentrate on the complexity of the OD algorithm without the overhead of interpreting each individual source of data.

The on-boarding process, and the rules that are generated for a particular data source, provide a level of trust in the data that has been supplied. Data curation is an ongoing process that ensures that any new data is consistent with the appropriate rules. This is achieved by monitoring both the data format (e.g. are the same fields present in the data) and accuracy, by comparison with ground-truth sources (i.e. is the error standard deviation as expected). A data source that does not comply with the expected rules can be flagged to an operator and the source prevented from being used in downstream products until the reason is better understood. In this way, data curation allows RED STAR to maintain its trust in each of the data sources and maintain a consistent quality in the generated products.

7. SDA ALGORITHMS FOR STATE ESTIMATION OF SPACE OBJECTS

The RED STAR system includes SDA Algorithms for estimating the state of space objects from a multitude of diverse and distributed sensors. Initial Orbit Determination (IOD) algorithms are used to estimate an initial state for a space object when there is no prior estimate (or when there has been a significant change to the state). Orbit Determination (OD) algorithms are used to update the estimated state for a space object with new observations.

Ideally, SDA Operations are based on estimates for the state of space objects using observations from multiple sensors that are of diverse type and geographically dispersed. The SDA Algorithms of RED STAR serve as experimental capabilities for performing multi-sensor state estimation of space objects. An orbital state estimate can be represented

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[ii] RED STAR uses a combination of ephemeris data for ground-truth from the Global Navigation Satellite System (GNSS) in Standard Product #3 (SP3) format or the International Laser Ranging Service (ILRS) in Consolidated Prediction Format (CPF). Future work will leverage the fused product of trusted sensors as an additional source of reliable orbit information [18].

by a multivariate Probability Density Function (PDF). For a normal, or Gaussian, distribution the PDF is completely described by a mean vector and covariance matrix.

The RED STAR algorithms for state estimation of space objects accept normalised sensor observations from the Data Curation function. Figure 9 shows a flow diagram for the treatment of sensor observations with various processes that implement IOD and OD. Processes that have been implemented are outlined with solid lines while processes that are planned to be implemented are outlined with dashed lines. Sensor observations that are grouped for a single object but are not deemed to be associated with a catalogued object are fed to IOD processes to initialise an orbit. Sensor observations that are deemed to be associated with a catalogued object are fed to OD processes to refine orbital state estimates.

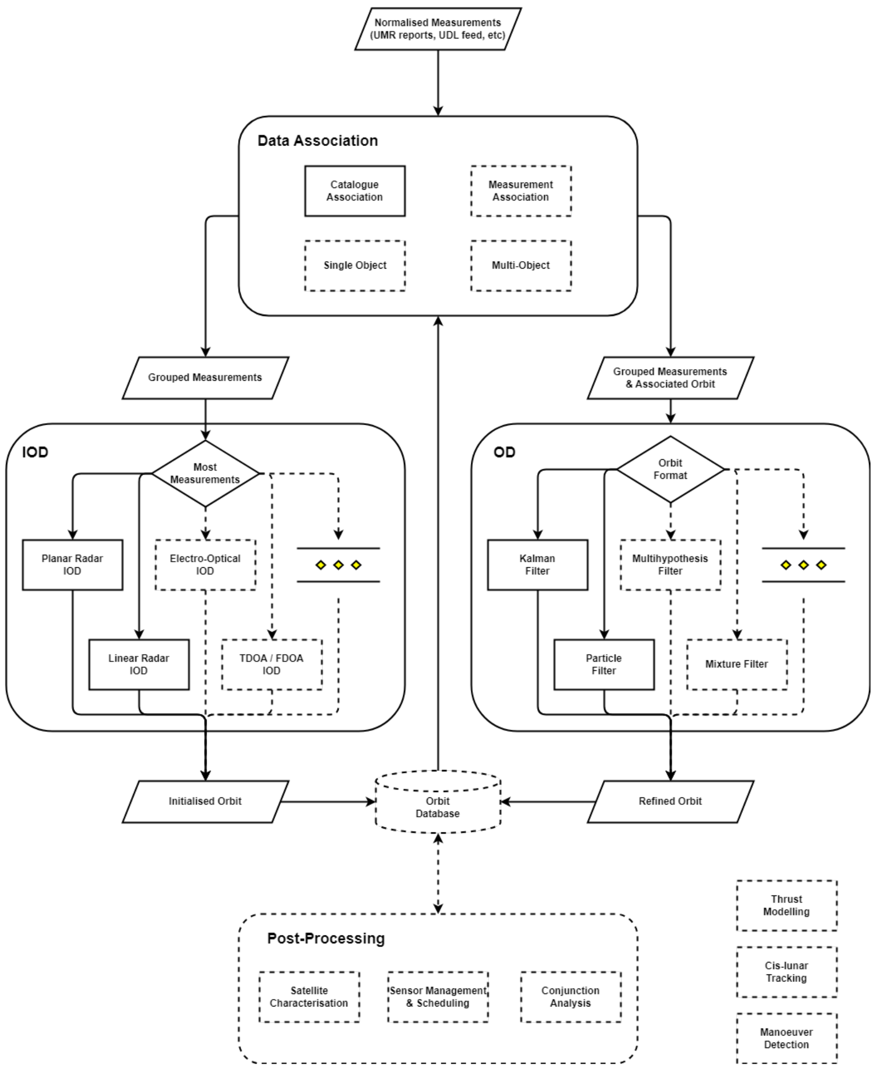

Figure 9. Flow diagram for RED STAR processing of sensor observations to perform IOD and OD

To demonstrate a specific example of the processing flow outlined in Figure 9, real observations from DSTG's decametric line-of-sight radar were collected whilst the array was in a linear configuration. This configuration geometry provides only a single angle that combines azimuth and elevation, called the coning angle. Additionally, the transmitter and receiver arrays were separated by about 2 km, providing pseudo-bistatic observations. Raw observations from a single space object were collected from the sensor using a simple measurement-level tracking algorithm and then pre-processed to decouple range from Doppler and resolve any range-rate ambiguities, as shown in Figure 10.

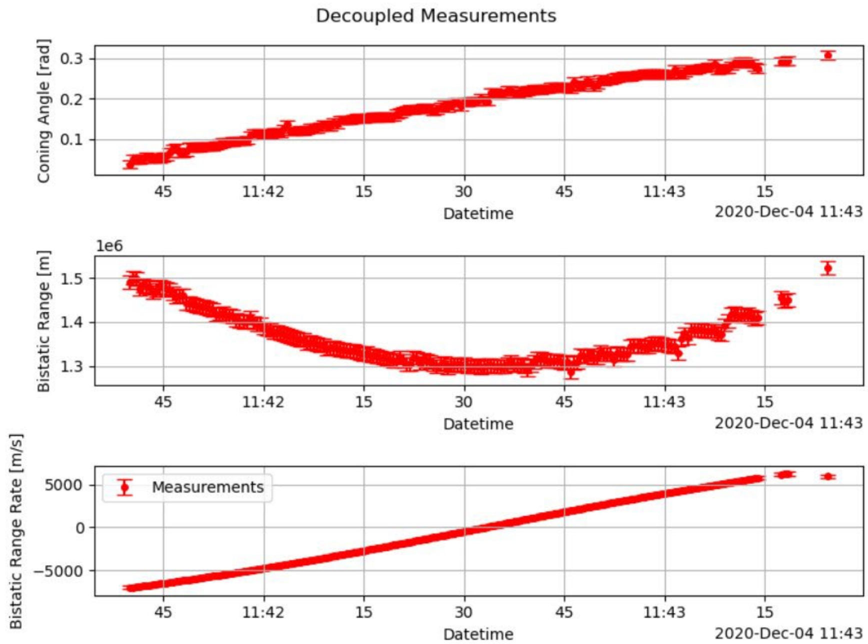

Figure 10. Pre-processed sensor observations of a single space object obtained from a linear array configuration of the DSTG decametric line-of-sight active radar

The Linear Radar IOD method expects a single radar observation with three components of coning angle, (bistatic) range, and (bistatic) range rate. A particle distribution of 10,000 samples was formed within the observation's estimated PDF, capturing the characteristic cone of a linear array. Assuming that the space object is above the top of Earth's atmosphere (~100km) and is in a low eccentricity orbit (unlikely to be >0.1), the particle distribution is further constrained. The two left plots within Figure 11 show the 3D position and velocity particle distributions using only the first observation of the linear radar. This technique is commonly referred to as a Constrained Admissible Region (CAR) approach [20]. These initial particles can be iteratively refined with all subsequent observations using an OD method called a Particle Filter [21]. The right plot within Figure 14 shows the evolution of the orbit solution space as more observations are included into the orbit estimate. Once the orbit state estimate converges with more observational data, the state can be converted from a particle-based representation to Gaussian-based for computational efficiency.

Many SDA activities, such as data association, collision probability assessment, conjunction assessment and sensor tasking, require appropriate estimation and propagation of a space object's state and associated uncertainty. If the uncertainty estimation and propagation involve unrealistic assumptions, then the distribution of possible object states may be unrealistic leading to either underestimation or overestimation of the uncertainty which may lead to inappropriate decisions. For example, overestimating the uncertainty may result in a high collision probability value and consequently scheduling an unnecessary collision avoidance manoeuvre with the consumption of propellant that may decrease the mission life of a satellite. Underestimating the uncertainty may result in a low collision probability exposing a pair of satellites to a risk of collision.

As part of the RED STAR research into SDA Algorithms, the uncertainty of a space object is characterised by developing an understanding of how various perturbation forces affect the PDF for a space object and comparing various uncertainty propagation techniques. Simulations were performed to understand the effect of various perturbation forces on the PDF. First, the PDF propagation was examined under the gravitational force of a point mass in a circular orbit (zero eccentricity). In this propagation, the uncertainty distribution expands along track, however, there is no change in either radial or cross track directions. Next, the PDF was propagated under various applicable forces in low earth orbit such as J2 (oblate Earth) perturbation, atmospheric drag, third body motion, and relativity in a circular orbit. In this propagation, the uncertainty distribution expands along track, radially, and in the cross-track direction. However, the cross-track expansion is very small.

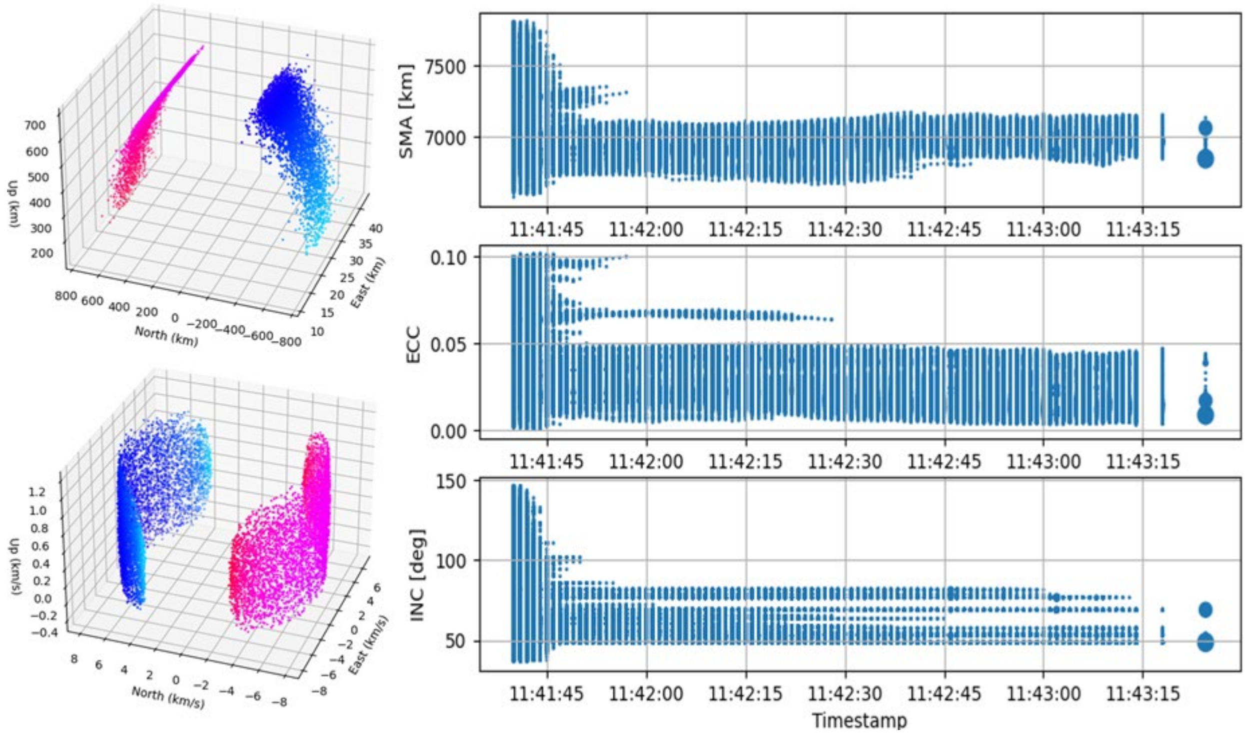

Figure 11. Left: Particle-based PDF using a single observation of a space object from a linear array radar. Right: Evolution of the PDF with the inclusion of more observations using a Particle Filter.

Figure 12 shows the evolution of a particle-based PDF under various applicable forces acting on a single space object. The left plot shows a single PDF with the particles in the same colour at the same percentile from the mean position. The right plot shows multiple PDFs corresponding to different times during the orbit. Here, the uncertainty distributions are magnified by a hundred times with respect to the orbit to display the changes in the shapes clearly. In this propagation, the uncertainty distribution expands in the In-track, Radial and in the Cross-track direction. Contrary to general assumptions, the curve of the uncertainty distribution is not always in the In-track direction of the orbit. It varies from In-track direction to the Cross-track direction and even opposite to the In-track direction according to the position of the space object in the orbit.

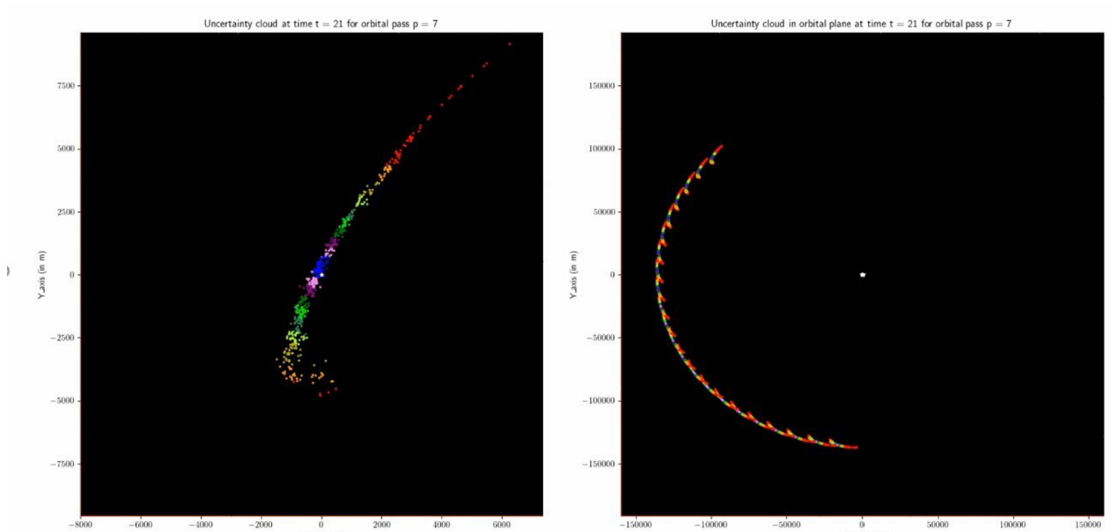

Figure 12. Uncertainty distribution propagation under multiple perturbation forces in an elliptical orbit

The particle filter method can estimate the propagated uncertainty accurately; however, it is computationally expensive. When many space object estimates and uncertainties need to be propagated, such computationally expensive methods are less practical. Therefore, a method to propagate space object states is required with low computational expense. While understanding the impact of various perturbation forces, preliminary investigations reveal that the J2 perturbation is the dominating force for space objects in the LEO regime. Since the J2 perturbation can preserve the characteristics of the PDF distribution qualitatively, a multi-fidelity model for the uncertainty propagation is being considered for efficient processing while retaining accuracy [22].

In addition to processing data from externally managed sensors, a sensor management function allows the ongoing sensing process to be improved. For a network of terrestrial and non-terrestrial sensors, SDA sensor management involves the optimal use of sensor resources to monitor and analyse space objects and their activities [21]. SDA sensing data are needed to perform various SDA activities such as tracking and surveillance, collision avoidance, object identification and characterisation, manoeuvre detection, tracking launches and observing space operations. The number of space objects is ever increasing, and the space environment is dynamically changing with growing risk of conjunctions. Planning and decision-making techniques are required to effectively manage the limited sensor resources. As part of the RED STAR effort, SDA algorithms for sensor management are being developed which seek to achieve SDA mission objectives while accounting for the various characteristics of the available sensor resources.

8. SDA MODELLING, SIMULATION AND ANALYSIS

Modelling and simulation activities augment real-world activities to inform and shape Australia's SDA operational systems. Various aspects of RED STAR can be developed, evaluated and implemented under conditions that are controlled through modelling and simulation with different levels of model fidelity. SDA Algorithms for orbit determination can be developed by simulations of space object ephemerides and of data from SDA Sensing capabilities. Candidate SDA architectures, comprising simulations of multiple geographically dispersed SDA sensors observing space objects, can be evaluated. Simulations of space scenarios during exercises can be implemented to train and test SDA capabilities including human and system responses. Analysis of data from both real-world activities and from modelling and simulation activities is required to derive scientific and technical information.

Simulations for multi-sensor Orbit Determination algorithm development enable the performance of OD algorithms to be considered for a wide set of conditions including different orbit regimes, space object manoeuvres and sensor characteristics such as sensor field of view, detection probability of the sensor and sensor noise parameters.

SDA Architecture Performance Analysis (SAPA) is an analysis tool developed with Matlab & STK to aid in understanding the virtual performance of a given SDA architecture (network of SDA sensors). A simplified workflow of SAPA is provided in Figure 16. Firstly, a list of objects of interest (e.g. TLE catalogue) and a set of SDA sensor specifications are used as inputs to compute the access opportunities between all SDA sensors and all objects over the duration of a scenario. The quality of every access opportunity is then estimated, before generating a global sensor schedule and computing metrics to quantify the performance of the sensor schedule. An example scenario consisting of several ground-based radars and telescopes modelled in SAPA is shown in Figure 14.

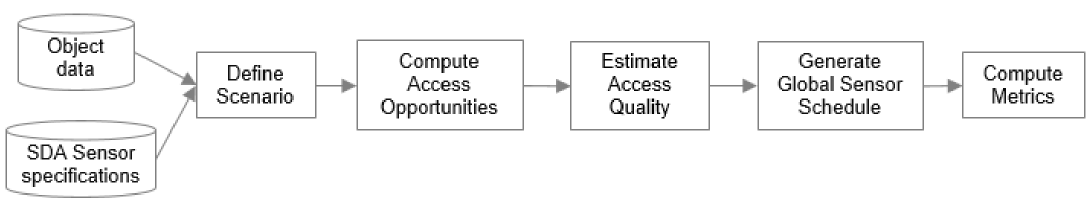

Figure 13. Workflow for the SDA Architecture Performance Analysis

A variety of analysis challenges related to the design and operation of SDA architectures are being considered by DSTG. SAPA is used to:

- Establish the baseline performance of existing SDA architectures;
- Investigate the contributions of new/proposed SDA sensors and data feeds;
- Optimise selection of SDA sensor type and location;
- Analyse resilience of an SDA architecture due to loss of SDA sensors and data feeds; and
- Investigate multi-sensor tasking and scheduling strategies.

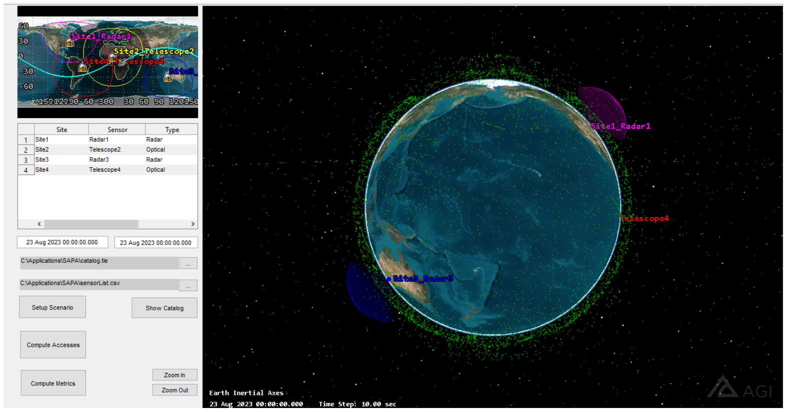

Figure 14. Example scenario of a set of SDA sensors that are deployed to monitor space objects

The modelling and simulation capabilities of RED STAR have been used to simulate launch, in orbit and re-entry phases of space operations during the international exercises with simulated and real-world live events known as the Sprint Advanced Concept Training (SACT) [11, 20]. Examples of space scenarios that have been simulated during SACT exercises are[iii]:

- Launch and payload deployments
- Direct Ascent Anti-Satellite (DA-ASAT), collision and breakup
- Co-orbital chasers performing close approaches
- Station keeping in LEO and GEO
- Satellite grappling
- Rendezvous and Proximity Operations (RPO)
- Satellite re-entries and Tracking and Impact Prediction (TIP) messages

Figure 15 shows an example scenario of a simulation-over-live event implemented during a SACT exercise. During the exercise the real-world Carbonite 2 (43115) satellite was considered a high value asset. A simulated trajectory for a chaser satellite was designed with a ground launch into an entry orbit (shown in magenta colour) followed by a transition to a spiral motion (green) about the Carbonite 2 satellite (cyan). Observation data from simulated sensors were published to the DRAGON Army exercise repository known as Trogdor or to the UDL, as required. The simulated observation data was available for processing and analysis by space operators.

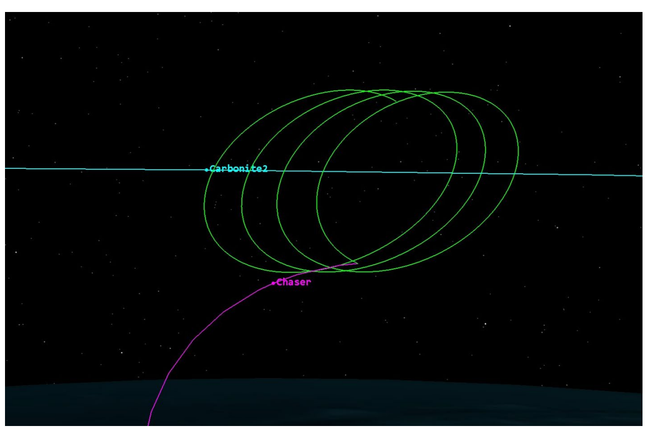

Figure 15. A sim-over-live scenario generated using the SDA Modelling and Simulation functions of RED STAR. A simulated chaser satellite conducts a spiral slow pass of the real-world live SSTL satellite, Carbonite 2

[iii] DSTG gratefully acknowledges that its participation in the role of White Cell exercise control during SACT exercises was assisted by US partners including US Joint Commercial Operations (JCO), US Air Force Research Laboratory (AFRL) DRAGON Army, BlueStaq and ai-solutions.

In addition to simulating the generation of sensor observations, DSTG has simulated Non-Earth Imaging (NEI) by modelling the characteristics of space-borne optical sensors to generate imagery of another satellite as shown in Figure 16. The trajectories, satellite attitudes and other details were defined using the Analytical Graphics, Inc. (AGI) Systems Tool Kit (STK) and the NEI satellite was simulated to perform a Natural Motion Circumnavigation (NMC) manoeuvre around the target satellite. The Electro-Optical Infra-Red (EOIR) package of STK was implemented to generate a set of simulated NEI products, for SDA space analysts to process.

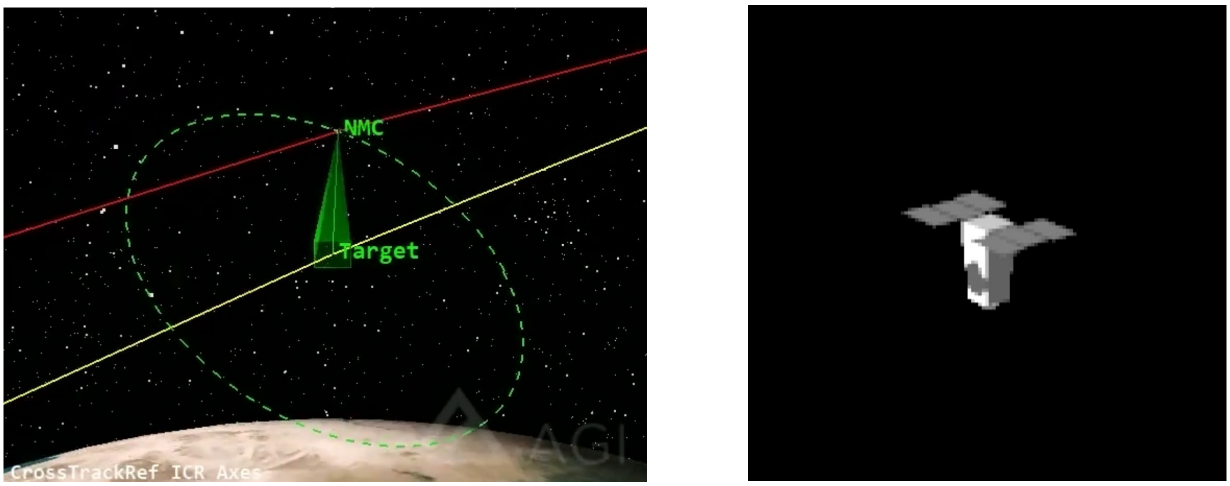

Figure 16. Simulation of a NEI satellite conducting a NMC manoeuvre around a target satellite (left) and a simulated NEI image of a target satellite (right)

Several prototype tools have been developed within RED STAR to aid in the analysis of SDA events. These tools perform functions such as: light curve analysis, spin rate analysis, and analysis of Rendezvous and Proximity Operations (RPO).

The RPO Analysis Tool of RED STAR ingests TLE data and performs two main processes:

1. Screening of orbits to determine candidate pairs of space objects that may be conducting RPO
2. Analysis and visualisation of a specified pair of space objects that may be conducting RPO

Criteria for an RPO are specified in the RPO Analysis Tool by defining parameters for an RPO expressed by the physical proximity, relative velocity and duration. Figure 17 shows an example output of the screening process using the RPO Analysis Tool where pairs of satellites have been identified that satisfy the RPO criteria.

	ID1	ID2	Name1	Name2	Range	Speed	Start	Stop	Duration	Country1	Country2	Type1	Type2	Size1	Size2	Launch1	Launch2	Perigee	Apogee	Period	Inclin.	Age1	Age2
1	35756	40146	OPTUS D3	OPTUS 10	9.38	0.28	2024-06-30 08:40	2024-07-04 08:40	4.007	AUS	AUS	PAYLOAD	PAYLOAD	LARGE	LARGE	2009-08-21	2014-09-11	35,772	35,801	0.997	0.04	0.51	0.38
2	56227	56977	SKYKRAFT-3B	LEMUR 2 AADAM-ALIYAH	16.2	2.35	2024-07-01 17:30	2024-07-01 19:50	0.056	AUS	US	PAYLOAD	PAYLOAD	MEDIUM	MEDIUM	2023-06-12	2023-06-12	457	465	0.065	97.54	0.12	0.51
3	55061	55034	SKYKRAFT-1C	LYNK TOWER 4	23.24	9.23	2024-07-02 19:00	2024-07-02 19:50	0.021	AUS	US	PAYLOAD	PAYLOAD	MEDIUM	MEDIUM	2023-01-03	2023-01-03	505	524	0.066	97.42	0.48	0.15
4	57956	56955	SKYKRAFT-3D	BLACKJACK ACES-2	50.89	19.21	2024-06-30 21:50	2024-06-30 21:50	0.007	AUS	US	PAYLOAD	PAYLOAD	MEDIUM	LARGE	2023-06-12	2023-06-12	495	507	0.066	97.54	0.51	0.45
5	55052	55026	SKYKRAFT-1D	FLOCK 4Y 19	61.16	3.28	2024-07-02 11:10	2024-07-02 11:10	0.007	AUS	US	PAYLOAD	PAYLOAD	MEDIUM	SMALL	2023-01-03	2023-01-03	468	484	0.065	97.42	0.24	0.43
6	57956	56226	SKYKRAFT-3D	OUTPOST MISSION 1	63.46	14.82	2024-07-04 08:00	2024-07-04 08:00	0.007	AUS	US	PAYLOAD	PAYLOAD	MEDIUM	SMALL	2023-06-12	2023-06-12	495	507	0.066	97.54	0.51	0.51
7	56229	56961	SKYKRAFT-3	ICEYE-X26	68.81	9.9	2024-07-01 01:30	2024-07-01 02:20	0.014	AUS	US	PAYLOAD	PAYLOAD	MEDIUM	MEDIUM	2023-06-12	2023-06-12	490	502	0.066	97.54	0.13	0.46
8	55052	55079	SKYKRAFT-1D	FLOCK 4Y 13	86.09	15.64	2024-07-02 19:50	2024-07-02 19:50	0.007	AUS	US	PAYLOAD	PAYLOAD	MEDIUM	MEDIUM	2023-01-03	2023-01-03	468	484	0.065	97.42	0.24	0.56
9	55052	55074	SKYKRAFT-1D	FLOCK 4Y 2	88.42	14.45	2024-07-03 02:50	2024-07-03 03:40	0.014	AUS	US	PAYLOAD	PAYLOAD	MEDIUM	MEDIUM	2023-01-03	2023-01-03	468	484	0.065	97.42	0.24	0.56

Figure 17. Pairs of satellites that have been screened and identified as RPO candidates using the RPO Analysis Tool

Figure 18 shows detailed analysis of the RPO between two satellites UNSW M2-A (47967) and M2-B (47973), flying in close formation using differential aerodynamic drag control [25]. The user selects a time window for a specific close pass. Time series plots on the left show data for the orbital element sets (ELSETS) with circles indicating time when ELSETS have been updated. Other time series plots show the relative position and visibility. A 3D plot on the right shows a Radial In-track Cross-track (RIC) plot which is coloured according to the time. A space shuttle graphic is used in the top right to depict the view angle of the primary satellite from the secondary satellite and the effects of solar illumination and Earth shadow.

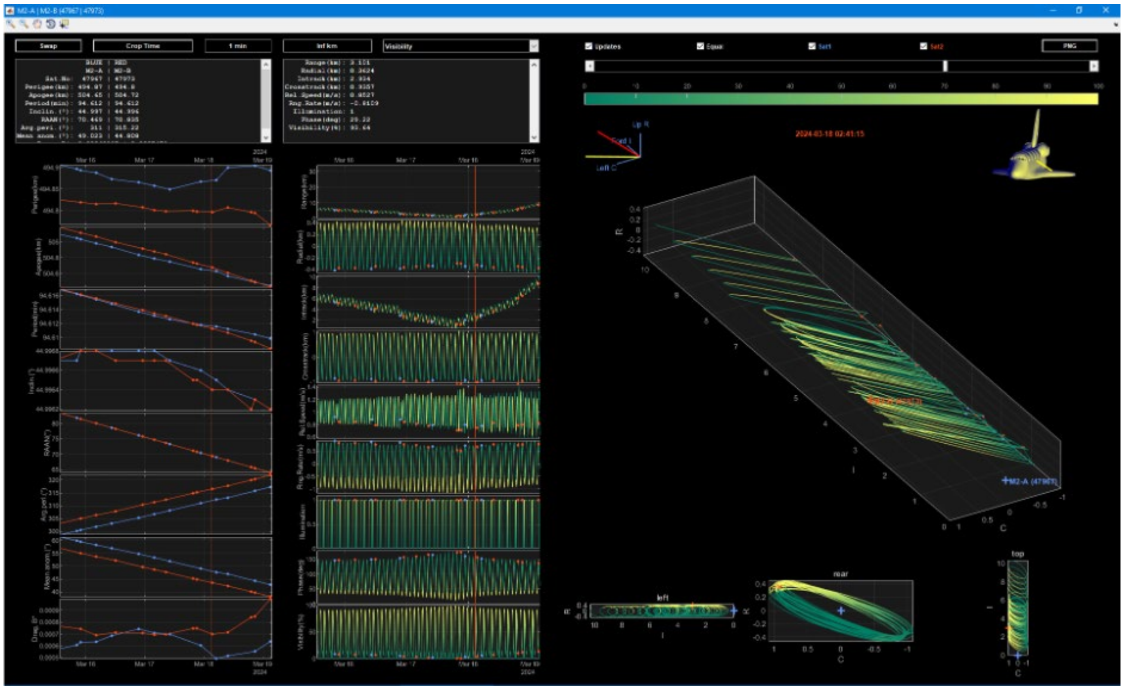

Figure 18. RPO Analysis Tool showing an RPO between M2-A (47967) and M2-B (47973)

9. SDA INTELLIGENCE ANALYTICS

The RED STAR SDA Intelligence Analytics effort focusses on the SDA aspects of identification, classification and characterisation and on the activities of space entities. Here, the term "space entities" includes space objects such as active and inactive satellites, and space debris in addition to terrestrial infrastructure such as ground stations and launch sites.

Information about space entities can be gleaned through SDA sensing in addition to a diverse set of multimedia sources such as from public and government information, including:

- Rich Text File documents: Reports, news articles, spreadsheets
- Imagery: Earth Imagery, Non-Earth Imagery [30]
- Models: Design diagrams, charts
- Video: Launch videos, simulation videos
- Audio: Pronunciation guides, presentations

The Space Information Integration and Fusion Experimentation (SPINIFEX) program within the RED STAR system aims to inform and shape SDA Intelligence Analytics capabilities for the operational community. Initial efforts for SPINIFEX consider how to (i) capture, (ii) store and (iii) communicate information about space entities.

The diversity of multimedia sources requires a flexible storage approach for data and information to be accessed and updated with fused products. Typical products include information reports, while new SPINIFEX products are being investigated such as annotated 3D satellite models. Such 3D models can inherently capture information such as size, shape, configuration, materials and attitude and can exploit the rich visualisation and processing of 3D models that is available in the gaming community. The 3D models may be used to perform modelling and simulation of signatures from SDA sensing systems to infer characteristics of space objects [20, 33].

Figure 19 shows the SPINIFEX concept of a Space Entity Dossier with a diverse set of multimedia sources providing information about the Hubble Space Telescope. The representation, fusion and visualisation of space object information are the focus of ongoing research.

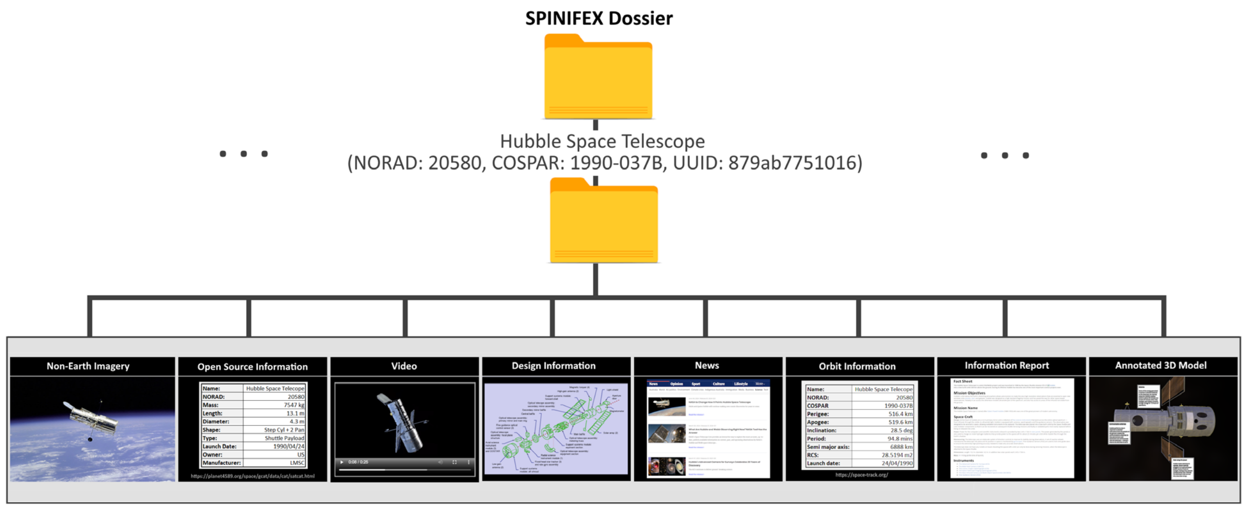

Figure 19. SPINIFEX concept of a Space Entity Dossier with multiple sources of information for the Hubble Space Telescope

10. CONCLUSION

Australia has played a vital role in space tracking owing to its geographical, political and environmental conditions.

Development of operational capabilities for SDA is informed and shaped by DSTG's experimental SDA system, RED STAR. DSTG's research and development activities continue into the various functions of SDA including (i) sensing, (ii) data curation, (iii) data management, (iv) repositories for data storage and retrieval, (v) algorithms for data processing, (vi) modelling, simulation and analysis and (vii) space intelligence analytics. RED STAR capabilities will continue to be prioritised according to the needs of current, planned and future SDA operations.

Ongoing development effort for RED STAR will expand the scope to address the response aspects of RED STAR, including sensor management and other response options. Further work is planned to process multiple types of sensor data for multiple space objects and to evaluate performance. Management of sensors according to specified operational criteria enables limited sensing resources to be applied for effective SDA operations. Effort is underway to perform space entity manoeuvre detection and estimation in order to highlight events of interest to SDA operators. Tools for inferring space entity activities will continue to be developed by applying Machine Learning and other approaches to the diverse data and information stored in RED ROSE.

11. ACKNOWLEDGEMENT

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12. REFERENCES

1. D. Hamacher, The First Astronomers, How Indigenous Elders read the stars, Allen & Unwin, 2022.
2. K. Noon, K. De Napoli, Astronomy, Sky Country, Thames and Hudson Australia, 2022.
3. -, Russians say rocket circling also, The Canberra Times, 7 October 1957
4. -, Sputnik sends stronger code signals, The Canberra Times, 14 October 1957
5. K. Dougherty, Australia in Space: A History of a Nation's Involvement, ATF Press, 2017
6. P. Morton, Fire across the Desert, Woomera and the Anglo-Australian Joint Project 1946-1980, Defence Science and Technology, 2017
7. -, Australia's Space Surveillance Radar reaches Full Operational Capability, Defence Media release, 7 March 2017
8. -, Space surveillance telescope is declared operational, Defence Media release, 30 September 2022

9. -, New Defence space capability boosts regional security, Defence Media release, 2 December 2023
10. -, Following the sun for space domain awareness, https://www.defence.gov.au/news-events/news/2023-09-01/following-sun-space-domain-awareness,1 September 2023
11. J.D. Gerber, Y. Picard, M. Brown, J. Held, F. Pelletier, T. Fuller, Sprint Advanced Concept Training (SACT): A renaissance in collaborative international space operations, AMOS 2020.
12. M. Hollick, D. Lingard, N. Stevens, C. Peck, P. Alvino, H. Duong, G. Hu, C. van Antwerpen, Buccaneer risk mitigation mission operations – lessons learnt, 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October, 2018
13. F. Agenbag, P.S. Alvino, D.C. Bandara, H.E. Bennett, M. Hollick, A.M. James, J. Kaduparambil-Jose, D.M. Lingard, F. Lorenzin, B. Lucas, A. Mckinnon, J.D. Nelson, C.V. Peck, C. Raddock, A. Raj, P.C.L. Stephenson, A. Strachan, T. Teske, P. Thornton, Deployable optics for the Buccaneer Main Mission (BMM), *Aeronautical Journal*, 127, pp. 2068-2081, 2023
14. G. Newsam, N. Gordon, An Update on SSA in Australia, AMOS 2011.
15. -, Commercial space operations technologies tested in real-world environment, https://www.space.gov.au/news-and-media/commercial-space-operations-technologies-tested-real-world-environment, 26 July 2023, (accessed 29 July 2024)
16. T.A. Hobson, I.V.L. Clarkson, T. Bessell, M. Rutten, N. Gordon, N. Moretti, B. Morreale, Catalogue Creation for Space Situational Awareness with Optical Sensors, AMOS 2016
17. D. Lang, D.W. Hogg, K. Mierle, M. Blanton and S. Roweis, Astrometry.net: Blind astrometric calibration of arbitrary astronomical images, *Astronomical Journal* 137, 1782-1800, 2010.
18. G. Frazer, M. Rutten, B. Cheung and M. Cervera, Orbit Determination using a Decametric Line-of-sight Radar, AMOS 2013
19. B. Hennessy, D. Gustainis, N. Misaghi, R. Young, B. Somers, Deployable Long Range Passive Radar for Space Surveillance. IEEE Radar Conference, March 2022
20. E. Heading, S.T. Nguyen, D. Holdsworth, I.M. Reid, Micro-Doppler Signature Analysis for Space Domain Awareness using VHF Radar, *Remote Sens*., 16(8), 1354, 2024
21. T. Kelecy, E. Lambert, B. Sunderland, V. Desai. Dynamic Calibration of Multiple Data Types, AMOS 2019.
22. A. Antón, J.M. Lozano, K. McNally, S. Hannon, Data curation activities for Space Surveillance and Tracking, AMOS 2023.
23. J. Stauch, T. Bessell, M. Rutten, J. Baldwin, M. Jah and K. Hill, Joint Probabilistic Data Association and Smoothing Applied to Multiple Space Object Tracking, *Journal of Guidance, Control and Dynamics*, Vol 41, January 2018
24. B. Ristic, S. Arulampalam, and N. Gordon, Beyond the Kalman Filter: Particle Filters for Tracking Applications, Artech House, 2004
25. B. Jones, R. Weisman, Multi-fidelity orbit uncertainty propagation, *Acta Astronautica*, Vol. 155, pp 406-417, February 2019
26. R.P. Patel, V.V. Sheffey, J.D. Gerber, R. Burfield, R. Waterer, J. Tippets, D. Stout, E. Bohner, Defense Readiness Agile Gaming Ops Networks (DRAGON) Army, AMOS 2022
27. N. Moretti, M. Rutten, T. Bessell, Space Situational Awareness Sensor Tasking: A Comparison between step-scan tasking and dynamic, real-time tasking, International Conference on Information Fusion, 2018.
28. S. George, A. Ash, T. Bessell, J. Frith, L. Scott, J. Skuljan, R. Furfaro, V. Reddy, PHANTOM ECHOES: A Five-Eyes SDA Experiment to Examine GEO Rendezvous and Proximity Operations, AMOS 2020.
29. S. George, A. Agathanggelou, Grant Privett, P. Halpin, W. Feline, A. Ash, P. Chote, L. Scott, J. Skuljan, J. Alvino, J. Frith, PHANTOM ECHOES 2: A Five-Eyes SDA Experiment on GEO Proximity Operations, AMOS 2021.
30. M. Brown, R. Boyce, E. Peters, S. Gehly, S. Boland, R. Jeffreson, A. Kremor, T. Bateman, C. Capon, B. Smith, G. Bowden, L. Glina, LL Qiao, S. Balage, K. Gupta, R. Purwanto, T. Bessell, T. Reddell, J. Bennett, M. Lachut, T. McLaughlin, A. Lambert, Formation Flying and Change Detection for the UNSW Canberra Space 'M2' Low Earth Orbit Formation Flying CubeSat Mission, AMOS 2022.
31. J. Gerber, G. Badura, J. Bell, K. White, Joint Commercial Operations (JCO) – Integrated Space Operations with Event Ledgers, draft, AMOS 2024.
32. P. Loch, A. Marcireau, S. Kirkwood, G. Cohen, H. Jayakody, W. Crowe, S. Law, V. Pascente, G. Withey, P. Karki, Vantage Point: Lessons from doing coordinated space imaging, AMOS 2023.
33. M. Brown, B. Smith, C. Capon, R. Abay, M.C. Polo, S. Gehly, G. Bowden, C. Bright, A. Lambert, R. Boyce, SSA Experiments for the Australian M2 Formation Flying CubeSat Mission, AMOS 2020.