Joint Commercial Operations (JCO) – Integrated Space Operations with Event Ledgers

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ABSTRACT SUMMARY

The Joint Commercial Operations (JCO) and Combined Space Operations (CSpO) Architecture Working Group (CAWG) teams conducted a series of collaborative experiments to explore techniques in distributed space operations utilizing an innovative new service known as '*Space Operations Event Ledgers*'. Event Ledgers are data structures representing all objects in a specified scenario. Event Ledgers enable the rapid distribution of these scenarios to multiple space operations cells and applications. The objective of the experiment was to demonstrate that distributed space operations could be conducted between geographically and programmatically disparate groups, each utilizing their own sovereign tools and across multiple classification levels. The need for this capability was identified by the CAWG, which recognized that one of the critical deficiencies in effective multi-national space operations centers (SpOC) collaboration was the lack of a unified machine-to-machine (M2M) transfer protocol. Many SpOC have no effective method for electronically communicating on-going real world space operations. For example, if there was an active space threat such as an adversary performing one of the following: direct ascent anti-satellite, rendezvous and proximity operation (RPO), or conjunction, how would these be rapidly disseminated? The core issue was "how would sovereign space operations centers in distinct international SpOC (separated by both geography and classification levels) integrate to *exchange common situational awareness at combat operations cadence*?" The JCO worked in collaboration with the Air Force Research Lab (AFRL) Dragon Army software development team to design and implement a data structure that met these criteria and deployed within the Unified Data Library (UDL). The team embedded it within the JCO/Dragon Army Mission Management Board (MMB) and Synchronization Services (SS) framework. The CSpO CAWG team nominated several candidate vignettes of varying complexity that would demonstrate the utility of the new service. The vignettes proposed included 'New Foreign Launch (NFL) to Geostationary Earth Orbit (GEO) RPO', 'Low Earth Orbit (LEO) Launch to RPO', 'Satellite Re-entry', and multiple 'Resident Space Object (RSO) Uncorrelated Track (UCT)' notifications. The JCO and CAWG then coordinated with the international Sprint Advanced Concept Training (SACT) experiment series to coalesce a diverse set of international stakeholders to prove the efficacy of the new Space Operations Event Ledger concept. The initiative received broad support from government, commercial, and academic institutions within the SACT community. Significant participation included the Australian Defence Science and Technology (DSTG) Research and Development Space Target Awareness and Response (RED STAR) program, Australian and US divisions of Saber Astronautics, Georgia Tech Research Institute (GTRI), French commercial company Exotrail, US Exoanalytic (through an initiative with the Defense Innovations Unit (DIU)), Lockheed Martin Australia, and the Canadian company Northstar. The SACT experiments were conducted throughout the week of 12-16 November 2023. The various candidate space operations events were designed by the AFRL Dragon Army using modeling and simulation (M&S) and published in real-time through the UDL. Via the MMB and SS, Space Operations Event Ledgers were periodically published throughout the experiment. The results of the experiments were successful, and each participating stakeholder demonstrated the ability to integrate various Event Ledgers into their unique systems and extend the analyses of the operational event with additional research. This paper examines the design and execution of the CSpO CAWG Event Ledger experiments and promotes the further adaptation of the service throughout the space community. Adoption of the Space Operations Event Ledgers by the broader space community may be a key enabler for collaborative international space operations at combat cadence.

INTRODUCTION

Background. The advent of the Joint Commercial Operations (JCO) Global has significantly accelerated space operations collaboration throughout the international community. JCO Global is an international cooperation of nations that have organized to operate a 24/7 virtual space operations center aligned with our mutual defense and safety of flight operations. The JCO now consists of fifteen (15) national organizations that work together to maintain 24-hour operations, in three primary shifts. Participating nations consist of members from defense, civil, and other agencies in Australia, New Zealand, France, United Kingdom, Colombia, Brazil, Canada, Japan, the North Atlantic Treaty Organization (NATO), and others. Through the JCO, these countries now have an unclassified virtual space operations center (SpOC) that employs a geographically distributed space surveillance sensor architecture to conduct threat monitoring, maneuver detections, and anomaly assessment.

The surveillance architecture is extensive with over 150 sites across the planet, the JCO is processing over 1 million independent measurement observations daily. The JCO is chartered to primarily conduct protect and defend (P&D) space operations monitoring. *Despite the daily international collaboration, there remains several foundational impediments to achieving a truly seamless international SpOC suitable to support our combined national defense at a combat operations cadence. One of the primary impediments being that the applications that comprise these centers do not effectively communicate events with one another from machine-to-machine (M2M)*. When one team identifies a new critical event, a partner nation SpOC must then go through a time-consuming, manual process of reconstructing the events in their sovereign applications to continue working on the event. Examples of events that are handled by the JCO today include satellite breakups, uncooperative rendezvous and proximity (RPO) operations, new foreign launch, launch to early operations (LEOP), newly discovered uncorrelated tracks (UCT), and others. As the threat environment in space becomes increasingly contested, the ability to rapidly react to situations that may escalate in a matter of minutes is critical. It is therefore similarly critical that the software applications supporting the Command and Control (C2) of these international SpOC transact a single common operating picture (COP) of the events in near real-time. Simply storing the data in a shared repository is not sufficient. The amount of data within the Unified Data Library (UDL), for example, can make it difficult to determine which sensor observations another SpOC member has processed and analyzed. At any given moment in the UDL there may contain a half-dozen or more current perceptions for the location of the Russian Luch Olymp (40258) satellite, each perception contributed by various stakeholders such as Exoanalytic, SAFRAN, Kratos, Cloudstone, PinePark, US 18th Space Defense Squadron (SDS), and others. At any given time, whose perception are we all using? What data sets were used to trigger an alert situation? Whenever the JCO alerts on a situation it publishes a Notice to Space Operators (NOTSO) alert. This is a good start, but the challenge for a receiving SpOC then becomes, "*Ok, I can see multiple perceptions of all the satellites identified in the NOTSO alert… which ones do we agree we should all use for this operation?!*". The ambiguity leads to the potential for significant, 'fog of war' miscommunications or delays. The Combined Space Operation (CSpO) Capability Architecture Working Group (CAWG) was chartered to address interoperability concerns throughout the allied and partner nation SpOC community. To explore suitability of solutions, the CAWG worked with the JCO to consider machine-to-machine (M2M) remedies. Any suitable solution would need to be able to address a wide variety of relevant space operation mission sets including NFL, RPO, Closely Spaced Objects (CSO), UCT, direct ascent anti-satellite (DA-ASAT) attacks, and others, spanning all orbit regimes from Low Earth Orbit (LEO) through to Cislunar. To be relevant to the whole CSpO community, the solution would also need to consider how the events could move rapidly between applications and transact through different classification levels.

Solution. To address this deficiency, the JCO conceived the '*Space Operations Event Ledger*' to enable multiple stakeholders and application to rapidly exchange the situational awareness (SA) information encapsulating an entire event. The Event Ledger contains a specified listing of all data points and major timestamps associated with a specific event including raw measurements, two-line elements (TLE), satellite State Vectors (SV), maneuver detections, conjunctions, launch sites, start / stop times, description, priority, and other elements necessary to comprehensively (*and unambiguously*) define an ongoing space operation.

The CSpO CAWG, including representatives from United Kingdom (UK), Australia (AUS), Canada (CAN), United States (US), France (FRA), and Germany (GER) prioritized the mission sets that the team believed would be suitable set for the initial tests.

Launches:
- Chinese Long March 3 to GEO, Xichang
  - Nov 13th at 1530Z
  - Targeting *Allied GEO Satellite*
- Chinese Long March 4 to LEO, Taiyuan
  - Nov 14th at 2348Z
  - Targeting Tandem X (36605)

RPO:
- *Allied GEO Satellite*, begin Nov 13th at 1306Z
- Tandem X / TerraSar X, begin Nov 15th at 0400Z

Uncorrelated Track (UCT):
- UCT 1: Pacific Region – Nov 13th at 0200Z
- UCT 2: Americas Region – Nov 13th at 1800Z
- UCT 3: Meridian Region – Nov 14th at 0800Z
- UCT 4: Americas Region – Nov 14th at 1900Z
- UCT 5: Pacific Region – Nov 15th at 0200Z
- UCT 6: Meridian Region – Nov 15th at 1300Z

Re-entry:
- Chinese CSS Daughter satellite separate on Nov 13th at 1615Z and re-enter on Nov 15th at 1300Z

Figure 1- CSpOC CAWG Nominated Event Ledger Scenarios

The mission sets selected contained three major categories including NFL, DA-ASAT attacks to both Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO), and UnCorrelated Tracks (UCT). As content to test these, the JCO Exercise Team developed a series of candidate vignettes that would be executed during the upcoming November Sprint Advanced Concept Training (SACT) [1] exercise. Events were designed with various levels of complexity, in some cases including tumbling satellites.

The Dragon Army software development team developed supporting processing that leverages several existing services including the JCO Mission Management Board (MMB), Dragon Army Sync Service (SS), and the UDL to compose and pass Event Ledgers to participating stakeholders/applications. The system would automatically release an Event Ledger entry update any time an operator would 1) create a new event, 2) publish or update a NOTSO, and 3) close an event.

To prove the efficacy of the Event Ledgers it would be necessary to show that a wide variety of systems could ingest and utilize the data. The JCO and CSpO CAWG reached out to members of government, academia, and the commercial community to find stakeholders who would help test the Event Ledgers by incorporating them into their bespoke tools and services. The following organizations implemented the Event Ledgers: Defence Science and Technology Group (DSTG) Australia, Saber Astronautics, Exotrail, Exoanalytic (through a Defense Innovation Unit (DIU) program), Georgia Tech Research Institute (GTRI), and Northstar. Table 1 below summarizes the organizations that integrated the Event Ledgers, which community they represented, and what derivative specialty analyses they provided utilizing the incoming data. The core tools used were the Australian Research and Development Space Target Awareness and Response (RED STAR), Space Cockpit, GTRI Encoder for Prediction of Irregularly Sampled Lightcurve Periodicity, Simulation in Python for Space Entities (SPySE), and Northstar OD Automated Processing tools.

Table 1- Event Ledger Participants

Organization	Tool Set	Country	Community	Specialization
DSTG	RED STAR	AUS	Government	Orbit Determination (OD), multiple classification levels, 3D visualization
Saber Astronautics	Space Cockpit	AUS & US	Commercial	Launch processing, OD, 3D visualization
Exotrail	Exotrail	FRA	Commercial	OD, maneuver detection & characterization
Exoanalytic	SPySE	US	Commercial	Load, assess maneuver
GTRI	Encoder for Lightcurve Periodicity	US	Academia and University Affiliated Research Center (UARC)	Automated stability classification
Northstar	Automated Processing	CAN	Commercial	OD, stability assessment

Each of the stakeholders above successfully imported Event Ledgers, loaded the data into their respective applications, and performed additional derivative analyses. Teams demonstrated several core space operations services including orbit determination (OD), stability characterization, maneuver detection, maneuver characterization, 3D visualization, and transport of data up classification levels. The Australian DSTG team went on to actually trend how Event Ledgers evolved throughout their evolution.

The experiment was run continuously over a 96-hour period during the November SACT of 2023. Throughout the SACT the Dragon Army M&S team injected vignette data into the UDL. The new Dragon Army services within the MMB and SS detected when JCO C2 operators created new events which subsequently triggered the composition and publication of Event Ledgers into the UDL. The experiment leveraged the SACT regional cells rotating through the Pacific, Merdian, and Americas teams to maintain continuous command and control (C2). Ledgers were published periodically throughout the exercise by active JCO crew from the US, the United Kingdom SpOC, and New Zealand SpOC. These JCO C2 ops teams coordinated to publish Event Ledgers during the SACT at specific times to enable all regions (Americas, Meridian, and Pacific) to experience all types of events.

The experiment was a success with all teams demonstrating the ability to import one or more of the Space Operations Event Ledgers. The DSTG Australian team was able to move the Event Ledger material from unclassified to classified processing centers. Multiple teams performed Initial Orbit Determination (IOD) and OD on the optical, radar, and passive radio frequency (RF) data embedded in the Event Ledgers. Academic institutions performed automated light curve periodicity analyses to assess stability. The most important element is that each team started from the same unambiguous perspective of the event from within their own tools, regardless of the complexity of the events. Figure 2 below illustrates some of the 3D and graphical results of the team.

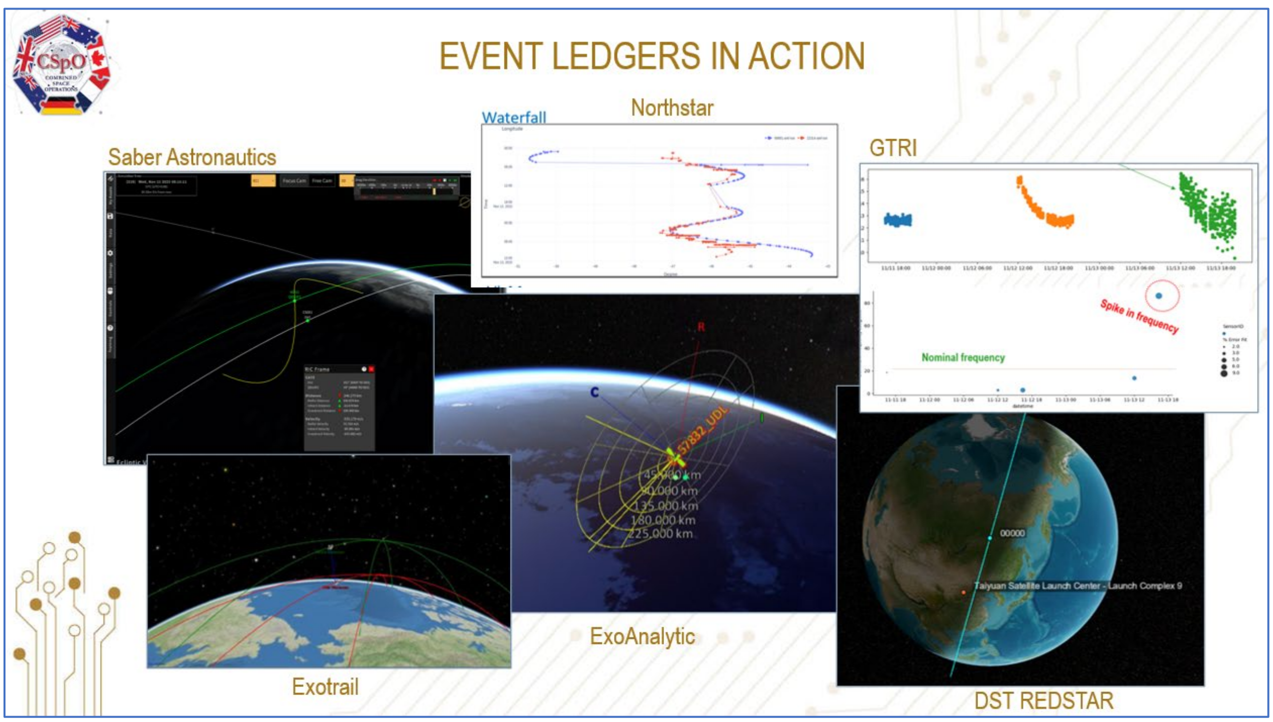

Figure 2- Collage of SACT 24-1 Event Ledger Experiments 3D

This paper will review the considerations that went into the design of the Space Operations Event Ledgers, the basic elements of an Event Ledger, timelines for the event publications, and some sample results from several of the teams utilizing the data. The paper will show how teams from various community groups within space operations (academia, government, and commercial) were able to import and utilize the scenarios. If matured and operationally accepted by the broader community, Space Operations Event Ledgers have the potential to solve a significant interoperability limitation in international space operations and provide methodology to conduct space operations at a combat cadence.

METHODOLOGY

When provided the task by the CSpO CAWG, the JCO considered the general problem, "*How to integrate SpOC and tools enabling the rapid dissemination of space situational awareness within a combat operations timeline?*" The design would need to incorporate at least the following considerations:

- What commonly accessible set of repositories could be used?
- The transfer of time critical data across multiple classification levels.
- Ensuring data governance
- Seamlessly handling both real-world and modeling and simulation (M&S) data
- Utilization of established standards for representing multiple data types:
    - Satellites (state vectors, TLE, ephemeris)
    - Ground facilities
    - Remote surveillance observations (radar, EO, passive RF)
    - Telescope and other imagery
    - Tasking messages
    - Mission objectives and other meta data

To begin, the selection of the Unified Data Library (UDL) as the common data management platform met all the requisite criteria. Specifically, the UDL:

- contained all the basic data types necessary for the candidate mission sets (NFL, DA-ASAT, UCT, and Re-Entry) would need; including SV, TLE, Maneuver message, launch facilities, and others;
- was a central element of the JCO (and thereby utilized by at least 15 countries at the outset);
- was able to transact data in near real-time from unclassified, to environments at higher security classifications;
- natively contains sufficient embedded governance rules that would allow access of specific data to authorized users only and that had the requisite account privileges, commonly known as Data-Centric Security (DCS). Data governance is an important aspect for authorized distribution. Even when sharing data between allies, the proprietary data of commercial companies must still be protected.

The anatomy of the Event Ledger was, by design, intuitive and simple. Figure 3 below illustrates the basic format of a Space Event Ledger.

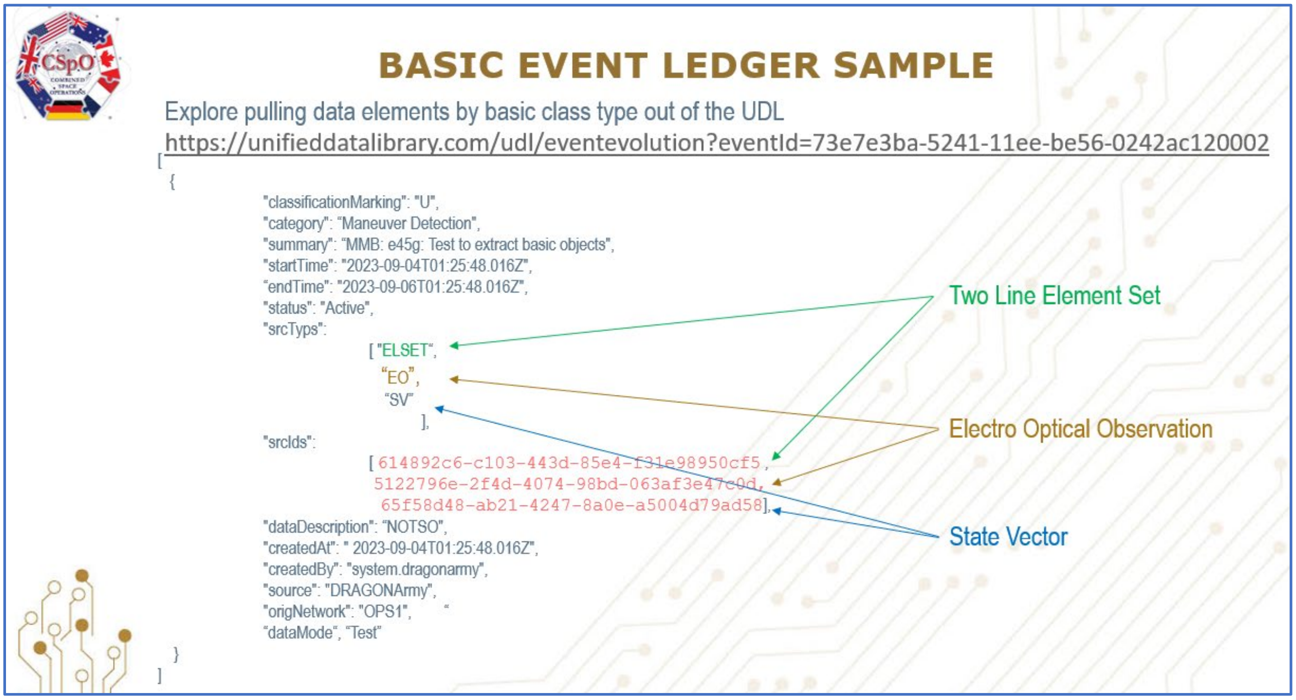

Figure 3 - Basic Space Operations Event Ledger Example

The Event Ledger is an instance of the UDL Event Evolution data type as shown in Figure 3, where the fields for the Event Ledger include classification markings, category, status, start and end time, creation dates, originating source, and data mode (Test, Experiment, Real, etc). The core element of the Event Ledger is the "srcTyps" (Source Types) and "srcIds" (Source Identification) arrays at the center of the document in Figure 3. The two arrays, srcTyps and srcIds, are paired and form a Hash table. In other words, element 1 of the srcTyps array is paired with element 1 of the srcIds array, so on and so forth. The srcIds contain the unambiguous data location ID in the UDL for the corresponding objects. These IDs are called Universally Unique Identifier (UUID) in software development vernacular. Stakeholders can use the UUID and object type (TLE, SV, Maneuver Detection) to retrieve the actual object definition. *An Event Ledger can be uniquely referenced by its own UUID, enabling stakeholders to pass specific version-controlled perspectives of the event ledgers themselves over time*.

Example of retrieving an observation with UUID:

https://unifieddatalibrary.com/udl/eoobservation?obTime=>2022-04-10T05:45:00.000000Z&id=5122796e-2f4d-4074-98bd-063af3e47c0d

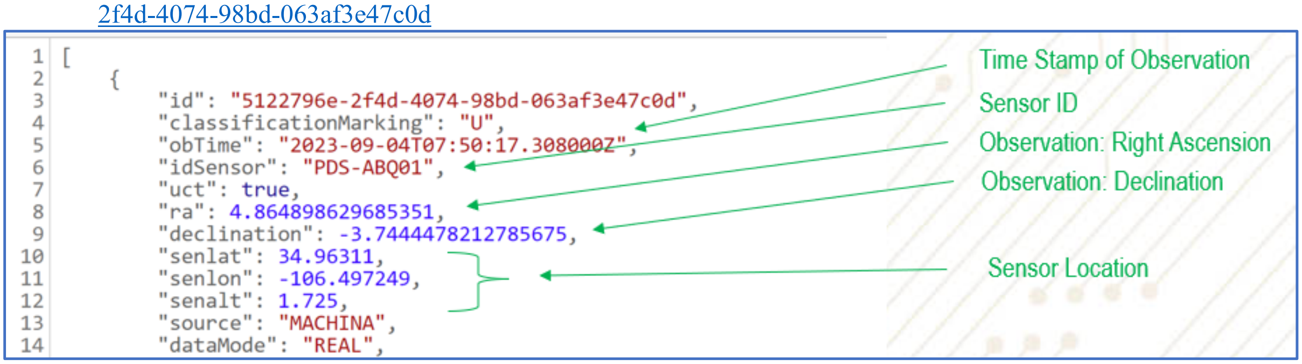

Figure 4 - Example of Sensor Observation pulled from Event Ledger

Figure 4 above shows the results of retrieving an optical data message type from the UDL utilizing a UUID. Employing this message construct, an entire vignette may be unambiguously defined and reconstructed in multiple applications. As described earlier, multiple sources of information for a satellite or other object may be contained in the UDL (each a perception from a different vendor). The Event Ledger solves that problem by utilizing the UUID to precisely define the exact information to be considered in the operational scenario. The UUID will point to exactly one record within the UDL. That UUID is the same at multiple classification levels within the UDL allowing Event Ledgers to be transferred from unclassified to higher security classification environments without changing content.

The team considered the life cycle of the Event Ledgers. Figure 5 below shows the processing chain in the diagram.

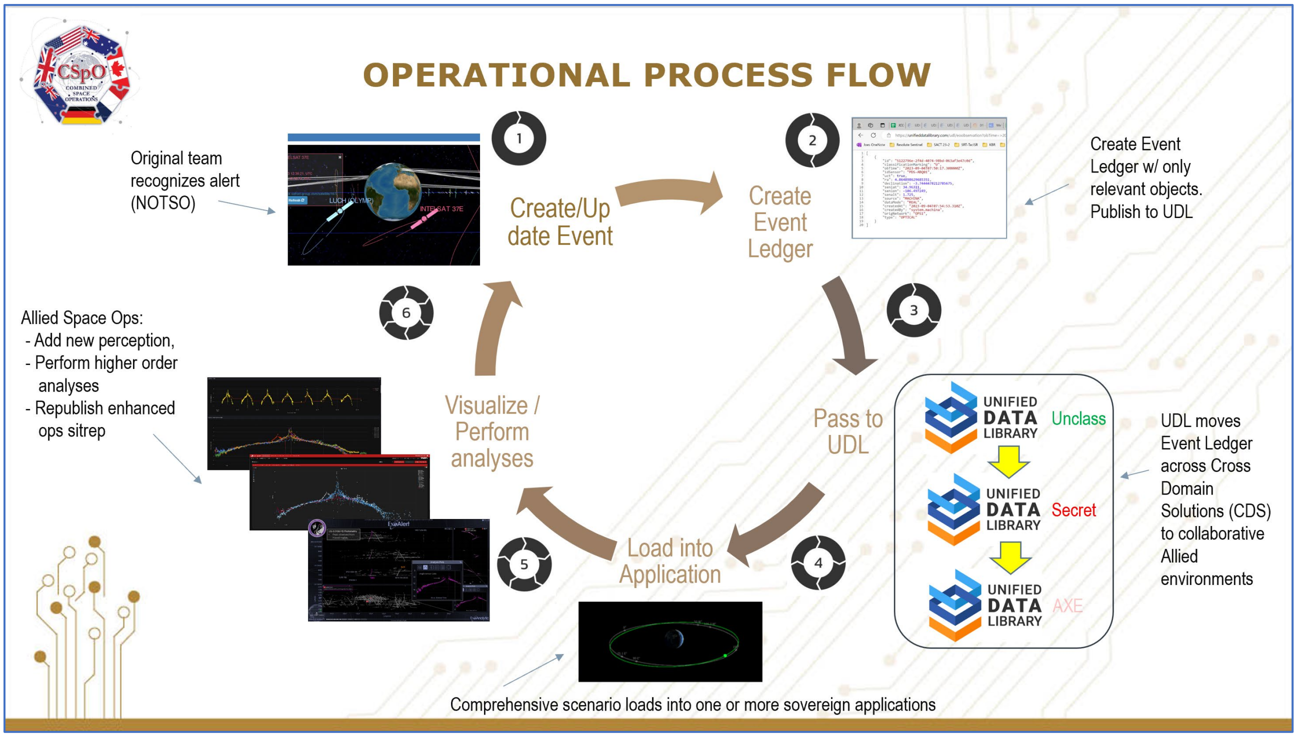

Figure 5 – JCO/CAWG Event Ledger Cycle

In Step 1 from Figure 5, a SpOC operations team identifies that there is an ongoing operation of significance. Step 2, through the JCO/Dragon Army MMB, the teams create an Event Notice to Space Operators (NOTSO) alert which triggers the publication of an Event Ledger. In Step 3, the Event Ledger is published to the UDL which will pass it automatically to their respective Unclassified, Secret, and Top-Secret enclaves. Note, partner nations at Secret may soon be able to access Event Ledgers at the Secret level through the Allied eXchange Environment (AXE). In Step 4, the Event Ledgers are discovered and loaded into various applications. This was demonstrated during the experiment by DSTG, Saber Astronautics, Exoanalytics, GTRI, Northstar, and Exotrail. Step 5, with the initial Event Ledger alert loaded, each of the corresponding teams performs derivative analyses on the data. Examples of derivative analyses include lightcurves, IOD, OD, maneuver detections, satellite state updates, and others. In Step 6 the process begins to repeat as these stakeholders *update* Event Ledgers with information from subsequent analyses. These teams can add new records to the UDL and then append these records to the srcTyp and SrcId fields. In this way the Event Ledgers are now rapidly beginning to exchange SSA with multiple SpOC to share and evolve the space operation event in near real-time. Finally, in Step 6, a new and enhanced Event Ledger update is published to the UDL and available for others to continue collaboration.

The JCO Exercise team then took the direction of the CSpOC CAWG to develop the events outlined in Figure 1. The team developed a variety of schedules and scheduled when specific events would occur. Multiple events were developed to demonstrate the full span and suitability of Event Ledgers to transact Events between SpOC and tools within the community. Recapping the vignettes outlined by the CAWG, these included NFL to RPO and DA-ASAT in both LEO and GEO as well as UCT processing. Re-Entry was an element added as part of a Chilean Desired Learning Objective (DLO) later in the experiment. Figure 6 below illustrates the first of the vignettes designed, a Chinese launch to RPO with a GEO satellite. The team chose to simulate a hypothetical non-cooperative called the Shijian-21X (SJ-21X) satellite to launch out of Xichang and rendezvous with an allied satellite. The design document is a Gantt chart showing major elements along the execution timeline of the event. Along the y-axis are the main Mission Sequence elements beginning with a Public Satellite Research Analysis (PSRA) notification alert that a launch has been publicly reported. The design continues from MMB ticket creation through to the Chinese SJ-21X departing.

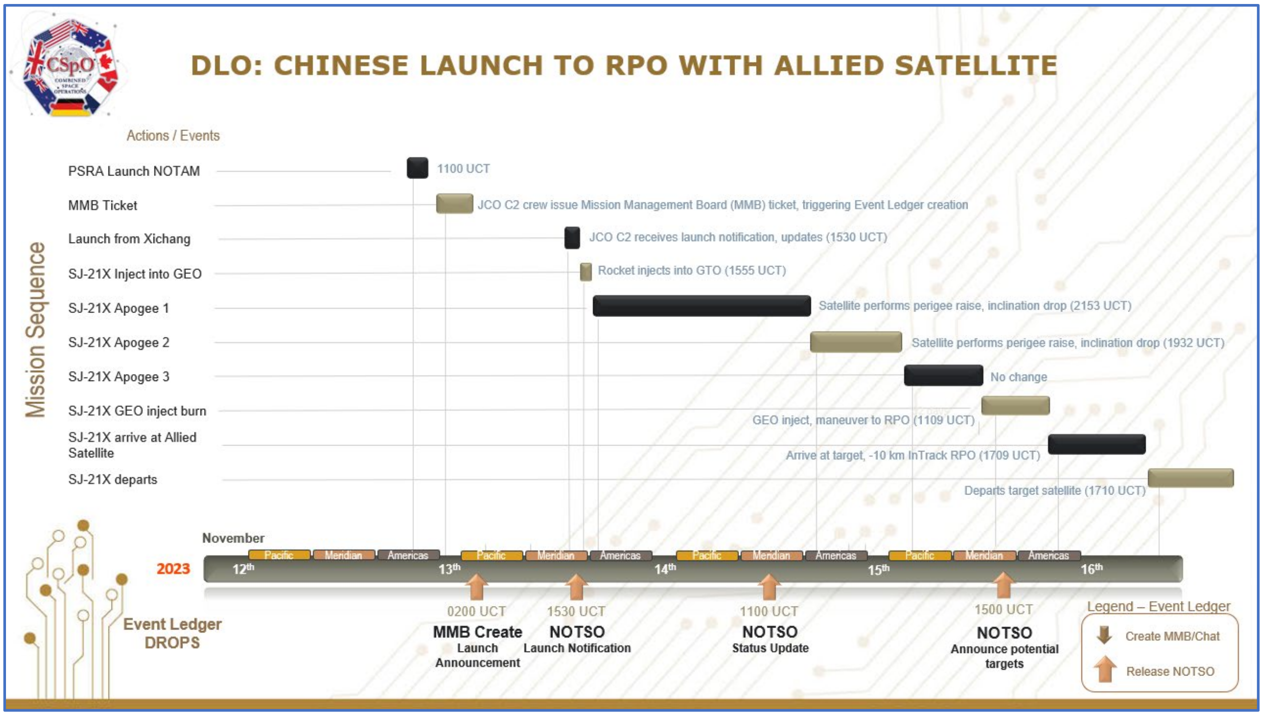

Figure 6 - Vignette 1: Lauch to RPO at GEO for Event Ledgers

The major time sequences of the events are denoted along the horizontal axis of Figure 6. Note that dates are depicted ranging from November 12th through the 16th. Also note that the time blocks for regional cell operating hours are labeled for Pacific, Meridian, and America. Times when Event Ledgers are published to the UDL are labeled with large orange arrows along the timeline. The sub-system used to publish the Event Ledger is shown under the arrow. For example, a Notice to Space Operator (NOTSO) alert due to a Launch Notification occurring during the Meridian shift. Within the Gantt chart are bars that indicate when specific M&S events are occurring. For example, SJ-21X is shown as conducting an apogee burn around November 13th (2153Z) and the satellite drift is continuing through to late in the day on November 14th. This indicates that observations may be expected on SJ-21X in its first GEO Transfer Orbit (GTO) during this segment.

The design teams developed the vignette artifacts to convey to the Dragon Army M&S teams how the events should be constructed. These diagrams were also provided to the companies, academia, and government stakeholders preparing to conduct the experiment and load Space Operations Event Ledgers.

Two sets of additional Event Ledger design diagrams were constructed for Launch to RPO (see Figure 7) with a LEO satellite and various UCT vignettes (see Figure 8). The UCT vignettes were designed to increase in complexity, moving from very trivial single satellite delta-V burns in GEO through to complex multi-stage delta-V with RPO that result in a Re-Entry. Note that the Dragon Army team incorporated additional metadata elements in the M&S that allowed teams to attempt advanced processing. This included a satellite with an observed light curve with changes in the visual magnitude corresponding to rotation of the satellite . Originally the team had planned to include Time Difference of Arrival (TDOA) and Frequency Difference of Arrival (FDOA) values to emulate the passive RF domain, but these were not readily used by the stakeholders during the initial experiment.

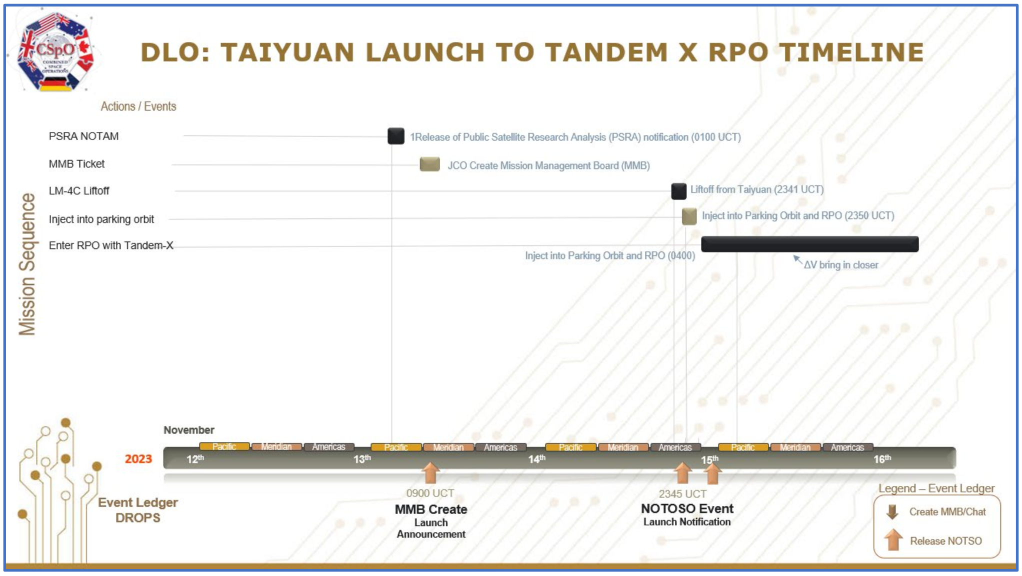

Figure 7 - Vignette 2: Launch to RPO with Event Ledgers

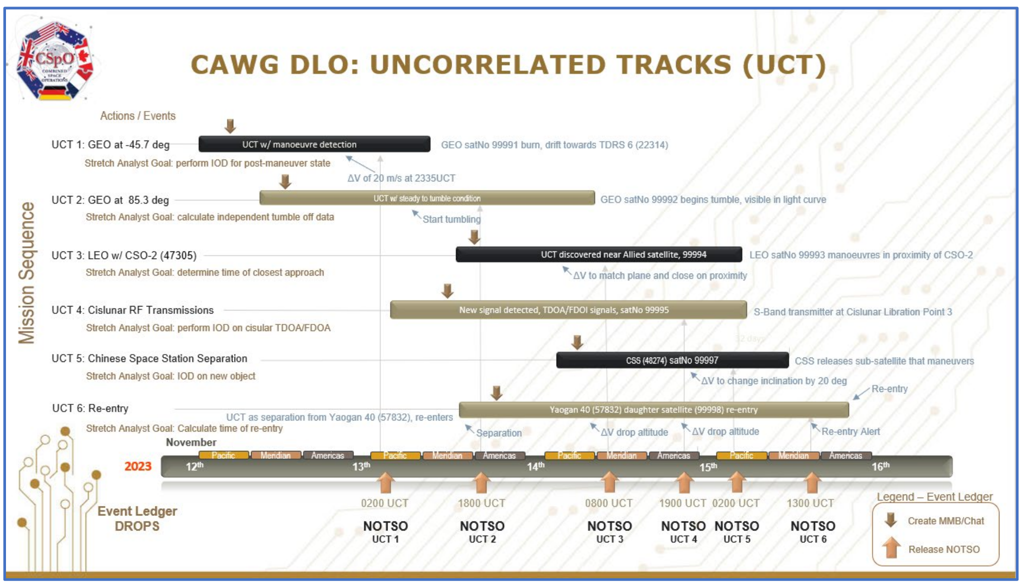

Figure 8 - Vignettes 3 thru 6 for UCT in Event Ledger (w/ Re-Entry)

EXERCISE USE CASES – OBSERVATIONS AND RESULTS

GTRI – Stability Assessment

The academic team at Georgia Tech Research Institute (GTRI) utilized the Event Ledgers to conduct an automated Lightcurve Characterization DLO during the SACT. Prior to analyzing light curves that are pushed to the UDL, an analyst typically collates individual EO observations to form a light curve. This involves determining which factors (phase angles, collection times, sensor locations, etc.) will generate operationally relevant algorithm predictions when the assembled light curve is fed to a Machine Learning (ML) algorithm. While simple in theory, this can be a challenging task due to differences in factors such as temporal cadence, measurement quality, and solar phasing that exist across different UDL data providers that are observing satellites of interest over intersecting timeframes. The Event Ledgers provided a solution to avoid the time-consuming and potentially subjective task of assembling EO observations into a light curve. In this way, Event Ledgers greatly improved the ability to quickly parse light curves of operational interest. Over the course of the SACT event, the Event Ledgers allowed GTRI to perform ML-based light curve analysis on a combat operations timeline by using the rapidly disseminated light curves of interest. Figure 9 illustrates the basic elements and design process that GTRI utilized during the SACT, starting with the loading the initialization data from the Space Operations Event Ledgers.

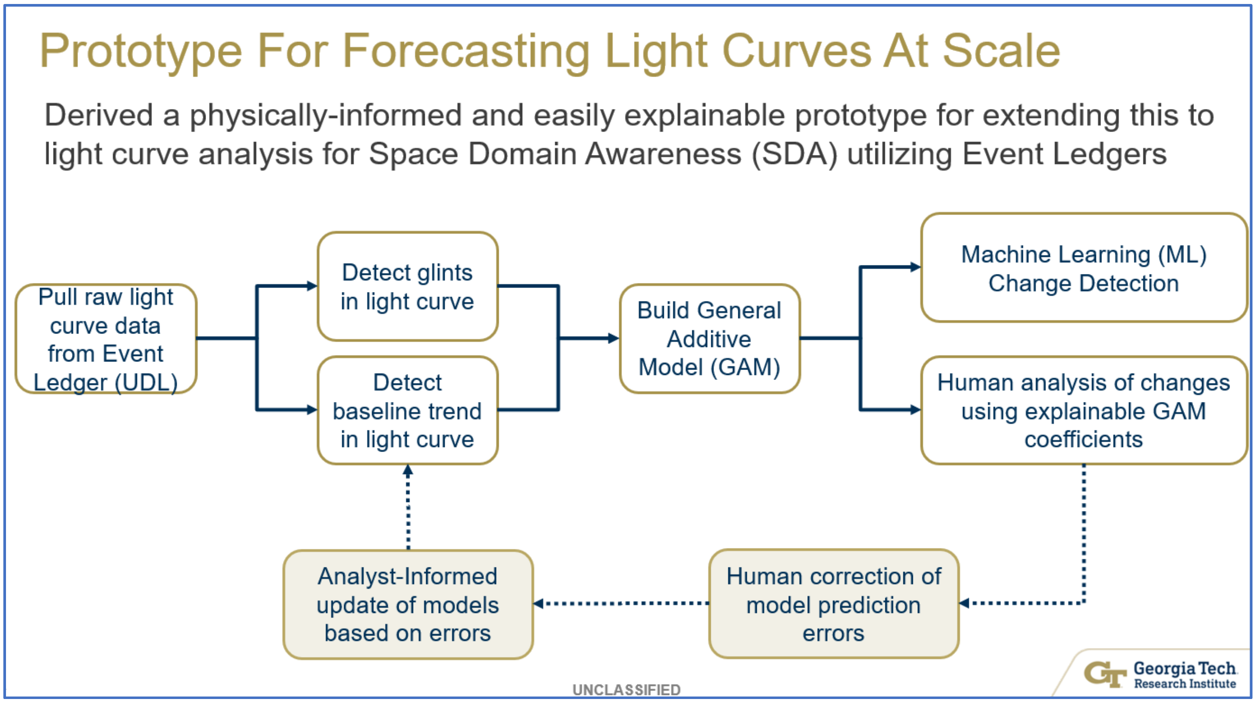

Figure 9 - GTRI Lightcurve Processing model utilizing Event Ledgers

During the SACT event, GTRI deployed a Pattern of Life (PoL) ML algorithm to assess frequency "heartbeats" present in satellite light curves as data was streamed onto the UDL in the form of Event Ledgers. The algorithm rapidly assembled a light curve from the Event Ledger, fed the light curve to the ML algorithm, and then pushed a JSON packet back to CSpO. The JSON packet contained the dominant frequency heartbeat that was present in the event ledger's light curve. This "heartbeat monitoring" capability potentially allows CSpO analysts to determine when the stability status of a satellite changes. Additionally, the ML algorithm assesses the data quality that was used to generate the frequency heartbeat prediction. The data quality assessment algorithm detects any aliasing in the light curve, alerting the analyst of event ledger light curves that are untrustworthy due to temporal under-sampling. A diagram of the pipeline is shown in Figure 10.

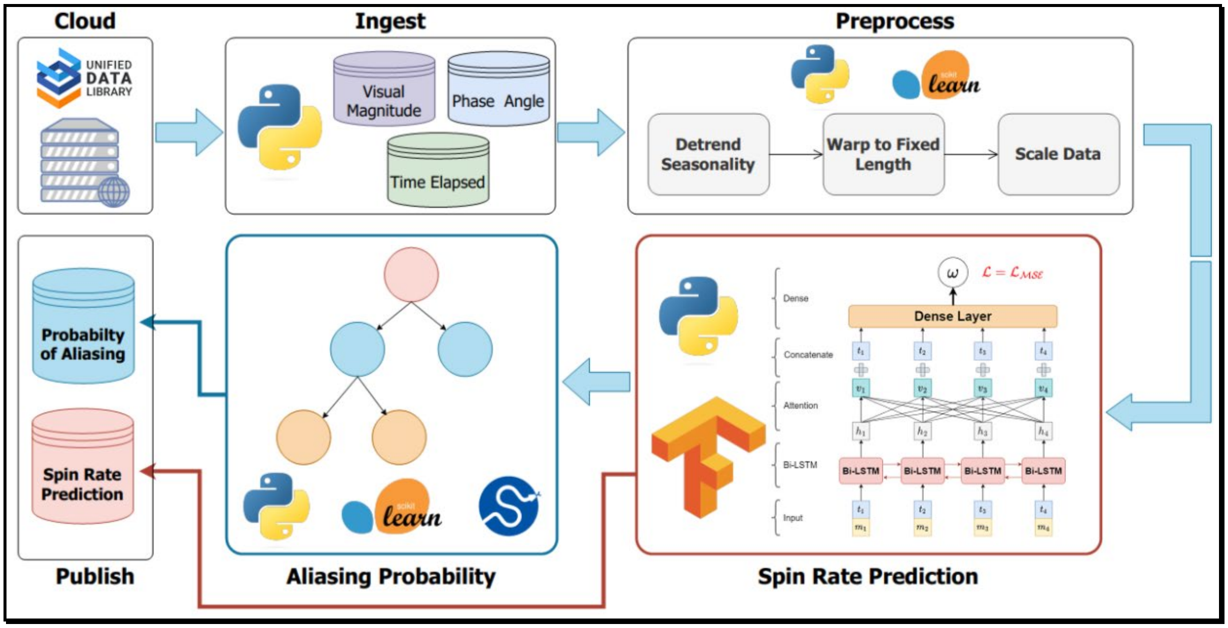

Figure 10 - GTRI's pipeline for ingesting event ledger information and predicting the frequency "heartbeat" present in the light curve for stability analysis.

GTRI's ML algorithm was developed to handle irregular time steps via the inclusion of a Bi-directional Long Short Term Memory (Bi-LSTM) layer that ingests the time lag in between successive data points. In this way, the ML algorithm can handle varying cadences across data providers and any data dropouts that occur due to weather changes. These capabilities were both tested by the simulated event ledger light curves provided by CSpO during the SACT event. Additionally, the algorithm ingests EO measurement uncertainties provided in the event ledger. The algorithm uses these measurement uncertainties when making predictions in order to mitigate the influence of noisy observations on frequency estimates.

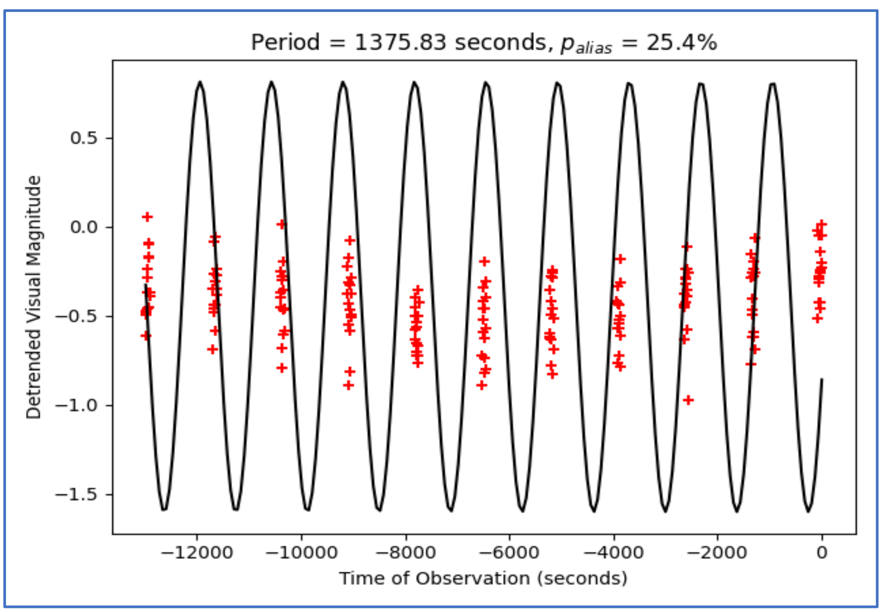

Figure 11 - Predictions by GTRI's ML system on the event ledger UCT data. At this point in the SACT event, the light curve was on the threshold of becoming aliased.

Over the course of the SACT event, GTRI deployed the ML-based PoL algorithm on simulated light curves provided by CSpO. Specifically, GTRI pulled data from a CSpO Uncorrelated Track (UCT) using the event ledger framework. The UCT contained simulated EO brightness data of a Geostationary Orbit (GEO) satellite that was in a tumbling mode of operation. GTRI preprocessed the datasets and fed them to their PoL algorithm. The returned JSON packets provided CSpO with an understanding of the varying rate of tumbling of the object over the course of the SACT event. Additionally, GTRI was able to identify when aliasing occurred in the light curve datasets and report this information back to CSpO on a daily basis. Such information can be used in a real operational environment to inform a telescope provider of when they need to increase cadence of measurements on a satellite. An example prediction on the simulated UCT data is shown in Figure 11. This result was considered a success, as GTRI was able to integrate the event ledger framework into their ML systems and exchange common situational awareness at an operational cadence with CSpO.

Australian – DSTG Radar Orbit Determination and Profiling

The Defence Science and Technology Group (DSTG) conducts science and technology activities to shape and inform the development of Australia's Defence and National Security capabilities. DSTG has developed an experimental Space Domain Awareness (SDA) system known as the Research and Development Space Target Awareness and Response (RED STAR) to support science and technology advice for operational SDA capabilities. As part of DSTG's contributions towards integrated space operations, a MATLAB-based tool for ingesting Event Ledger data was developed. The tool enables event data to be readily downloaded and all event data is automatically downloaded from the UDL by default. The user can select all events or a subset of the events for analysis. An interactive time series display enables a user to inspect specific data records. The tool was designed to account for the complexity of each event since each event could contain multiple updates and each event update can link to thousands of sensor observations or to other records in the UDL.

Figure 12 is a screenshot of the DSTG Event Ledger tool, showing eight rows with each row corresponding to a unique event considered during the 2023 SACT event. The labels for each event contain event data from the UDL including dataMode, dataDescription, category, status, source (indicated in pink text), summary (green) and eventId (grey). The horizontal axis corresponds to time. Colored marks are used to represent the UDL records associated with a given event. A legend for the type of event record is included at the very top of the display. Each event may include multiple event updates, represented by tall yellow lines. Other records are displayed as shorter markers and color-coded by type for Electro-Optical observations (EO), Radar observations (RADAR), Passive RF, difference of arrival observations (DOA), launch site metadata (LS), Point of interest metadata (POI), state vectors (SV), and orbital element sets (ELSET). The DSTG Event Ledger tool allows users to zoom in on any event or time period and to select any record to display the corresponding details. In Figure 12 the Event selection corresponds to a total of 10,407 records associated with the event update (centre); the Radar selection corresponds to a radar observation that has been simulated by ai solutions (top); the ELSET selection corresponds to an orbital element set provided by Saber Astronautics.

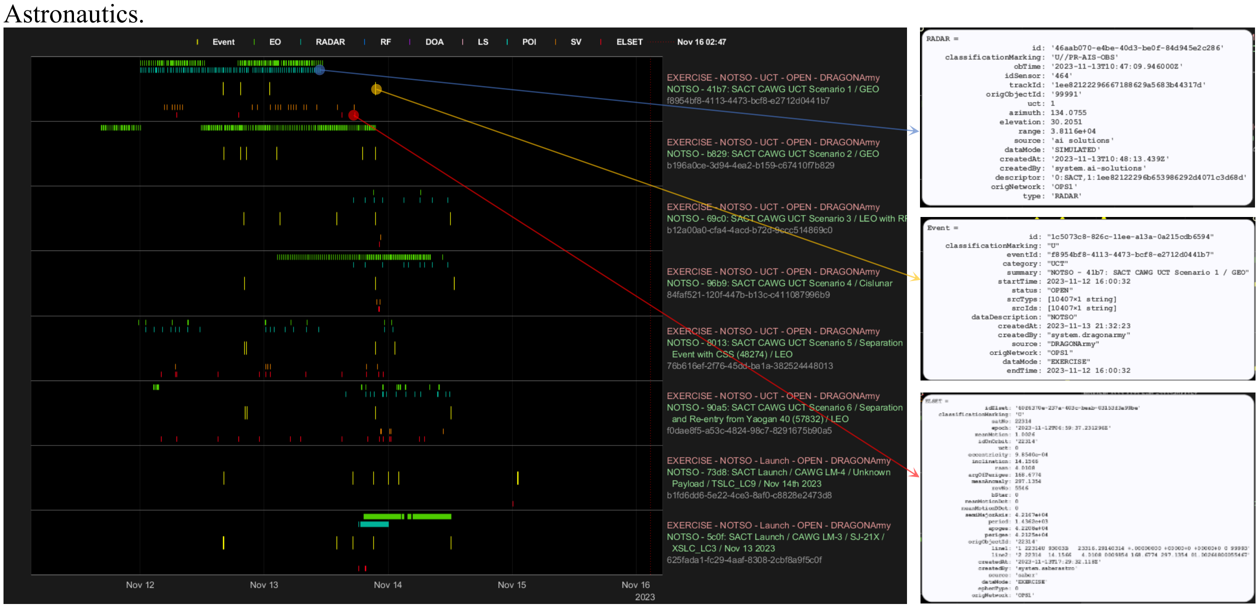

Figure 12- DSTG Event Ledger tool with data from SACT 2023 (left) and selected UDL records (right)

Following the conduct of the 2023 SACT exercise, the functionality of the DSTG Event Ledger tool has been implemented in a RED STAR application that is accessible to authorized users via a web-based interface. Further work is planned to link the tools to explore Event Ledger data with tools to process and analyze data thereby streamlining workflows.

The Event Ledger data accessed by the DSTG RED STAR system was all obtained from the Unclassified instance of the UDL. During the 2023 SACT exercise, DSTG successively pushed copies of the Event Ledger data to classified networks as part of allied efforts to conduct integrated space operations. The RED STAR capabilities include experimental SDA algorithms developed to perform IOD and OD. The IOD and OD algorithms were applied to the SACT CAWG Scenario 1 in which an UCT on a single space object was processed. The UCT comprised a set of observations from a simulated ThothX Radar observing a simulated GEO space object (simulated NORAD ID: 99991). State vectors were produced using the radar observations of the UCT.

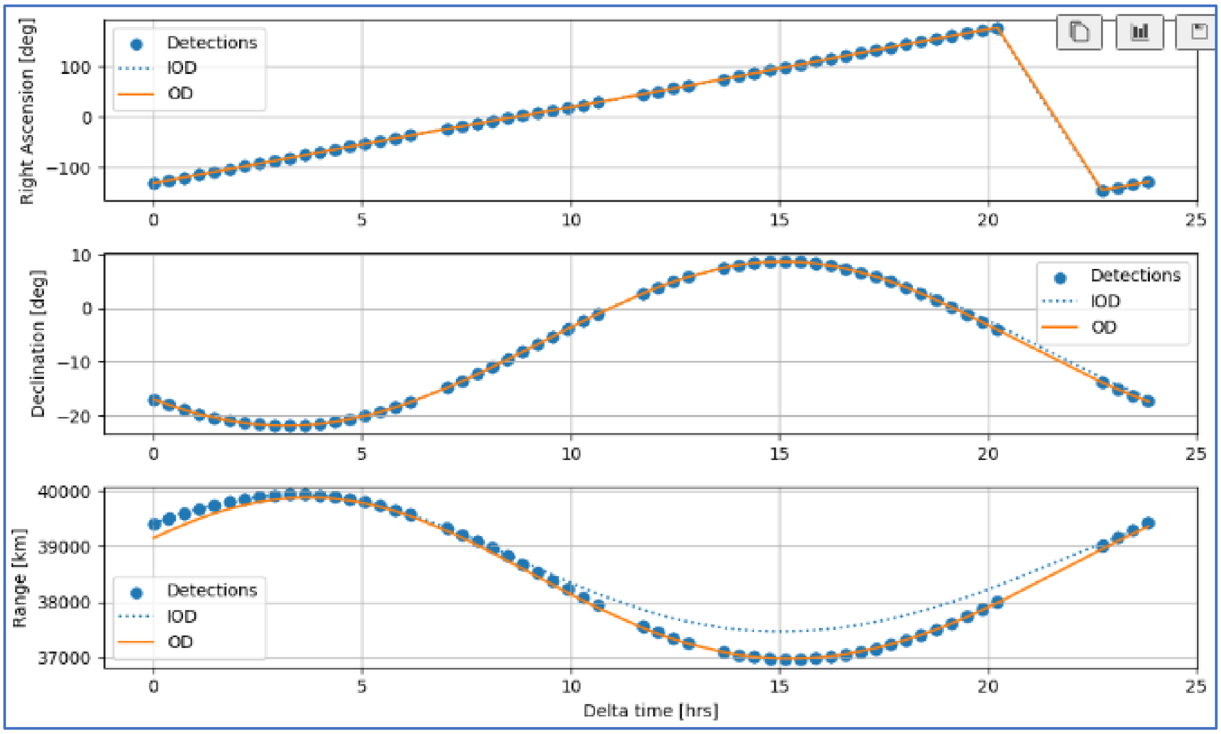

Figure 13. Simulated radar observations from event "SACT CAWG Scenario 1" and orbit estimates produced by RED STAR algorithms for IOD (first few observations) and OD (subsequent observations)

Figure 14 shows the orbits for the two objects within the SACT CAWG Scenario 1 event. The orbit for the real-world Tracking and Data Relay Satellite System TDRS-6 (NORAD ID: 22314) is displayed using the ELSET obtained from the Event Ledger. The orbit for the simulated object (NORAD ID: 99991) is displayed using the state vectors computed by the process outlined in the previous paragraph. The exercise context for the scenario was that the simulated object in GEO performed an impulsive burn to drift towards TDRS-6. Future work for RED STAR includes the detection and estimation of space object maneuvers and alerts for when a space object is likely to approach another.

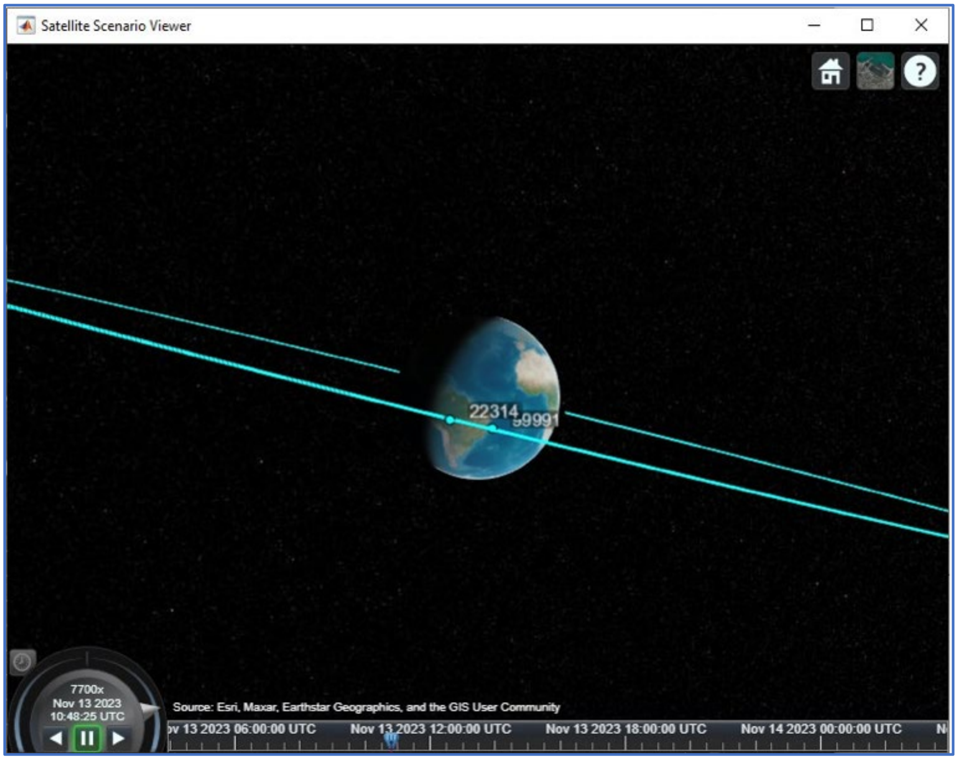

Figure 14. Orbits of the real-world object 22314 and the simulated object 99991 corresponding to the event entitled SACT CAWG Scenario 1

Figure 15 shows the orbits for the two objects within the SACT CAWG Scenario 6 event. The orbit for the real-world Yaogan 40 (NORAD ID: 57832) is displayed using the ELSET obtained from the Event Ledger. The orbit for the simulated object (NORAD ID: 99998) is displayed using the state vectors computed using DSTG's RED STAR IOD/OD algorithms applied to a UCT of simulated radar observations. The exercise context for the LEO scenario was that Yaogan 40 deployed a simulated object which then re-entered Earth's atmosphere.

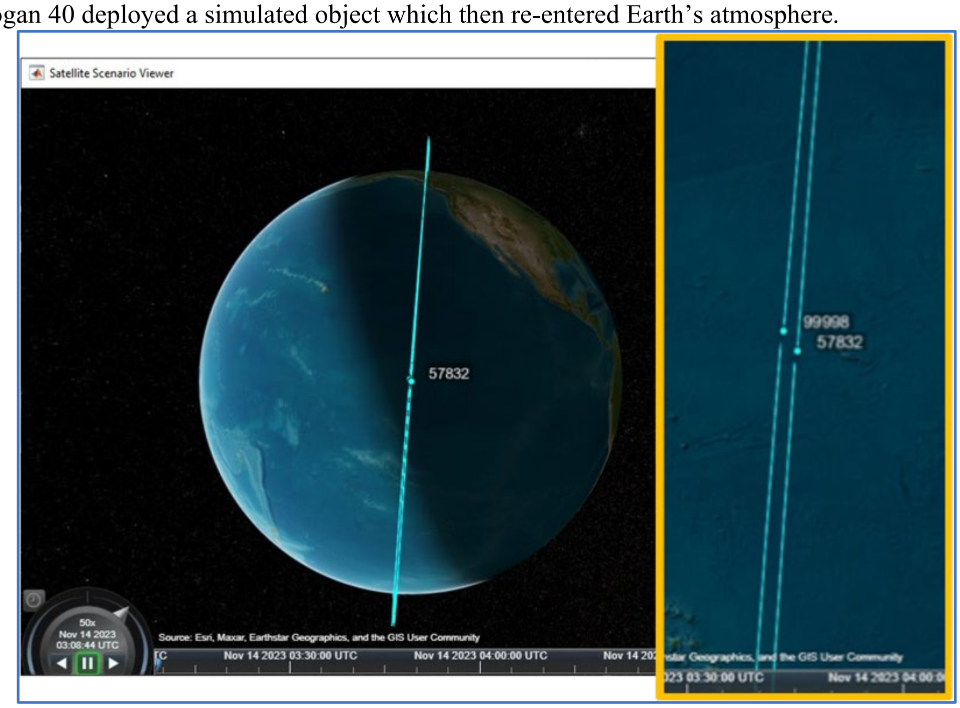

Figure 15. Orbits of the real-world object 57832 and the simulated object 99998 corresponding to the event entitled SACT CAWG Scenario 6

Saber Astronautics Space Cockpit

The dual Australian and American company, Saber Astronautics, contributed significantly to the initiative with the integration of Event Ledgers into their Space Cockpit space operations toolset. Figure 16 below illustrates the Saber tools (left) visualizing optical observations of Space Operations Event Ledgers while Site Leads in Australian Responsive Space Operations Center (RSOC) work desired learning objectives (DLO) during the November SACT.

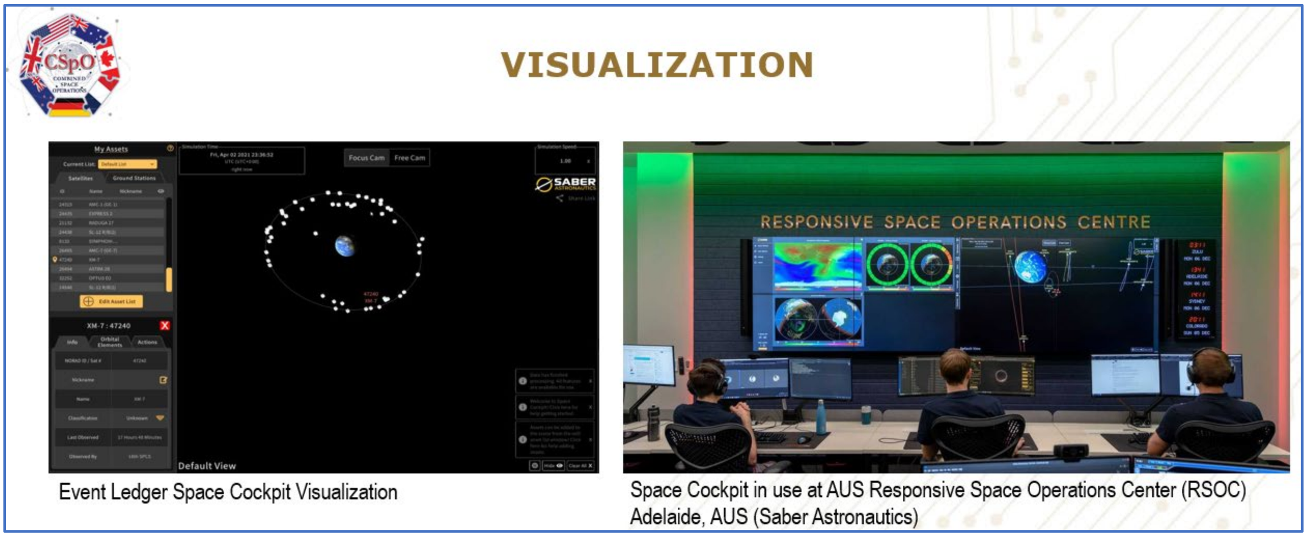

Figure 16 - Saber Astronautics in Australia employing Event Ledgers in toolsets

Saber completed the dynamic loading of all Event Ledgers to include State Vectors, TLE, observations, and Launch Facilities. The system was able to successfully utilize raw observations to generate IOD and maneuver detections from the data. Some of the more complex scenarios were over 10,000 observations in addition to TLE and State Vectors, which stressed the import routines.

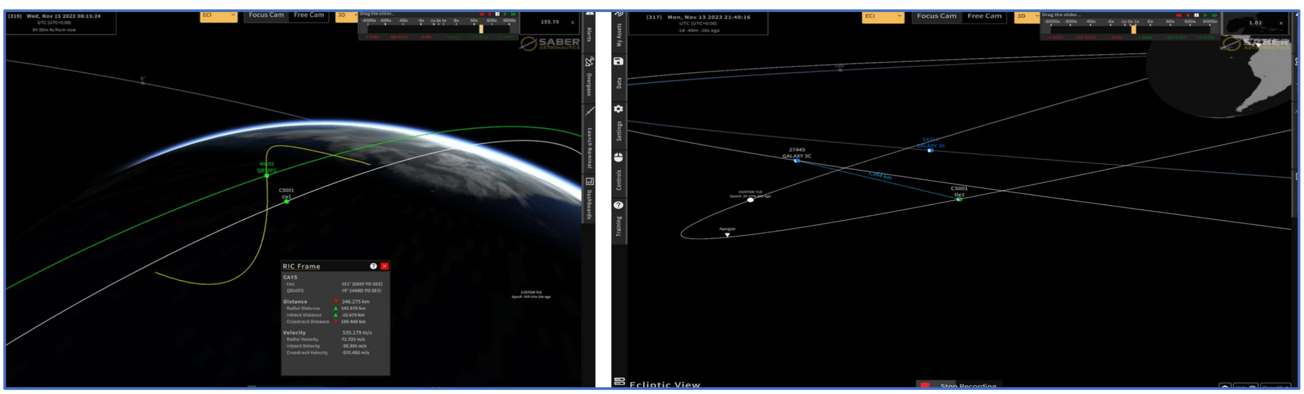

Figure 17 - Saber Astronautics Space Cockpit visualizing LEO (left) and GEO RPO (right) from Event Ledger in 2023 SACT

Figure 17 above illustrates One of the key differentiators of the Saber Astronautics solution was the ability to load an event directly from Event Ledger UUID through a single uniform resource location (URL) Link. This feature enabled loading of the scenario by simply double clicking on a web-link. *During the SACT, the White Cell Control team was able to pass Event Ledgers to the community with one-button click access*.

Additional Significant Contributors

The Event Ledgers were additionally used by representatives from Exotrail (France), Northstar (Canada) and Exoanalytic (US). Each of these companies imported Event Ledgers during the SACT and performed a variety of extend analyses including IOD/OD and maneuver detection.

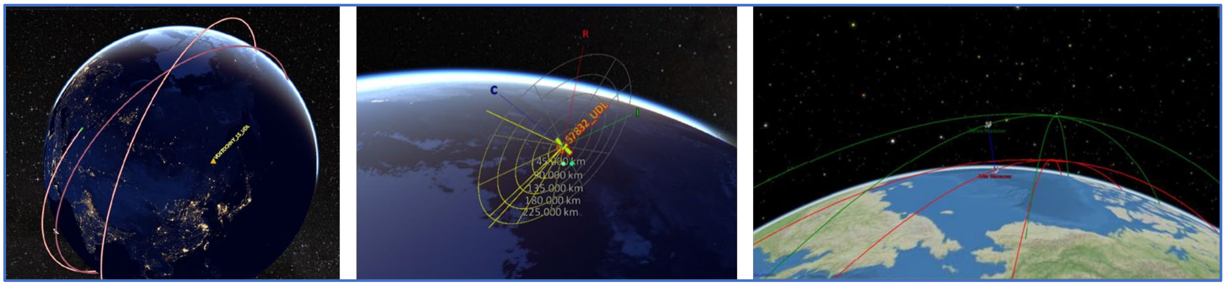

Figure 18 - Exoanalytic SPySE (left and center) and Exotrail (right) display Event Ledgers in SACT 2023

Figure 18 above illustrates several examples of the US company Exoanalytic and French company Exotrail importing multiple Event Ledgers into their respective analysis tools. Below, Figure 19 is an excerpt of Canadian company Northstar's process model for importing Event Ledgers to utilize for IOD as well as Waterfall and stability assessment. The lower right graphic in Figure 19 shows a classic transition from stable to tumbling in a lightcurve plot.

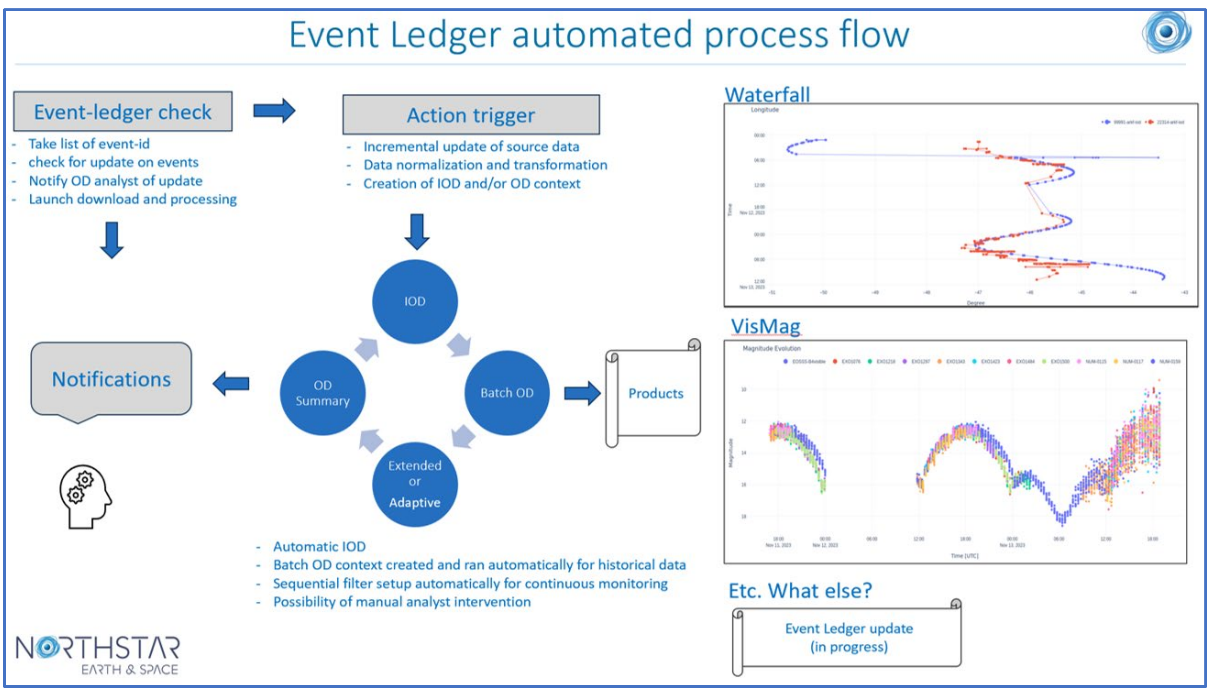

Figure 19 - Northstar processing of Event Ledgers in SACT 2023

The ability for each of these stakeholders to so rapidly integrate with Event Ledgers and extend the analysis is a key indicator that the format is suitable for combined space operations across a broader international community.

Future Potential Defense Collaboration through JCO

The initial experiment series of the Space Operations Event Ledgers was considered successful, as it demonstrated the ability for multiple teams to share unambiguous space operations events in near real-time, to various applications and across multiple classifications. Today, the Event Ledgers are currently published automatically through the JCO via NOTSO on a daily basis. There remains a significant amount of work to do in order to address the CSpO CAWG implementation objectives, including connection to secret enclaves for all member nations. The intent for this is likely through the Space Systems Command (SSC) Allied eXchange Environment (AXE) instantiation of a UDL accessible to a broad partner nation community at Secret classification. Event Ledgers need to find further adoption by more SpOC including the National Space Defense Center (NSDC) and others. The German Space Situational Awareness Centre (GSSAC) in Uedem, Germany is currently developing automatic readers that will import Event Ledgers into Systems Tool Kit (STK). Deficiencies exist in the current formulation, especially when 10,000+ observation may be contained in a single document as tools may find it difficult to load. The JCO and Dragon Army are considering modifications to embed more verbose 'Analyst Comments' in the document that are time and object stamped. It is recommended that further work on Event Ledgers be adopted by the NATO Federated Mission Network (FMN) Space Tiger Team. One challenge identified with such a broad set of data is the potential for data sets to be included in analysis which other SpOC cannot access. This was tested and confirmed to work as expected, validating the ability to protect data while using Event Ledgers. When commercial data records are procured and submitted to the UDL via the Global Data Marketplace, a new UUID is created for that record. If one observation is submitted to multiple customers, each gets a unique UUID, despite the data being the same. If one of these customers links that observation into an Event Ledger, then distributes that to others who don't have access to that procured data, they will not see this observation. Work is being done to identify a potential solution to this issue, while still maintaining full privacy, commercial integrity, and security within the UDL.

Discussion and Conclusion

Implementation of the 'Space Operation Event Ledgers' has been shown to have potential as a methodology to enable international SpOC to exchange unambiguous situational awareness information of space operations event at high cadence. The methodology is sufficiently abstracted and intuitive to be efficiently integrated into multiple bespoke applications as well as traverse up multiple classification levels. In attempts to address CSpO CAWG identified requirements, Event Ledgers have potential be one important element of enabling integration between multiple SpOC in near real-time. The experiment here demonstrated that the service could effectively be utilized by representatives from across academia, government, and commercial sectors. The utilization of UDL as a consolidated data management platform allowed the JCO/Dragon Army development teams to adapt existing solutions to the complex task of managing data governance and establishment of basic object type definition (i.e. State Vectors, TLE, maneuver detections, facilities, conjunctions, etc). Throughout the SACT experiment, the Event Ledgers were utilized by Australian, United States, French, and Canadian analysts to load and extend the operational status on LEO & GEO DA-ASAT, Re-Entry, UCT, and Launch vignettes. Future work on Event Ledgers is required to make representation of very large data sets more efficient as well as embedding of time-stamped analyst notes/comments. Space Operations Event Ledgers are now an automated product of JCO NOTSO and available for prototype utilization in daily operations. Event Ledgers enable bespoke applications to transact space operational data with one another. Examples include Space Cockpit, RED STAR, STK, and others. Further adoption of the Space Operations Event Ledgers by the broader space community would enable M2M operations and accelerate combined space operations in preparation for potential future space conflicts.

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1. REFERENCES

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