An Australian Conjunction Assessment Service

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ABSTRACT

This paper presents results from a new operational conjunction and threat warning service developed in Australia. As part of the Space Environment Research Centre (SERC) – a collaboration under the Australian Government's Cooperative Research Centre scheme – a conjunction and threat warning service has been developed to support satellite operators and enable a laser debris manoeuvre experiment.

The founding members of SERC are EOS Space Systems (Australia), RMIT University (Australia), ANU University (Australia), Lockheed Martin (US), Optus (Australia), and NICT (Japan). The overall goal of SERC is to demonstrate the remote manoeuvre of on-orbit objects using a ground-based laser. Small perturbations or "nudges" will be made to an object's orbit so that a collision is avoided. The method is useful for reducing the risk of potential collision events for objects that have no ability to manoeuvre. If successful, the mitigation method will serve to reduce the growth in debris in low-Earth orbit by avoiding collisions, until other active debris removal methods can remove mass from the near-Earth orbit environment.

Before manoeuvring an object in space, accurate knowledge of the debris environment is needed to select the right conjunction pair. Then the ability to predict the future paths of the satellite and debris objects accurately is also needed to assess whether the manoeuvre will decrease the risk of a collision. This is a fundamental component that has been developed within the Space Asset Management (SAM) program at SERC. The service is equally applicable to the laser manoeuvre demonstration experiment and regular conjunction assessment services for satellite operators. The SAM program has worked closely with Optus Satellite Systems to develop the service. Optus operate a fleet of 5 geostationary satellites. Their experience in conjunction avoidance manoeuvres has provided valuable guidance in the development of the conjunction assessment service. Case studies and results from the conjunction and threat warning service are presented.

The operational system is backed by a centralised database-backed storage system that maintains traceability. This allows follow-up analyses into space events, where each space situational awareness product can be provided, along with the information that was used to generate it. Efficient sensor scheduling methods are employed for tasking a network of sensors using information gain. The conjunction assessment case studies provided in this paper are followed up by tasking EOS Space System's network of tracking sensors in Australia.

Observation track correlation methods have been developed that reliably associate each tracklet with an object. The automation of the data pipeline and the orbit determination process provide updated state vector information which is then used in follow-up conjunction assessments. The conjunction analyses along with nonlinear and non-Gaussian state error propagation provide a conjunction data message with actionable information. Object

characterisation techniques have also been developed based on the light signatures of objects of interest which assists with the demonstration that an on-orbit perturbation has been successful.

This paper also presents the objects selected as candidates for the laser manoeuvre campaign, including the object characteristics that have been determined during the tracking campaigns.

The paper finishes with the next steps for the Conjunction and Threat Warning service, including the future capabilities that will be integrated in to the service.

1. INTRODUCTION

The Space Environment Research Centre (SERC) is an industry-led Cooperative Research Centre for Space Environment Management. The founding members of SERC are EOS Space Systems (Australia), RMIT University (Australia), ANU University (Australia), Lockheed Martin Corporation Australia (Aus / US), Optus (Australia), and NICT (Japan). One of the SERC objectives is to demonstrate the remote manoeuvre of an orbiting object using photon pressure delivered by a ground-based laser system.

A Conjunction and Threat Warning (CATW) capability has been developed in the Space Asset Management program at SERC that is designed to provide satellite operators with high reliability conjunction warnings, and also for the SERC laser manoeuvre experiment. The manoeuvre experiment is planned for late 2019 and will be performed at the EOS Space Research Centre at Mount Stromlo Australia, see Fig 1.

Fig 1. The EOS Space Research Centre, Mount Stromlo ACT, Australia. [Credit: Francis Bennet]

The goal of the CATW service is to provide actionable conjunction assessment knowledge to satellite operators. This has been achieved in several ways, such as the fusion of multiple sources of data, high accuracy propagation and the inclusion of dedicated follow-up tracking, and reliable collision risk information.

For the manoeuvre experiment, an efficient high accuracy conjunction assessment method is needed to assess the effects of a planned manoeuvre. The ability to run one-on-all analyses using simulated manoeuvre effects is need to ensure the object is not manoeuvred into the path of another object, or into a less favourable orbit such as one that increases the risk to an important space asset. The manoeuvre is designed to reduce the overall collision risk, otherwise the object will not be engaged.

The demonstration of the manouevre will be verified by showing that a force was exerted in the slant range direction sufficient to produce a measureable effect to the orbiting object – either by demonstrating a lateral perturbation has been achieved or a change in the object tumble rate and orientation, or both. The lateral perturbation of the object will be assessed by using the highly accurate and sensitive passive optical and debris laser ranging systems at Mount Stromlo and Learmonth. The change in tumble rate will be detected using high rate photon counters, capable of 50+ kHz light sampling, and a fast frame sCMOS camera.

2. CONJUNCTION AND THREAT WARNING SERVICE

2.1 Conjunction Analysis Framework

To build the framework for the conjunction assessments, a number of capabilities had to be automated. Much of this was facilitated through a centralised database-backed catalogue server.

Currently, the conjunction service allows for:

- Whole catalogue all-on-all Two Line Element (TLE) conjunction assessments;
- TLE vs TLE (not accurate enough);
- Multi-TLE versus multi-TLE (batch orbit determination (OD) process fitting pseudo-observations);
- Combined Space Operations Center (CSpOC) Special Perturbations (SP) state vector vs. CSpOC SP state vector
- CSpOC SP versus operator ephemeris;
- Multi-SP versus Multi-SP (batch process fitting SP state vectors);
- SERC SP state vector versus SERC SP state vector;
- SERC SP versus operator ephemeris;
- Combinations of the above, e.g. CSpOC SP vs SERC SP.

Due to the modular architecture for the propagator interface, new state vectors and associated propagators can be implemented into the CATW service with ease. The SERC CATW service can fuse data from the sensor network to improve the collision predictions. Also, state error information is generated during the SERC ephemeris generation and so the probability of conjunction and the time until the error becomes non-Gaussian can be calculated. This information is not generally provided by CSpOC for the TLEs or SPs which limits the ability of satellite operators to make reasonable assessments of the risk posed by CSpOC conjunction warning messages.

The SERC Conjunction Risk Assessment Program (SCRAP) is implemented as a library that can be utilised in a number of ways. It can be implemented directly into an application, or connected to a server backend and accessed via a graphical user interface over a secure and authenticated connection. The daily analyses are run via a set of scripts that automatically pull public and SERC catalogue data, run the conjunction detection process and then analyse the results to automatically enqueue follow-up scenarios with more accurate data and propagation methods. Results are published in the standard Conjunction Data Message (CDM) format and fed back to the orbit determination process in order to identify possible objects of interest.

The CATW algorithm is implemented in OpenCL, allowing it to run on massively parallel graphics processors and multi-core CPUs. If the propagator also runs on a graphics processor, object population data can be transferred between the two processes directly in GPU memory without the need to download it to main memory first. Depending on the performance of the propagator up to 150 million object pairs can be checked for conjunctions each second in an all-on-all scenario.

Once a conjunction warning is delivered from the TLE all-on-all analysis, a batch fit to TLE pseudo-observations generated from multiple TLEs is automatically queued and the conjunction assessment is repeated for that conjunction pair with numerical propagation from the fitted state and covariance.

The CATW service has been set up as a server so multiple conjunction assessments tasks can be queued for execution. There is also a simple client front-end interface that the user can use to run and view the conjunction assessments, see Fig 2.

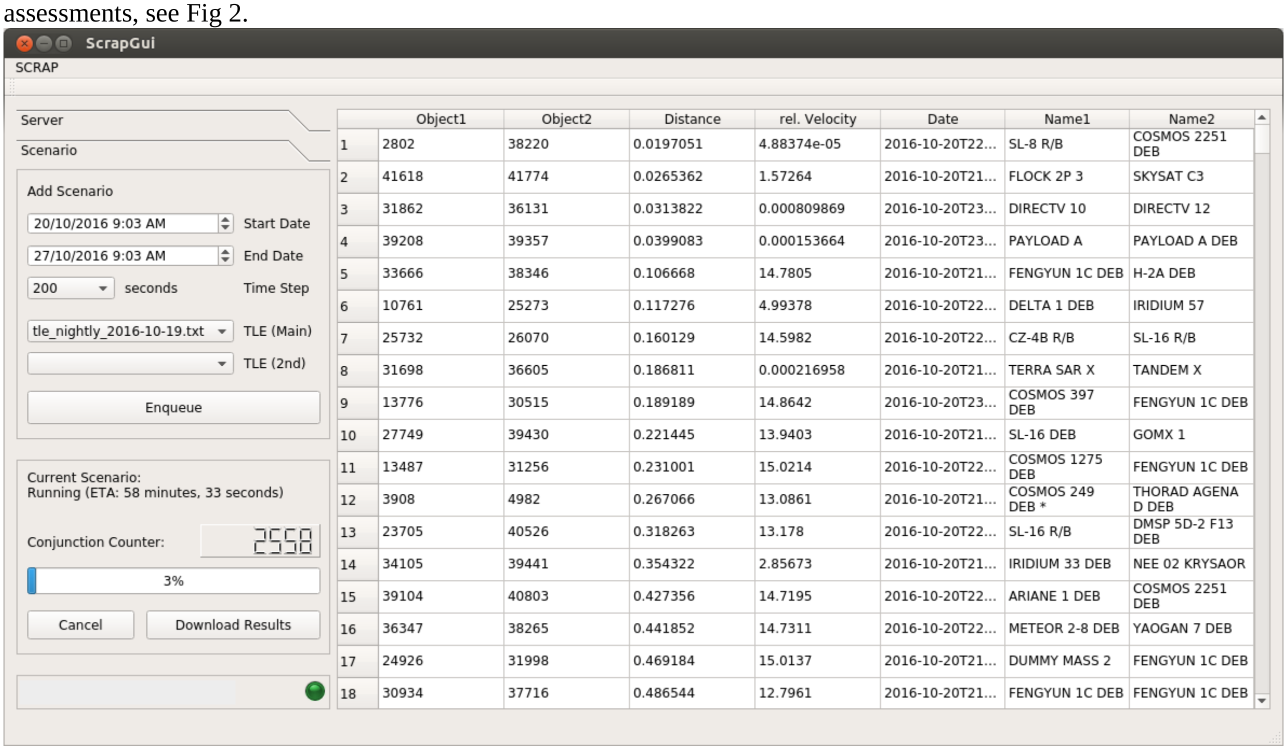

Fig 2: Example of the SCRAP interface

A simplified schematic of the CATW service components is shown in Fig 3. This centralised Space Object Catalogue (SOC) is a major component of the service and keeps track of the progress of the connecting modules. The simple connections between the modules improves the maintainability of the service as components can be replaced/upgraded without bringing down the whole service. The sesnor network provides tracking data which is delivered to the SOC and passed through the correlation procedures. The SOC decides whether there is sufficient information to update the ephemeris if so the SERC Catalogue Orbit Prediction and Estimation (SCOPE) is called to update the state and covariance. These are then distributed to the scheduler and the conjunction assessments modules and used in the collision proedcition refinement, with the result being delivered back to the SOC for action. External data is also stored in the SOC and distributed to the processes that require it. The SOC distibutes tasks to a series of nodes servers that run in parallel. The conjunction assessments are performed on GPUs for efficient computation.

The following sections provide more detail on the components of the SERC CATW service.

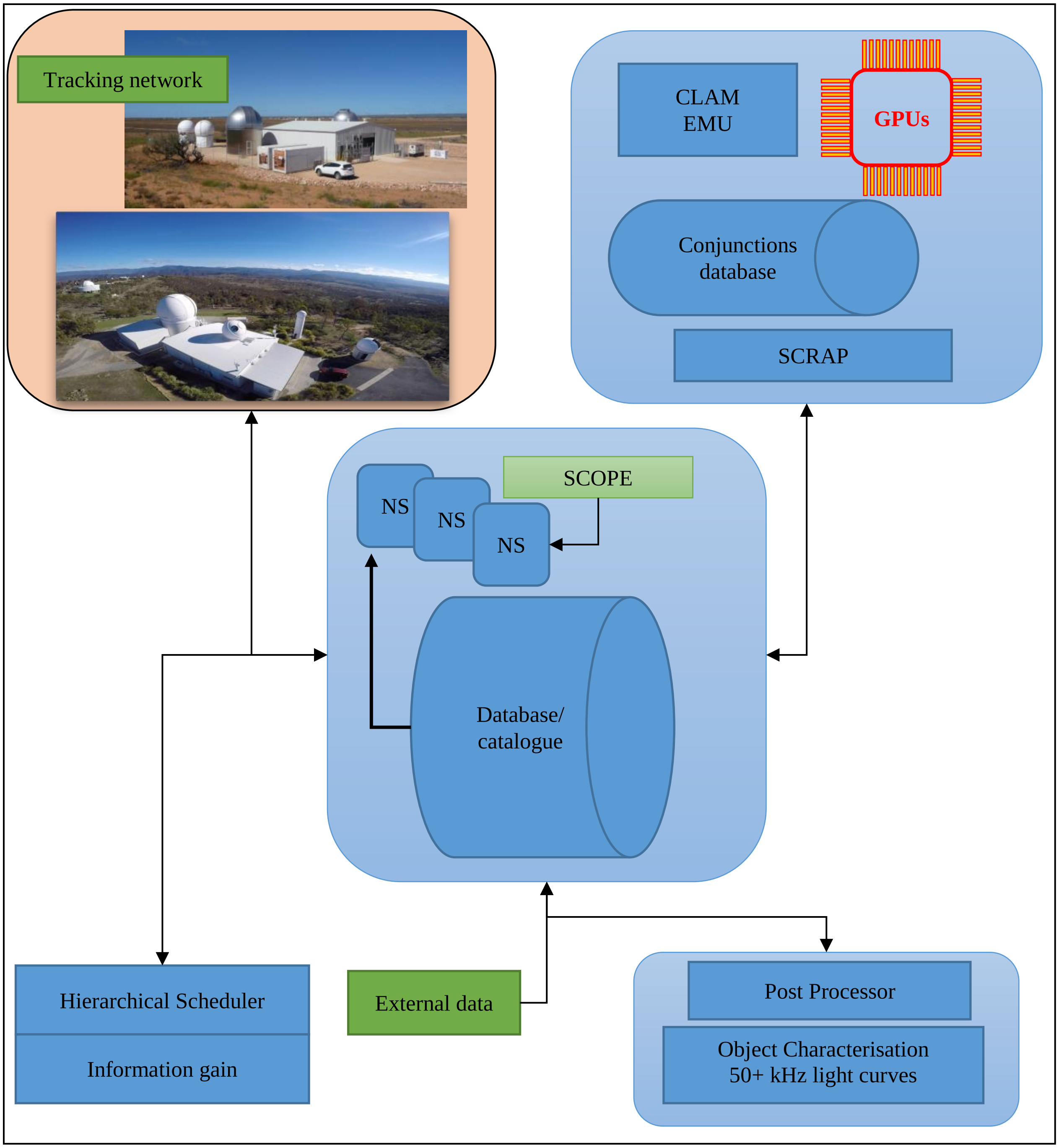

Fig 3: Schematic of the relationships between the various components of the CATW service. NS – Node Server, CLAM – Collision Likelihood Assessment Module, EMU – Encounter Metrics Utility

2.2 Database and Space Object Catalogue (SOC)

The SOC is a centralized database-backed storage system that maintains traceability. It is the central node for the CATW service and handles a lot of the automation tasks. The database automatically detects when new observations arrive for the sensor network and triggers the track correlation process and stores the result and the raw data. The track correlation process is triggered as soon as an observation track is delivered to the catalogue. As part of the process each individual observation is associated and as such multiple objects in the field of view are split into separate files for subsequent processing and storage. The states and covariances from the catalogue are used to validate the incoming observations using probabilistic data association. The track correlation algorithms have been validated in regular tracking operations and are very reliable.

The SOC then checks whether an OD process should be executed and distributes the task to the node servers that are running SCOPE for execution. Once completed the state and covariance are stored with detailed information from SCOPE. These states and covariances are also automatically sent to SCRAP for conjunction assessments. The SOC stores the CDM information delivered from SCRAP and displays them to the user through an HTML frontend GUI. It parses the information and sends the tracking list to the scheduling server which will assign tasks to the tracking sensors, by either the information gain based scheduler or one of EOS's internal scheduling methods. Once the sensors collect the tracking data, the SOC will receive the data and the cycle continues.

The SOC is also set up to perform other tasks. For example, report on the tracking network health through a health monitor server, analyze tracking statistics such as number of tracks, where the telescopes have observed, post processor performance, telescope calibration results. It has the facility for the user to download the tracking data, states and covariances, and CDMs.

2.3 Sensor Scheduling

Sensor scheduling for the catalogue maintenance is performed using an information-gain based scheduler, reported in the companion paper[1], and in earlier work [1, 2].

The Information-Gain based scheduler has been delivered by Industrial Sciences Group. The scheduler has been optimised in C++ and now allows for a larger network of sensors and distributes the tasking by maximising the information gain. The software has been tested and the scheduler will be used in the lead up to the manoeuvre demonstration.

There are several ways to task the EOS tracking network. As well as being able to parse the information gain based schedule tasking, the EOS Sensor network has been designed such that scheduling is a hierarchical process. Schedules from different sources can be executed with a priority of their own and at any stage emergency tasking can be accepted. This tasking can happen in near real time or be pre-programmed and the running tasking on the sensors is interrupted automatically to execute the emergency tasking. A priority scheduling process is used and the conjunction follow up tasking typically given the highest priority.

Once a conjunction warning is issued, the sensor network is cued for follow-up tracking to improve the orbit ephemerides and the conjunction assessment is repeated.

2.4 Object Characterization

Object characterization is the process of determining information about an object's characteristics, such as shape, size, material, stability and orientation. This information is important in predicting orbital perturbations caused by non-conservative forces, such as drag and solar radiation pressure, and object identification for observation correlation. Object characterization is also useful in identifying potentially dangerous debris, with rapidly rotating objects more likely to experience shedding or break up events.

A multi-object tracking algorithm for optical imagery has been developed to perform automated photometric analysis on space objects. The algorithm detects and tracks both objects and background stars in imagery through a Fast Fourier Transform approach, allowing for the extraction of corrected magnitude and position measurements. The changing magnitude of an object over time is known as a light curve and can be used to determine information about an object's characteristics. An example is provided in Fig 4 which shows the light curve of a Falcon 9 rocket body extracted from observations recorded on the 0.7m telescope at Mt Stromlo. A Lomb-Scargle periodogram of the light curve is provided as well. There is a clear periodicity evident in the light curve, which appears on the Lomb-Scargle periodogram as the dominant peak at a period of 41.3 seconds. Given the symmetrical nature of the rocket body it was determined to have a spin period of 82.6 seconds.

[1] Shteinman, D., Yeo, M., Ryan, A., et al., Design & Development of an optimized sensor scheduling & tasking Program for Tracking Space Objects, AMOS 2019, Sep 17-20, Maui HI

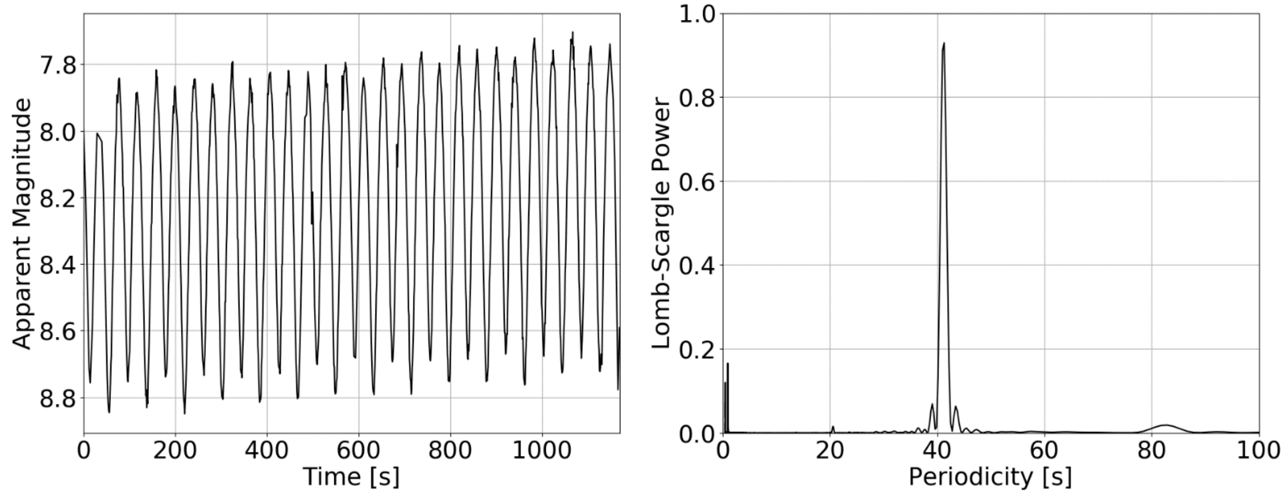

Fig 4. Extracted Light Curve and Lomb-Scargle Periodogram of a Falcon 9 R/B (NORAD ID: 40108)

An opto-electronic device for counting solar photons reflected from a satellite towards a ground receiver telescope has also been developed. The high-rate, single-photon sensitivity light curves can be collected at rates of 50 kHz and can be used for the space object characterization, nano-torque detection and the photoacoustic experiments. One of the detectors is being installed on the 0.7m telescope at Stromlo, see Fig 5, and another on the 1-m telescope in Zimmerwald. There are plans for further deployments for a global network.

Fig 5. The A2 telescope at Mount Stromlo

As part of the SERC laser manoeuvre demonstration, the detector will be used to characterize objects of interest. Their spin characteristics of the objects will be accurately determined prior to laser engagement and immediately after to determine if there has been a change in the spin rate of the object. A change in spin-rate would indicate that the laser has exerted a force on the object that has generated a torque. A potential application of this combined technology is in the stabilization of tumbling objects.

2.5 SERC Catalogue Orbit Prediction and Estimation (SCOPE)

SCOPE is the main software for ephemeris generation and has been automated through the SOC. An OD event is triggered if there is a new incoming observation track and SCOPE is called to update the orbit. A state and covariance is generated which are automatically handed off to the conjunction assessment process.

A batch least-squares (BLS) approach is used, with the following perturbation forces selectable:

- Earth gravity field
- Solid Earth and ocean tides
- Atmospheric drag

- Solar Radiation pressure
- Solar-lunar and planetary gravity
- General relativity
- Earth albedo
- Thrust manoeuvres
- General accelerations

Several types of observational data can be fitted, including passive optical observations, laser ranging, radar observations, RF observations, GPS positions, pseudo observations generated by propagating TLEs using SGP4, and precision control ephemeris data. Initially these tracks from the various sources are weighted by default values based on the typical nominal noise of each sensor type in the network.

Once sufficient observations become available, an OD process is triggered and the procedure begins by loading all of the satellite, force model, observations information. The automation procedure checks the database for known object physical characteristics such as the area, mass and coefficients of drag and reflectivity. If these are not explicitly stated combined ballistic coefficient and radiation coefficient data is used to define the object characteristics. These are stored in the database as a time series and used to seed the OD process. If physical parameters are not known, the process checks whether an estimate of the area-to-mass ratio can be derived from using the Ballistic Coefficient Estimation Method [3] or a similar method in the case of SRP. The physical values for operational or defunct satellites may can also be derived from their schematics (where available) or by obtaining object characteristics using automated web scraping tools. When all of the prior cases are unsuccessful, a default value is used.

The OD process is then run and follows a traditional Batch Least Squares method, see [4] for example, except that a multi-start optimization process has been added to increase the reliability through the automation. Once this process is complete an OD solution is classified as one of the following and summary information is displayed through the catalogue interface:

- SUCCESS – the process passed all of the quality checks;
- QUARANTINED – the process didn't meet at least one of the quality checks, operator to intervene;
- NOT_CONVERGED – the OD process diverged;
- FAILED – rare case where the OD process may have been interrupted and didn't complete. The process will automatically retry the OD process.

Further developments will introduce comparison between the propagated state and covariance matrices from different OD processes – of the same object – to assess the statistical consistency between prior and subsequent orbit determinations.

2.6 Conjunction Assessments

The conjunction assessment system has been validated in several test scenarios using SERC's own catalogued states as well as CSpOC special perturbations, and ephemeris data provided by Optus Satellite Systems – a major Australian telecommunications provider that operated a number of GEO satellites. Results have been validated and are in line with conjunction threat warnings from CSpOC. SERC researchers and executive travelled to Optus in Belrose on the 7th June 2019 to demonstrate the outcomes from the trial service.

2.6.1 Optus conjunction assessments

Several historical close approach scenarios were used to validate the results of the CATW service and demonstrated to Optus. An example is the close approach between Optus 10 and a Block DM-SL R/B on 26th November 2018. This is a particularly interesting case due to the highly eccentric orbit of the Block DM-SL R/B. The comparison is shown in Tab 1.

Tab 1. Comparison of miss distance calculations comparing CSpOC results for two case: (1) CSpOC SP vs. Optus Ephemeris, (2) CSpOC SP vs SP, with the SERC SP vs Optus Ephemeris.

	CSpOC SP vs Ephemeris	CSpOC SP vs SP	SERC SP vs Ephemeris
Miss Distance	5,809 m	6,781 m	5,864 m
TCA	2018-11-26 18:30:09	2018-11-26 18:30:13	2018-11-26 18:30:07

The CSpOC results compare well with the SERC SP vs Optus ephemeris. In two cases the Optus ephemeris data was used with the SP vs SP case not using the Optus ephemeris data. We can see that the assessments compare well.

2.6.2 Other Australian Objects

As well as focusing on the Optus fleet, SERC is also running regular conjunction assessments for the other Australian assets, and defunct objects (Tab 2). Note: the Optus fleet is included for completeness. These objects are now all in the SERC CATW checks and will be routinely tracked along with objects that come within close approach of them.

Tab 2. All objects listed as Australian in the SATCAT

Norad ID	Satellite Name	Apogee	Perigee
4321	OSCAR 5 (AO-5)	1477	1434
15993	OPTUS A1 (AUSSAT 1)	35953	35904
16275	OPTUS A2 (AUSSAT 2)	35898	35858
18350	OPTUS A3 (AUSSAT 3)	36209	36137
22087	OPTUS B1 (AUSSAT B1)	36123	36053
22089	OPTUS B1 R/B(STAR 63F)	36406	396
23227	OPTUS B3	36256	36211
23229	OPTUS B3 PKM	38108	360
25398	WESTPAC	817	814
27598	FEDSAT	803	789
27831	OPTUS C1	35809	35763
29495	OPTUS D1	35802	35771
32252	OPTUS D2	35803	35770
35756	OPTUS D3	35797	35775
40146	OPTUS 10	35805	35768
40940	SKY MUSTER (NBN1A)	35795	35778
41794	SKY MUSTER 2	35794	35779
43014	BUCCANEER RMM	810	459
43694	PROXIMA I	514	489
43696	PROXIMA II	514	489
43809	CENTAURI-1	592	570

2.7 Collision Risk Assessments

Important advancements have been made in recent years regarding the actionability of information on predicted possible conjunctions [5, 6]. It is important to acknowledge that some of the foundations upon which conventional methods rely are being questioned (e.g. [6]).

With this in mind, SERC's CATW starts out with a pre-assessment of the predicted close approach based on the predetermined state and uncertainty at the time of closest approach (TCA). Herein, the estimated miss distance and relative velocity are updated with: i) estimated close approach duration, ii) normalised miss distance (Mahalanobis distance) at the given TCA, iii) the minimum Mahalanobis distance in the vicinity of the TCA, iv) information on the normality of the given uncertainties in the vicinity of the estimated close approach and v) a low-accuracy, Monte-Carlo pre-assessment of the collision likelihood. For manual assessment, this information gives a good first impression of a situation, bearing in mind, that all uncertainties are assumed to be aleatory in nature. This is important to understand to be able to draw the appropriate conclusions for any further action. This information also builds part of the basis for scheduling observations.

The CDM from November 11, 2018 (CDM_ID:21335433) for the above case is used to exemplify the state of the collision risk assessment. The CDM yielded a miss-distance of 227 m at a relative speed of 1.4 km/s:

CSDS_CDM_VERS	=1.0	
COMMENT	=CDM_ID:21335433	
CREATION_DATE	=2018-11-21T19:18:28	
ORIGINATOR	=JSPOC	
MESSAGE_FOR	=OPTUS 10	
MESSAGE_ID	=40146_conj_29521_2018330183017_325192303736	
TCA	=2018-11-26T18:30:17.84	
MISS_DISTANCE	=227	[m]
RELATIVE_SPEED	=1388	[m/s]

Given the combined uncertainty of the two objects, the normalised miss-distance at TCA was 3.1138 standard deviations. The chance of the two objects' states occupying the same space is well below 5%. Just 1 second later, the Euclidean distance is already at 1.4 km; the normalized distance however, is only 0.3927 standard deviations. This is shown in the SERC Encounter Metrics Utility (EMU) software in Fig 6.

Fig 6. Comparison of the normalized miss-distance standard deviations at TCA and 1 second later. The left figure shows the normalized miss-distance of 3.1138 standard deviations at TCA, the right figure shows a normalized miss distance of 0.3927 standard deviations 1 second later.

Fig 7 shows a case where the test for normality fails for one of the object's estimated state error within half an orbit before as well as after the TCA. This begs the question of whether the true estimated state error at TCA from which the covariance matrix was generated perhaps itself already exhibited some non-Gaussian features? The information content in any collision probability assessment that does not account for this lack of information is therefore questionable. We compute the collision likelihood nevertheless, using a Monte-Carlo approach and obtain a likelihood of 0.00012676338782. At a sample size of 1924846 and given a confidence level of 95%, the Dagum bound [7] yields a remaining relative error of 5%.

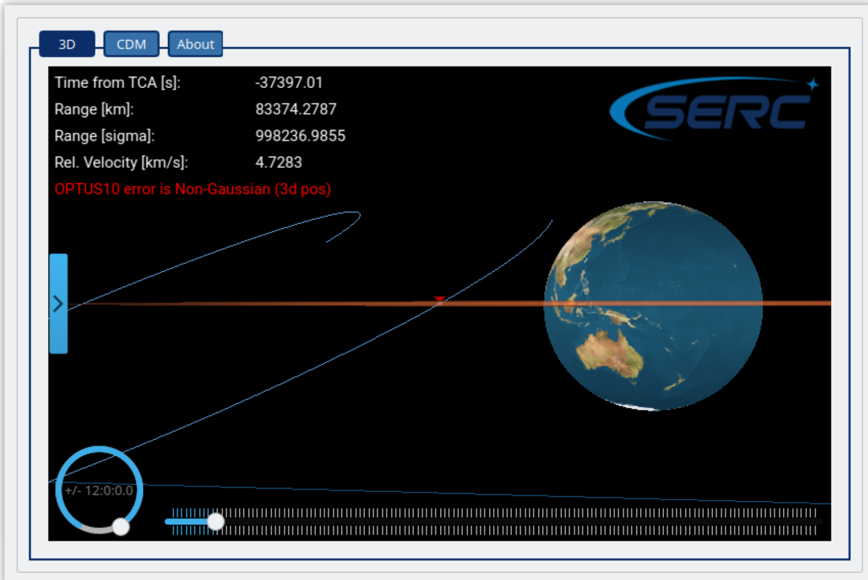

Fig 7. Example of when one of the state errors fails the test for normality

In this case, the apparent lack of information on the realism of the state uncertainty as well as the normalized miss distance are reason enough for assigning a high priority for re-observation.

3. LASER MANOEUVRE CAMPAIGN

In this section we list some of the objects of interest for the laser manoeuvre campaign. The manoeuvre candidates were chosen based on their ballistic coefficient, B_C, defined as

$$B_C = \frac{m}{C_d\, A}$$

where C_D is the drag coefficient, A is the cross sectional area, and m is the mass of the object. The objects that have larger area-to-mass ratios are more likely to be able to be manoeuvred using photon pressure delivered by a ground-based laser, though more difficult to predict accurately.

Prior to the debris manoeuvre campaign, the objects in Tab 3 will be laser-ranged to produce accurate ephemeris data.

Tab 3. Debris candidates for the manoeuvre campaign. Note the inverse ballistic coefficient is listed

NORAD ID	Name	Owner	Apogee [km]	Perigee [km]	RCS [m^2]	$1/B_C$ [m²/kg]
4842	THORAD AGENA D DEB	US	921	886	0.1133	**1.01**
8397	THORAD DELTA 1 DEB	US	955	909	0.0504	**3.86**
10839	DELTA 1 DEB	US	980	913	0.0189	**4.17**
21335	DELTA 1 DEB	US	962	866	0.0528	**4.18**
21343	DELTA 1 DEB	US	933	784	0.041	**0.60**
21543	DELTA 1 DEB	US	959	846	0.0107	**2.84**
21985	DELTA 1 DEB	US	986	936	0.0083	**2.23**
25834	SL-14 DEB	CIS	870	806	0.0339	**11.76**
26828	DELTA 1 DEB	US	973	889	0.0041	**1.77**
27479	TRANSIT 5B-1 DEB	US	860	802	0.01	**2.94**
27742	COSMOS 1823 DEB	CIS	903	686	0.0069	**7.09**
28611	NIMBUS 2 DEB	US	950	891	0.013	**2.58**
29138	TRANSIT 14 DEB	US	894	886	0.036	**3.19**
29180	TRANSIT 15 DEB	US	903	832	0.0052	**3.31**
29265	TRANSIT 15 DEB	US	849	786	0.0083	**3.08**
29276	TRANSIT 15 DEB	US	903	865	0.005	**3.17**
30308	FENGYUN 1C DEB	PRC	857	702	0.008	**2.03**
31402	METEOR 2-17 DEB	CIS	924	909	0.0095	**0.42**
31551	FENGYUN 1C DEB	PRC	918	786	0.0182	**0.95**
31942	FENGYUN 1C DEB	PRC	976	751	0.0114	**2.24**
32444	FENGYUN 1C DEB	PRC	846	739	0.012	**1.63**
33508	TRANSIT 16 DEB	US	972	900	0.0317	**3.07**
33699	FENGYUN 1C DEB	PRC	749	664	0.0159	**1.35**
38522	CZ-4 DEB	PRC	932	824	0.0096	**3.02**
38524	TRANSIT 5B-1 DEB	US	972	856	0.0129	**1.98**
38525	TRANSIT 5E-5 DEB	US	723	638	0.0045	**2.11**
38526	TRANSIT 5E-5 DEB	US	738	619	0.0099	**2.73**
38527	TRANSIT 5E-5 DEB	US	793	705	0.0275	**2.71**
38530	TRANSIT 5E-5 DEB	US	786	725	0.007	**3.70**
38541	TRANSIT 16 DEB	US	984	919	0.0157	**0.64**
40406	METEOR 2-17 DEB	CIS	914	902	0.0145	**1.63**
40408	DMSP 5D-2 F13 DEB	US	800	774	0.047	**2.90**
40439	DMSP 5D-2 F13 DEB	US	773	698	0.028	**2.47**
40514	DMSP 5D-2 F13 DEB	US	691	670	0.0142	**1.97**
40585	DMSP 5D-2 F13 DEB	US	725	659	0.0105	**2.98**
41047	DMSP 5D-2 F13 DEB	US	741	673	0.0086	**5.51**
41048	NOAA 16 DEB	US	810	773	0.1049	**4.87**
41088	NOAA 16 DEB	US	795	772	0.1045	**1.98**
41407	NOAA 16 DEB	US	821	752	0.0038	**2.84**
41535	NOAA 16 DEB	US	781	760	0.0034	**4.56**
41738	NOAA 16 DEB	US	802	797	0.0044	**1.44**
41927	WORLDVIEW-2 DEB	US	701	644	0.0283	**2.81**
42287	TRANSIT 5E-5 DEB	US	793	715	0.0059	**1.80**
42332	DMSP 5D-2 F13 DEB	US	794	774	0.0104	**3.04**
42336	NOAA 16 DEB	US	829	760	0.005	**3.48**
42389	NOAA 16 DEB	US	838	823	0.0061	**2.05**
42414	NOAA 16 DEB	US	802	752	0.0067	**2.22**
42443	NOAA 16 DEB	US	807	787	0.0042	**1.09**
42607	SEASAT 1 DEB	US	710	675	0.0463	**3.43**
42667	THORAD DELTA 1 DEB	US	818	800	0.0101	**2.74**

The Akari lens will also be considered as it was previously studied by Mason et al. [8]. Several objects have also be selected based on the high-rate photon counting campaign. Objects with well resolved spin and orientation models will be selected to analyse the perturbations caused by the laser.

4. NEXT STEPS

There is still some work to be done in optimising the service. As well as further optimisations to the processing speed, the service will be transitioned onto new GPU equipment. Eight new Asus RTX2080TI Turbo 1350MHz GPUs have been installed in a 10-GPU rack server. The CATW service will be transitioned onto the new equipment to cater for an increase in demand. This will be performed in October 2019.

Also developed during SERC is the ability to perform orbit determinations on manoeuvring objects. This is a key component and a demonstration of the data fusion of the Optus RF data with passive optical data has been completed. Orbit solutions for the Optus fleet can be performed within SERC as an extra service to satellite operators. The ability to ingest new data types with ease means the service can be extended to other operators. For example Optus native RF ranging format and manoeuvre log formats have been successfully parsed in the process.

A result of a conjunction assessment may be to perform an active avoidance manoeuvre. Another option is to delay or bring forward a planned station keeping manoeuvre. One of the next steps in the SERC CATW service is to automate the manoeuvre planning procedure.

SERC will continue to perform conjunction assessments for Australian objects and will work with Australian satellite operators to assist in the protection of Australian assets and the preservation of the space environment,

4.1 Future Directions with Machine Learning Applications

The light curve database generated by this algorithm will be used for future research on object classification using a time series-based recurrent neural network (RNN). Furfaro et al. [9] demonstrate that 1-dimensional feedforward convolutional neural networks (1D-CNN) outperform traditional machine learning methods such as bagged trees and support vector machines in classifying objects based on light curve data as rocket bodies, payloads and debris. RNN approaches, such as the Long Short Term Memory (LSTM) algorithm, are expected to be better suited to real light curve data as they are able to account for temporal patterns, missing data and varying input lengths. RNNs will be compared with 1D-CNNs on the extracted light curve dataset to determine if characterisation performance can be improved.

4.2 Covariance/conjunction realism

Alfano has detailed the dilution region in the probability of conjunction estimation as a measure of estimating reliability of results in and later publications. For the sake of actionability, later publications greatly expand on this [5]. Delande et al. [6] argue that distinguishing between aleatory and epistemic uncertainties in the conjunction assessment may yield superior results. In particular, probable collision likelihood results are replaced by possible collision likelihood results. This allows a more intuitive understanding of the results and lends itself well to system automation.

The current approach assumes only aleatory uncertainties. An emphasis is put on efficient detection and treatment of state uncertainty volumes with and without non-Gaussian features. This is a prerequisite for both outlined methods for conjunction assessment.

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REFERENCES

1. Gehly, S. and J. Bennett, *Incorporating Target Priorities in the Sensor Tasking Reward Function*, in *Advanced Maui Optical and Space Surveillance Technologies Conference*. 2015: Maui, Hawaii.
2. Gehly, S. and J. Bennett, *Distributed Fusion Sensor Networks for Space Situational Awareness*, in *68th International Astronautical Congress*. 2017: Adelaide, Australia.
3. Sang, J., J.C. Bennett, and C.H. Smith, *Estimation of ballistic coefficients of low altitude debris objects from historical two line elements.* Adv. Space Res., 2013. **52**(1): p. 117-124.
4. Vallado, D.A., *Fundamentals of Astrodynamics and Applications*. Fourth ed. 2013: Microcosm Press, Hawthorne, CA.
5. Alfano, S. and D. Oltrogge, *Probability of Collision: Valuation, variability, visualization, and validity*. Acta Astronautica, 2018. **148**: p. 301-316.
6. Delande, E., M. Jah, and B. Jones, *A new representation of uncertainty for collision assessment, AAS 19-452*, in *29th AAS/AIAA Space Flight Mechanics Meeting*. 2019: Ka'anapali, Hawaii.
7. Alfano, S., *Satellite conjunction Monte Carlo analysis.* Advances in the Astronautical Sciences, AAS09-233, 2009. **134: 2007-2024**.
8. Mason, J., et al., *Orbital debris–debris collision avoidance.* Adv. Space Res., 2011. **48**(10): p. 1643-1655.
9. Furfaro, R., R. Linares, and V. Reddy. *Space Objects Classification via Light-Curve Measurements: Deep Convolutional Neural Networks and Model-based Transfer Learning*. in *The Advanced Maui Optical and Space Surveillance Technologies Conference*. 2018.