

# Optical techniques for space environment management

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## ABSTRACT

The Space Environment Research Centre (SERC) is a fully-funded multi-national research collaboration for the management and mitigation of space debris using optical technologies. SERC is tasked with developing mitigation strategies for the many debris objects not amenable to space-based interventions.

SERC research leverages very accurate information from a new optical space tracking network to develop viable near-term strategies to manage debris using only ground-based infrastructure.

SERC has sufficient resources to conduct full-scale on-orbit testing of candidate approaches. We report on SERC progress in astrodynamics, precision catalogs, conjunction processing, adaptive optics and high power lasers as well as the architecture of the research effort.

## 1. INTRODUCTION

The Space Environment Research Centre (SERC) is a not-for-profit international research collaboration funded by the Australian Government (34%) and other participants (64%). The key objective of SERC is to improve the safety of navigation in space, and ultimately to safely move space debris using ground-based lasers. The initial research and development budget is \$50M (USD) plus an infrastructure budget of \$60M (USD) and a planned program expansion in 2018 will see these R&D and infrastructure budgets expanded.

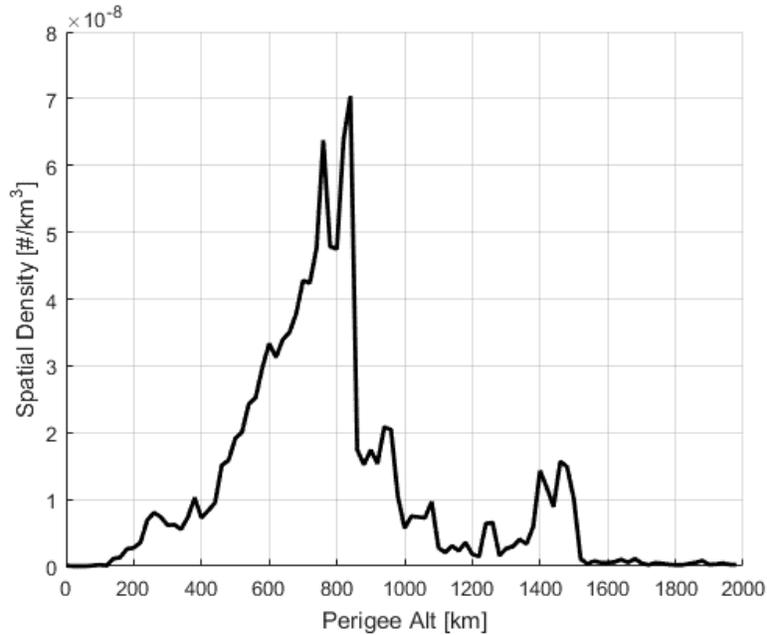
The founding participants in SERC represent government, industry and universities across several countries. The program expansion will follow this trend. The founding participants are EOS Space Systems (AUS), The Australian National University (AUS), RMIT University (AUS), Australian Government – Department of Industry, Innovation and Science (AUS), Optus (AUS), Lockheed Martin (US), and the National Institute of Information and Communications Technology (JPN).

The primary goal of SERC is to contribute to the mitigation of the growth of debris objects in low-Earth orbits by using ground based laser stations to perturb debris orbits and avoid collisions. The well-known collisional cascading phenomenon [1] (or *Kessler Syndrome*) whereby collisions between Earth-orbiting objects become the dominant source of new debris, will mean new missions will become prohibitively risky. Active assets may move out of harm's way if they are maneuverable but little can be done for conjunctions between non-maneuverable objects or debris-on-debris conjunctions.

Critical regions in the near-Earth environment, for example, the altitude band around 800 km (see Fig. 1) are targets for future active debris removal missions [2]. These remediation missions will remove hazardous mass from the environment as is needed to stabilize the growth in the debris field as mitigation measures alone are insufficient [3]. A recent review of the various methods for active debris capture and removal may be found in [4]. Space-based debris removal missions are expensive due to a launch requirement for each debris removal; however, large objects may be removed, effectively reducing the total on-orbit debris mass.

Another proposal is the use of high-powered ground-based pulsed laser systems to ablate the surface of the debris and perturb the orbit sufficiently so that the object reenters the Earth's atmosphere [5]. These systems may be used repeatedly but they rely on very high powered pulsed laser systems which may be difficult to acquire [6].

Space-borne laser systems have also been considered [7, 8]; however, these are costly and require a launch and rely on high powered laser systems.



**Fig. 1. Plot of the spatial density of catalogued objects<sup>1</sup> in low-Earth orbit**

The maneuver by ground-based Continuous Wave (CW) laser systems discussed in this paper does not remove mass from the environment but seeks to buy time by reducing the growth rate of the debris field through collision avoidance. This technique offers a relatively cost-effective short-term prospect for mitigating debris growth, and also establishes a technology base for other laser techniques to be applied as they mature. A network of CW lasers can also support active debris removal efforts by de-spinning tumbling objects allowing for a safer rendezvous [9].



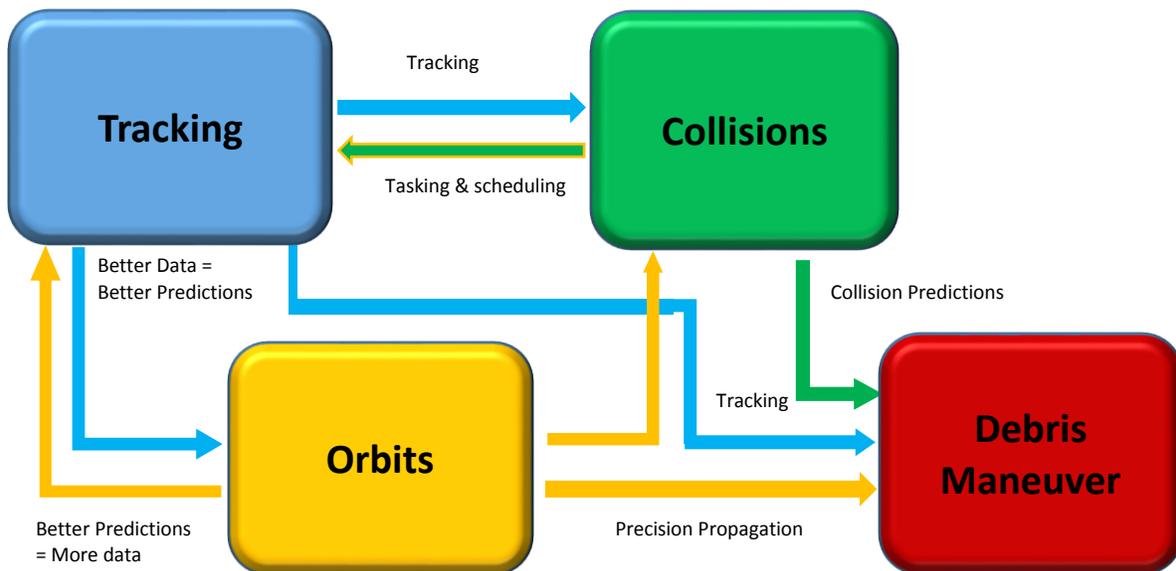
**Fig. 2. Existing EOS Space Research Centre at Mount Stromlo, Canberra, Australia.**

<sup>1</sup> Satellite Catalog (SATCAT), <http://celestrak.com/pub/satcat.txt>, accessed 4-Nov-2016.

The demonstration system is being developed at Mt Stromlo, Australia, at the EOS Space Research Centre ( Fig. 2). The site is already equipped with a debris tracking laser and a 20 kW CW laser equipped with adaptive optics will be installed for the demonstration. The following section briefly outlines the structure and content of the SERC research programs.

## 2. KEY SERC PROGRAMS

The research and development required to achieve remote maneuver of Earth-orbiting debris objects is split within SERC into four main research programs. Fig. 3 shows a schematic of the research programs and their main interdependencies. More detail may be found at [www.serc.org.au/research/](http://www.serc.org.au/research/).



**Fig. 3. Schematic of SERC Research Programs and their interdependencies**

A brief overview of the research focus of each research program is as follows:

*Research Program 1: Identification of Space Objects and Preservation of the Space Environment* is tasked with improving the accuracy and reliability of observations of Earth-orbiting objects including active debris laser ranging in low-Earth orbit (LEO) and adaptive optics (AO) enhanced imaging, tracking, and energy transmission through the atmosphere. This program develops and builds all of the ground tracking and beam delivery systems for the maneuver.

*Research Program 2: Orbit Determination and Predicting Behaviours of Space Objects* is developing improvements in orbit predictions and new models for the atmospheric mass density in low-Earth orbit. This program will give more accurate and reliable orbital predictions in low-Earth orbit which are crucial for the conjunction assessments and laser maneuver planning and execution.

*Research Program 3: Space Asset Management* focuses on developing a space object catalogue and conjunction and threat warning service for satellite operators. The database and catalogue will comprise precision tracking data of objects likely to be involved in a conjunction as well as object specific parameters estimated in object characterization studies. This program is a critical component for a safe maneuver of debris using laser photon pressure.

*Research Program 4: Space Segment* will use the developments achieved in the other programs to engage specific space objects for remote maneuver. SERC will launch up to three satellites as instrument platforms, including instrumentation to measure the actual radiation flux achieved on the object, the forces applied, and the orbit perturbation achieved through laser photon pressure.

Each program is critical to achieve a successful ground-based laser maneuver of an on-orbit object. As well as on-board instrumentation on the test satellites, ground-based tracking assets will monitor the laser maneuver using light curve analysis and orbit determination of precision optical and laser tracking data. The conjunction threat warning software will analyze the pre- and post-maneuver orbits to ensure the probability of conjunction is reduced rather than posing a threat to any other object. In the next Section we briefly discuss the conjunction analysis and the requirements to perform a maneuver.

### 3. CONJUNCTION ANALYSIS

An integral part of the maneuver campaign is the conjunction and threat warning service. To avoid moving a piece of debris into a collision path, it is necessary to identify all objects in the vicinity and schedule intensified tracking as a first step before a maneuver is attempted. A conjunction probability assessment will be made for pre- and post-maneuver with the maneuver simulated as accurately as possible including the uncertainties in the engagement success. Only once a conjunction has been reliably identified and it is established that a maneuver reduces the collision probability in the broadest context, will a maneuver mission be initiated. Once a piece of debris has been engaged and maneuvered by SERC it will then remain as a high priority object for follow-up tracking.

The conjunction assessment software propagates all catalogue objects for an *all-on-all* conjunction analysis. It can be run every hour for the entire catalogue to produce a 7 day prediction for collisions. The catalogue can be updated continuously with new tracking data or with updated orbit propagations for special objects, for example, updated orbit predictions from fitting observations collected on objects identified in the collision screenings. Tab. 1 shows the number of close approaches for varying screening thresholds for a seven day prediction.

Screening Threshold	Number of Close Approaches
<5km	42,000 per week
<1km	3,000 per week
<500m	700 per week

**Tab. 1. Number of conjunctions for a 7 day prediction**

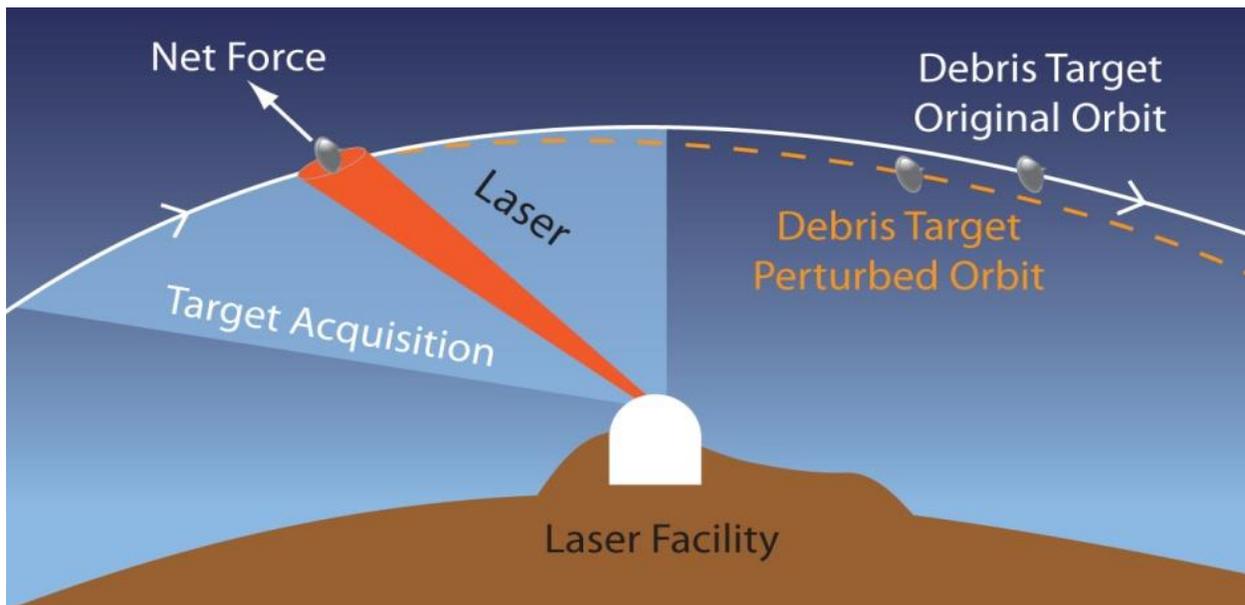
It would be prohibitive to engage in maneuver campaigns for all potential conjunctions due to the number of close approaches, even at the 500 meter threshold. The predicted miss distance for the Iridium 33 and Cosmos 2251 collision which occurred on the 10<sup>th</sup> February 2009 was 584 meters [10]. This shows the importance of high precision orbit predictions in achieving a practical approach.

SERC applies the all-on-all conjunction screening to identify objects for follow-up tracking, so that the number of close approaches can be reduced well below 70 per week, or 10 per day. The conjunction report is sorted for conjunctions with objects of interest (e.g. intact spacecraft) and closest approaches, and the optical and laser tracking systems are tasked using the scheduler to update the catalog with precision tracks for these priority objects. In most cases the new orbits would exclude the objects from the conjunction list and the remaining objects could be monitored or engaged in a maneuver campaign as required.

To assist in maneuver planning and execution, Research Program 3 is contributing in object characterizations (for example, spin determination using light-curves), orbit determination and prediction of non-spherical objects in high-Earth orbits, nonlinear covariance propagation, and fast conjunction assessments. The conjunction assessment code is being optimized for fast computation on Graphics Processing Units (GPUs). Even though special attention is being devoted to optimization for GPUs, the software can also run on a multi-core Computer Processing Unit (CPU). Nonlinear covariance matrix propagation methods are being developed and optimized for reliable conjunction probabilities. The GPU optimization will enable a near real-time assessment of the change in conjunction probability during a maneuver as the orbit is updated. These capabilities are supportive to the maneuver campaign; however, without a high-powered laser the concept cannot be demonstrated. In the next section we discuss the laser maneuver of debris objects using CW laser radiation.

#### 4. MANEUVER BY CONTINUOUS WAVE LASER RADIATION

Laser maneuver by photon pressure is a mitigation measure to help delay the debris growth and buy time until more permanent solutions reach fruition. SERC have extended the NASA LightForce [6, 11, 12] concept to build an operational system to demonstrate its feasibility. An illustration of the laser maneuver by photon force concept is shown in Fig. 4.



**Fig. 4. Illustration of the laser maneuver concept**

The method will be most effective at engagements below 1,000 km, covering the most congested altitudes. Rather than pulsed laser ablation, the maneuver campaign will use CW lasers of 20-100 kW which produce radiation pressure of a similar magnitude as the Sun. Due to the small perturbations achievable, multiple engagements are necessary to sufficiently perturb the object's orbit.

The laser maneuver needs to be sufficient to overcome positional uncertainties. Dedicated observing of debris objects using precision optical and laser debris tracking can provide orbit predictions with ca. 100 meter errors after 48 hours. Thus, if we assume a maneuver engagement period of 48 hours and positional uncertainty in orbit predictions of 100 meters, to ensure a collision is avoided the object would need to be moved more than 200 meters.

Parameter	Value
Orbit Altitude	500 km
Debris Dimension	20 cm
Debris Mass	0.17 kg
Beam Director Diameter	1.8 m
Laser Power	20 kW
Laser Beam Quality ( $M^2$ )	1.2
Delivered Strehl	0.3
Area to Mass Ratio	0.19 m <sup>2</sup> /kg

**Tab. 2. Parameters for a worked example of laser engagement for debris orbit maneuver**

We consider a simple engagement scenario to illustrate the concept for the scenario contained in Tab. 2.

Using the values in Tab. 2 and allowing for transmission loss through the atmosphere and a 1.8 meter beam director equipped with adaptive optics, gives the plot of the force versus zenith distance in the along track direction as shown in Fig. 5. Integrating and dividing by the mass of the object gives a  $\Delta v = 0.32$  mm/s for the pass. This means for a 1mm/s change in the case considered, at least 3 passes would be needed. Therefore, for a practical system a combined power of 60+ kW would be required to exert the required  $\Delta v$  in one pass.

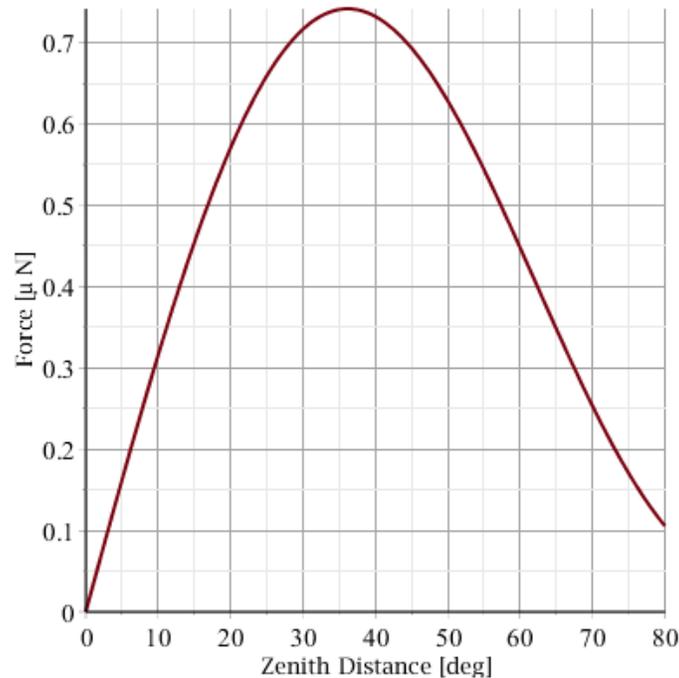
To test the effectiveness of laser photon pressure maneuver, SERC will build and launch two satellites for on-orbit measurements and to calibrate laser beam properties in space. The satellites will carry corner cube reflectors, laser energy and power measurement sensors, precision navigation instrumentation, and radiation sails. The use of the onboard sensing capability will be available to collaborating agencies.

#### 4.1 PROJECT TIMELINE

SERC is funded to demonstrate the feasibility of using non-threatening CW lasers to reduce the rate of collisions. The timeline for demonstration of debris maneuver is as follows:

1. Precision debris tracking and orbit propagation already exists;
2. 2016: Adaptive Optics system operational;
3. 2017: 20 kW CW laser and cooled deformable mirror delivered;
4. 2018: Launch test satellite #1 for beam monitoring on orbit;
5. 2019: Launch test satellite #2 for thrust measurement;
6. 2020: Debris maneuver experiments.

Outputs from all of the research programs are needed to achieve the demonstration. Launching test satellites allows direct measurements of perturbation by on-board instrumentation, rather than experimenting with real debris before the technique can be safely and reliably applied.



**Fig. 5. Force versus zenith distance for the parameters considered in Tab. 2.**

## 5. CONCLUDING REMARKS

SERC is committed to demonstrate that photon pressure can be used to modify orbits of smaller debris objects by 2020. Key programs requirements are precision tracking of all objects in the vicinity of the maneuver, accurate orbit propagations for pre- and post-maneuver conjunction threat warning analyses, and energy concentration of the beam with adaptive optics corrections and precision beam directing.

Up to 50 percent of small debris objects (< 10 kg) may be candidates for laser relocation. The application of a laser photon pressure maneuver can reduce collision risk and buy time for the other debris removal campaigns to remove mass from the environment.

The need for multiple laser engagements requires great care in deciding on whether to commence an intervention, and ineffective or partial interventions in space must be avoided. To allow safe experimentation and the development of accurate and scalable models for later use, SERC will launch satellites to serve as “debris” targets.

## ACKNOWLEDGEMENTS

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