



## ANNUAL REPORT 2016 - 2017



Australian Government  
Department of Industry,  
Innovation and Science

**Business**  
Cooperative Research  
Centres Programme



### **The International Space Station**

must manoeuvre away from a  
possible space debris collision

**1 to 3 times per year**  
on average



### **What is space debris?**


Any human-made object in orbit  
that does not serve a purpose is  
considered space debris. For example,  
components of a spacesuit, retired  
satellites and wrenches



### **Space debris moves**

with high velocity in the range of  
**8km per second**


PRESERVING  
**SPACE**  
FOR THE  
**FUTURE**



**170 million**  
pieces too small  
to track are also in  
orbit



**30,000**  
softball-sized and larger  
pieces are currently  
orbiting Earth



**500,000**  
marble-sized pieces  
currently orbiting Earth

## OUR MISSION

The Space Environment Research Centre (SERC) will develop and commercialise technologies to reduce the threat to space-based infrastructure from space debris.

SERC will consolidate currently-independent research efforts to achieve a critical mass of effort to form a platform for new investment, by providing:

- a transparent framework for international research collaboration, ensuring equity for all collaborators regardless of nationality or whether a private or public entity;
- access to state-of-the-art space research programs and infrastructure;
- new funds for consolidating research program synergies and investigating new avenues; and
- exemplary management of research, consistent focus and strategic leadership.

## OUR VISION

SERC technology will play a key role in practical global efforts for space debris management, mitigation and removal.

SERC will be a collaboration vehicle of choice for compatible national, international and commercial efforts to address issues arising from space debris.



This report has been prepared in accordance with the 2016-17 Cooperative Research Centres (CRC) Programme Annual Report Guidelines and is submitted to comply with the requirements of Section 4 of the Guide.

The CRC for Space Environment Management is administered by the Space Environment Research Centre Limited (SERC).

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# ANNUAL REPORT

1.	Executive Summary	8
1.1.	Achievements	9
1.2.	Risks and Impediments	11
1.3.	Key Researchers	12
1.4.	Performance against activities	18
1.5.	Education and training	30
1.6.	Utilisation and Commercialisation	34
1.7.	Communications	35
1.8.	Governance – Board, committees and key staff	37
1.9.	Participants	44
1.10.	Collaboration	47
1.11.	Financial management	48



# APPENDICES

4.	Glossary of Terms	50
4.1.	SERC Publications	52
4.2.	SERC Scholarship Students	57



# REPORT FROM THE CEO

There is a significant risk to modern society from space debris.

The efficiency of our economies, and the safety and quality of modern life depend increasingly on satellites. From government to individuals we rely on space for time and weather; traffic management and navigation; and all manner of communications. Our emergency first-responders, defence personnel, search and rescue missions and law enforcement agencies rely on space technology. However collisions with space debris increasingly threaten our access to satellite technology.

The number of active satellites expected in orbit by 2025 has doubled over forecasts made only 3 years ago when SERC was established. In addition, important new human endeavours for the exploration of mars and the exploitation of the moon will heavily rely on the safety and security of earth orbit, even while adding to space traffic and collision risk. Management of space debris risk is an increasingly urgent activity.

SERC was established to apply new optical technology to this problem to provide both information and direct intervention. SERC research is already providing significant improvements in information predicting the orbits of debris, to allow active satellites to manoeuvre in time to avoid space debris collision. We will now apply that new information to intervene in space using ground-based lasers to manoeuvre space debris away from collisions which would otherwise accelerate the growth of the debris population.

We are making good progress, and have determined that SERC need not extend beyond its fixed term of 5 years ending in late 2019. Within this fixed term we will establish sufficient progress and momentum for SERC research to be exploited by others, including future collaborations amongst SERC participants and the newly-announced Australian space agency.

To enhance the sustainability of SERC research, SERC has increased its scope to better document and publish key research advances for future researchers, in some cases by adding near space or low orbit testing of key sub-systems. To further ensure the technology and capability is sustained beyond SERC, we have deployed substantial funds towards scholarships and are empowering emerging leaders in the field.

SERC is on track to inject sufficient technology, capacity and momentum to make a long-term contribution to reducing the risk from space debris.

**Dr Ben Greene**  
**Chief Executive Officer**



# REPORT FROM THE CHAIR

I am pleased to report that the CRC for Space Environment Management, under the administration of the Space Environment Research Centre Limited (SERC), has continued to make solid progress towards the achievement of our objectives. Much has been accomplished over the past year on the research front and we are now embarking on the practical phase of SERCs activities to improve the accuracy orbital debris tracking and then ultimately to demonstrate the manoeuvre of orbital debris using photon pressure from high-power lasers.

I am also pleased to note that we are well on track to meet our education commitments.

SERC's members include two universities: the Australian National University and RMIT University; three industry partners: EOS Space Systems, Lockheed Martin Space Systems Company (USA) and Optus Satellite Networks; and one international public sector research agency, the Japanese National Institute of Information and Communications Technology. I thank all the members for their ongoing support and commitment to SERC and greatly appreciate their significant contributions towards SERCs goals.

I would also like to thank my fellow directors, our CEO, Dr Ben Greene, and his management team, all the researchers in the CRC, for their continuing commitment to SERC. I was very pleased to welcome David Ball to the management team this year as our new Deputy CEO.

SERC has about two years to run. All Participants and researchers remain fully committed to meeting our research objectives and maximising our contributions towards better tracking and management of orbital debris. The protection of the space environment is critical in order to ensure that this valuable resource is preserved and remains available for future space endeavours.

**Mary O'Kane**  
Chair



## 60 SPACE OBJECTS

Populated in the SERC Space Object Catalogue

## 95 SERC RESEARCH PRESENTATIONS

across formal and other publications

## 20,000 VIEWS

of the SERC website



# 2016-2017 HIGHLIGHTS

## SERC GEO TRACKER TELESCOPE

Construction completed on 17 May 2017 and first light was achieved on 29 May with successful tracks of LAGEOS-1 and Optus C1 satellites

**8** RADIO INTERVIEWS  
**4** TELEVISION INTERVIEWS  
**29** WEB ARTICLES

National and international media coverage of SERC activities

**23** POSTGRADUATE  
STUDENTS

SERC is producing industry-ready students with multiple awards, accolades and internships being received during the reporting period

### From top right:

SERC 0.7m GEO Tracker Telescope under construction, SERC Researcher Doris Grosse being presented with an Early Career Researcher Finalists Award at the CRC Association Conference, ABC Television interview with Professor Moriba Jah, The SERC Research Colloquium



# EXECUTIVE SUMMARY

**The CRC for Space Environment Management is operated by SERC. SERC is an Australian Public Company, Limited by Guarantee and is funded through the Department of Innovation Industry and Science's CRC Programme and Participant contributions.**

SERC has been endorsed by the Australian Tax Office as a registered charity, effective 10 April 2014. SERC's Strategic Plan, adopted on 18 March 2015, outlines the mission, vision, core values and strategic objectives for SERC. The strategic objectives include:

- Identification and exploitation of synergies between the research efforts of initial participants so that the research objectives are collectively more advanced than would have been the case without SERC;
- Establishment of efficient, equitable and transparent processes for combining resources from a wide range of collaborating entities; and
- Development of new technologies to preserve the space environment and extend the benefits of space to future generations.

SERC's purpose is to pursue and promote world class research and education addressing the mounting risk of space collisions between satellites and debris.

This risk currently threatens individual spacecraft and ultimately the viability of the entire space environment. SERC has been established to build on Australian and international expertise in measurement, monitoring, analysis and management of space debris and to develop technologies to preserve the space environment.

SERC brings together skills and resources from leading universities, international and commercial research providers, industry and end-users to mitigate and ultimately remove the risk of space debris collisions.

SERC is consolidating independent research efforts to achieve a critical mass of effort forming a platform for new investment, by providing:

- a transparent framework for international research collaboration, ensuring equity for all collaborators regardless of nationality or whether a private or public entity;
- access to state-of-the-art space research programs and infrastructure;
- new funds for consolidating research program synergies and investigating new avenues; and
- exemplary management of research, consistent focus and strategic leadership.

SERC researcher adjusting the laser at the EOS Space Research Centre





## 1.1. ACHIEVEMENTS

There have been many highlights and achievements during the third year of operation including:

**Research Management Committee (ResMC).** The SERC ResMC has provided strong oversight and support to the research program. All members of the Committee attended the 2017 Research Colloquium and met with researchers and students to discuss the research progress. Professor Moriba Jah, Associate Professor, University of Texas has provided exceptional leadership, mentoring and research collaboration opportunities, taking a hands on approach with a number of SERC researchers and two PhD students.

**Research Program (RP).** SERC Research programs are on track to deliver on SERC's 30 June 2019 objectives. Research highlights and achievements are outlined in Section 1.5 of this Annual Report.

**Atmospheric Mass Density Model** – Significant progress has been made on the SERC Atmospheric Mass Density Model. This allows for more accurate orbit predictions for low earth orbit objects and is a major contribution to the industry.

**SERC Geostationary Earth Orbit (GEO) Tracker Telescope.** Construction of the SERC 0.7m GEO Tracker Telescope was completed on 17 May 2017. First light was achieved on 29 May with successful tracks of LAGEOS-1 and Optus C1 satellites. The SERC GEO Tracker Telescope will be further developed to provide a fully automated tracking system to feed data (information about space objects) into the SERC Space Object Catalogue (SOC) for conjunction assessments.

**Major Component Purchases.** Substantial progress towards the development of the following assets has been achieved: SERC High Power Laser, Stereo Scintillation and Detection and Ranging (SCIDAR) system and Adaptive Optics systems (AO imaging, track and push).

**Payload of Opportunity.** SERC identified and is progressing an opportunity to include a hosted payload on an Australian developed CubeSat. This CubeSat is due for launch in early 2018 and will enable SERC to undertake on-orbit validation of its AO systems.

**SERC SOC.** Significant advancement was made towards the development of the SERC Space Object Catalogue during the reporting period. The catalogue is populated with over 60 space objects and is now in testing mode.



**Participant Collaboration.** SERC Research Programs involve collaboration between all SERC Participants at research, education and end-user levels. Collaboration across the four research programs gained strong momentum during the reporting period. For example, Research Program 2 collaborates with Research Program 4 and provides atmospheric mass density models and reliable orbit determination (ROD) input to Research Program 3 to enable delivery of Research Program 4 outcomes. Similarly, Optus collaborates with all four research programs and provides access to satellite data and specifications which supports the development of the SOC and determining the dynamics of how debris objects behave in space.

**Conference Attendance and Presentations.** SERC received significant national and international exposure by supporting 66 attendees to deliver SERC technical papers at a range of space industry conferences and symposia; including the International Laser Ranging Workshop, (Potsdam, Germany) the Advanced Maui Optical and Space Surveillance Technologies Conference, (Maui, USA) and the European Conference on Space Debris, (Darmstadt, Germany).

**Publications.** During the reporting period SERC research was presented more than 95 times across formal and other publication categories. A paper by Dr Jerome Daquin et al. CMDA (2016) was nominated by Springer-Nature as one of the “180 ground breaking articles that could help change the world!”

**Citations.** Citations of SERC formal publications reached 123 citations during the reporting period.

**Scholarships.** SERC is well placed to meet or exceed its education milestones. To date, SERC has enrolled 23 postgraduate students and graduated one. By 30 June 2019, SERC expects to enrol a further three students and graduate 14; bringing anticipated totals to 26 postgraduate enrolments and 15 graduations. This would exceed the SERC education milestones outlined in the Commonwealth Agreement.

**Science Technology Engineering and Mathematics (STEM).** SERC supported a number of STEM activities during the reporting period including sponsorship and participation in The Australian Science Teachers Association's Science, Technology, Engineering and Mathematics teacher development program (STEM X) Academy, a professional development program for Australian science teachers; Café Scientifique, a Queensland initiative delivering science enrichment programs to primary and secondary students; and an International Baccalaureate (IB) enquiry into space junk.

**Summer Intern Program.** SERC provided research projects for eight summer interns participating in the ANU Summer Intern Program. Four of these students were subsequently employed by SERC to undertake research activities for SERC research programs.

**PhD Student Professional Development.** SERC PhD and undergraduate students participated in a full day professional development day at Mount Stromlo. Members of the ResMC and SERC Executive provided mentoring, thesis support and advice to students. An intellectual property (IP) workshop was also conducted to assist students identify, manage and protect IP.

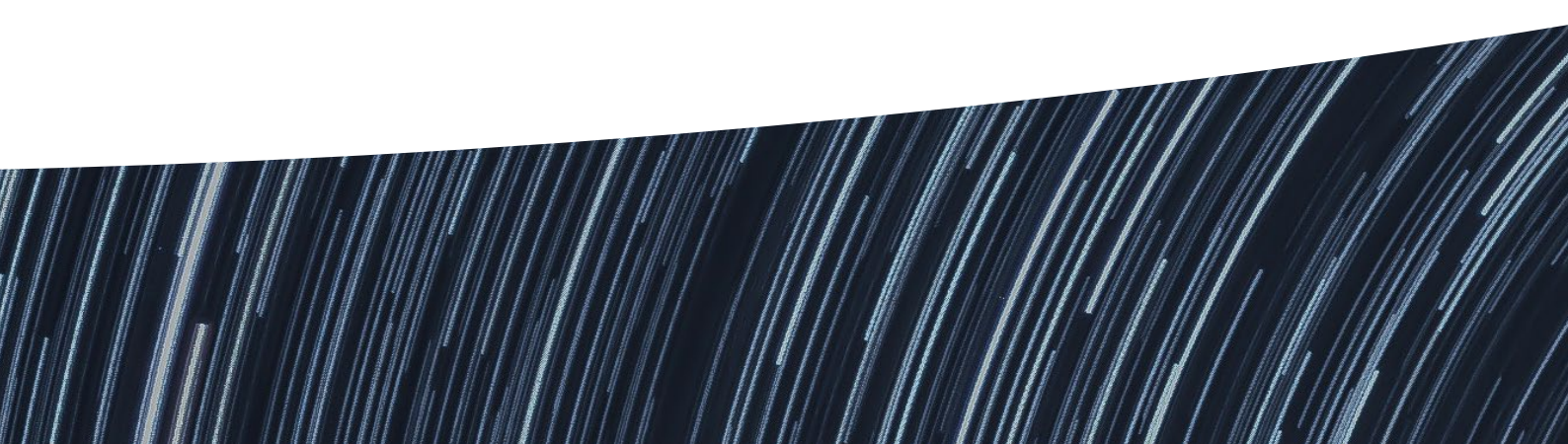
**Media.** SERC gained significant media attention during the reporting period. The Canberra Times ran a front page story on the SERC Colloquium, while the CRC Association and Nova Magazine ran feature articles about SERC research activities. In addition, the SERC Colloquium generated eight radio interviews, four television interviews and 29 web articles. International media coverage included articles in the New York Post, Indian Tribune, Scottish Sun and the Shanghai Daily.

**Website.** The SERC website is gaining popularity and received 20,000 views during the reporting period.

**Facebook.** 101 stories were posted to the SERC Facebook page during the reporting period resulting in 652 likes.

#### **Awards and Accolades.**

- SERC researcher, Dr Doris Grosse was a finalist in the CRC Association Early Career Researchers Award.
- Dr Grosse was also awarded, in a highly competitive process, an International Astronautical Federation (IAF) Emerging Space Leader Grant to participate in 2017 International Astronautical Congress in Adelaide. Dr Grosse participated as a panel member on the Next Generation Plenary Session – Innovative Methods for Assured and Secure Access to Space Resources.
- SERC PhD student, Samantha Le May, was invited to attend the International Academy of Astronautics (IAA) Space Debris Committee meeting. The IAA Space Debris Committee is made up of leading experts in the field who are responsible for the coordination of all activities related to space debris within the IAA. This was a great opportunity for this student to network with space industry leaders and to gain an international perspective on space debris research and priorities.
- SERC researcher, Dr Brett Carter received the American Geophysical Union 2016 Editor's Citation for Excellence in Refereeing in the journal of Space Weather in May 2017.
- SERC PhD student, Timothy Kodikara was awarded a visiting scholar position at the Finnish Meteorological Institute, Finland from November to January where he presented an invited oral presentation on his atmospheric density modelling work at the Global Modelling of the Space Weather Chain conference Oct 2016.
- SERC researcher, Jerome Daquin was awarded the best original research paper on Celestial Mechanics and Astrodynamics at the 7th International Meeting on Celestial Mechanics, (Viterbo, Italy).





## 1.2. RISKS AND IMPEDIMENTS

During the reporting period SERC did not experience any impediments or new risks which would materially degrade its ability to meet its Commonwealth objectives.

### Risk Mitigation

SERC maintains a comprehensive Risk Register which is reviewed regularly by management and the Board appointed Audit and Risk Committee (ARC). Risks with a high impact rating or above are reported to the Board. The ResMC also monitors the research risks and advises the Board accordingly.

A risk identification, management and mitigation seminar was presented at the 2017 SERC Colloquium. The seminar highlighted the importance of identifying and managing risk at a whole of organisation level. As SERC moves from a predominately research based organisation to a demonstration phase, risks associated with this new phase will be identified and managed accordingly.

Key risks addressed during the reporting period and strategies adopted to address these risks include:

**Loss of key personnel.** This is an ongoing business continuity risk which has been managed through regular Research Program meetings and annual staff performance reviews. The risk of losing key personnel increased during the reporting period due to the confirmation that SERC will wind up in 2019. Staff interviews have been conducted with key researchers and corporate staff to ensure SERC retains sufficient resources to deliver organisational objectives by 2019.

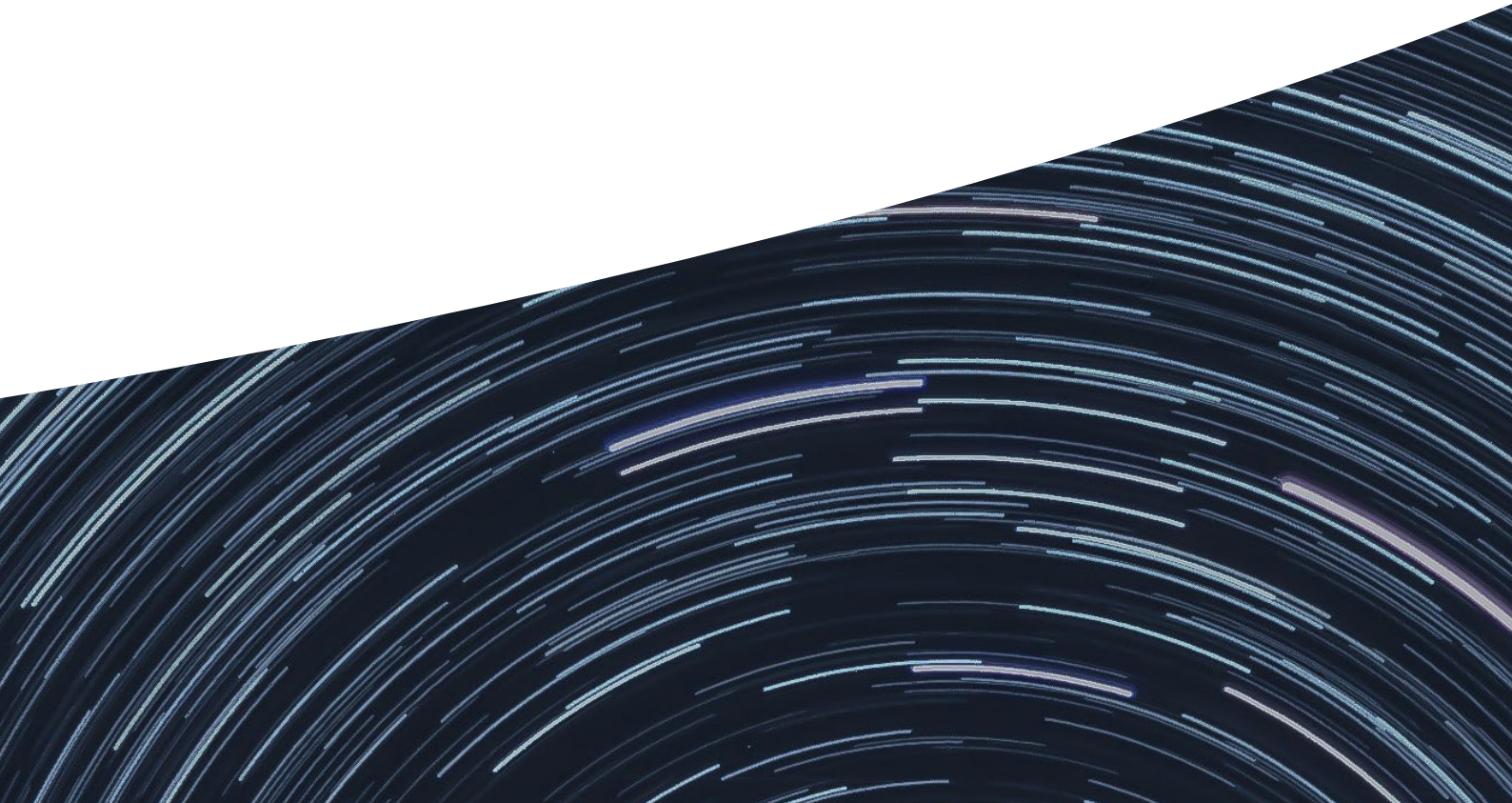
**Changes to 457 visas.** The changes to 457 visas announced during the reporting period added a new risk to the SERC Risk Register. A thorough audit of 457 visas has been conducted and extension applications were submitted prior to the major changes coming into effect.

**Inadvertent disclosure of IP.** The key IP risks relate to inadequate protection or poor exploitation. SERC relies on experienced Research Program leaders to implement SERC IP processes. The inclusion of robust non-disclosure and IP protection clauses in Participant Agreements and in staff and student contracts is a key element in protecting SERC IP. To enhance awareness, an IP workshop was conducted at the May 2017 Colloquium to assist researchers and students identify and protect SERC IP. During this reporting period background and foreground IP has continued to be identified and recorded on the SERC IP register.

**Failure to Meet End-User/Participant Requirements.** The SERC Executive communicates regularly with end-users and Participants to understand their requirements. Design review meetings were held during this reporting period across all four research programs to ensure the research is meeting end-user and Participant requirements.

**Failure to Deliver Research Outcomes.** SERC has an efficient but resilient research strategy which can accommodate multiple failures in the necessarily high-risk research effort. However there are some research outcomes which are fundamental to the success of SERC. These include the use of AO for beam propagation, the response of typical debris to laser radiation, and the achievement of unprecedented power and optical quality in laser beams. These risks have been monitored during the reporting period and contingency plans developed to mitigate risk to the SERC research program.

**Insufficient Resources.** This risk relates to the quality and quantity of in-kind commitments from Participants. This issue was anticipated in the framing of the SERC constitution where reviews are required annually of both the quantity and quality of in-kind contributions provided to SERC by its Participants for purposes of achieving research objectives.





## 1.3. KEY RESEARCHERS



**PROF CRAIG SMITH**  
**RP1 PROGRAM LEADER**  
  
**EOS SPACE SYSTEMS**

Professor Craig Smith is the CEO and technical director of EOS Space Systems. He leads a multi-disciplinary team of science and engineering innovators developing lasers, beam directors, precision timing systems, sensors, and control systems for the laser tracking products. Professor Smith has also held positions within EOS as CEO EOS Technologies (the US subsidiary of EOS) and Head of Research and Development. Prior to joining EOS Professor Smith was a Senior Research Fellow at the Australian Defence Force Academy. There he developed novel techniques for imaging-polarimetry and spectro-polarimetry at thermal IR wavelengths. These remote sensing techniques are able to provide materials characteristics from the thermal signature of an object. Professor Smith has lectured in Physics and Electronics and Military Ballistics and is an Adjunct Professor at RMIT University. He obtained Bachelors and PhD degrees in Physics from the University of Melbourne.



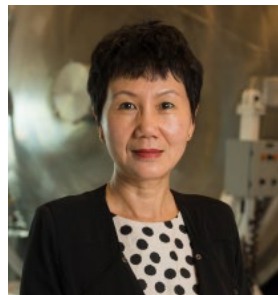
**ASSOC PROF FRANCOIS RIGAUT**  
**AO PRINCIPAL SCIENTIST**  
  
**ADAPTIVE OPTICS ANU**

Dr François Rigaut obtained his PhD from Paris Diderot University (Paris 7) in 1992 on the first Adaptive Optics (AO) system for astronomy, COME-ON, then developed in Europe and used at the ESO La Silla observatory. Since then, Dr Rigaut has been involved in the technological and theoretical developments and promotion of Adaptive Optics at several institutes, the Canada France Hawaii Telescope, the European Southern Observatory and the Gemini Observatory; and through various instruments: PUEO, NAOS, Altair and lately the Gemini multi-conjugate AO system (GeMS), the first and only Laser Guide Star Multi-Conjugate Adaptive Optics system. Dr Rigaut is the Adaptive Optics Principal Scientist at the ANU Research School of Astronomy and Astrophysics, concentrating on two main projects: the design of a Ground Layer AO system for the Subaru Japan national telescope, the Laser Tomography AO system for the Giant Magellanic Telescope and an AO prototype for conditioning of laser beams used in space debris tracking, nudging and de-orbiting.



**DR JAMES WEBB**  
**GUIDE STAR LASER SCIENCE**  
  
**EOS SPACE SYSTEMS**

Dr James Webb is EOS's instrument scientist, where he applies a diverse range of skills accumulated over more than 20 years in numerous defence, academic, commercial and industrial R&D roles. After a period with the RAAF and graduation as an electronics engineer, he founded and worked in a series of start-ups developing high speed inkjet printers, smart card readers, image compression and cryptographic utilities. Following further studies in explosives, adaptive and quantum optics he spent time as a researcher with UNSW, then in Hawaii as an electronics engineer at the UKIRT and JCMT telescopes. Upon returning to Australia, James resumed consulting in the areas of medical and security product development and defence communications while employed as an R&D engineer in the field of high accuracy positioning. He is currently focussed on the creation of new telescope control systems and the EOS Space Systems (EOSSS) guide star laser.



**AMY CHAN**  
**SENIOR DESIGN ENGINEER**  
  
**EOS SPACE SYSTEMS**

Amy Chan is the senior design engineer for EOS Space Systems (EOSSS), specialising in the Opto-Mechanical area. Amy has more than 26 years' experience with EOSSS where she designed the opto-mechanical structures for the development of various products including night vision, laser ranging, solid-state laser and single-frequency seed source technologies. Amy also designed opto-mechanical structures for a variety of other laser products including - Picosecond pulse width laser oscillator, Picosecond regenerative feedback amplifier, Nanosecond high-energy laser system, including pre-amplifier, power amplifier, CW high power (> 4000W) book piece laser and water-cooled frame (kW-class high-power continuous, pulse laser). Amy Chan holds a Bachelor of Engineering in Optical Instrument degree from Tianjin University, China and a Graduate diploma in Computing Science from the University of Canberra.



**ASSOC PROF CÉLINE D'ORGEVILLE**  
**AO GROUP MANAGER**  
  
**ANU**

Céline d'Orgeville joined the ANU RSAA Adaptive Optics (AO) group in 2012 to lead Laser Guide Star (LGS) activities at the Advanced Instrumentation and Technology Centre (AITC), Mount Stromlo, Canberra. Céline was appointed AO Group Manager in July 2016 and is also the AITC Student Convenor. Prior to moving to Australia, Céline worked at the Gemini Observatory where she led the design, fabrication and commissioning of the Gemini North LGS facility in Hawaii (1999-2006), and the Gemini South LGS facility in Chile (2007-2011). The Gemini South AO system, GeMS, is the only Multi-Conjugate Adaptive Optics facility in the world. The GeMS LGS facility is also unique in creating not just one but five sodium LGS to probe the atmosphere and enable GeMS to restore the diffraction-limit of the Gemini South 8-metre telescope over a 2 arcminute field of view.



**HIROO KUNIMORI**  
**SENIOR RESEARCHER**  
  
**NATIONAL INSTITUTE OF INFORMATION AND COMMUNICATIONS TECHNOLOGY (NICT)**

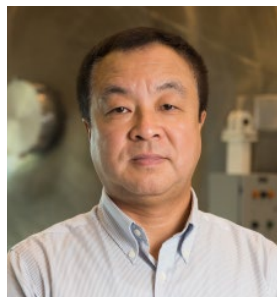
Hiroo Kunimori leads the optical communication and laser ranging project, Space Communication Lab, Wireless Network Research Center, NICT and is the NICT Member Representative for SERC. Hiroo Kunimori has extensive experience in deep space communication and geosynchronous satellite communication and ranging, next-generation inter-satellite laser communications, very long baseline interferometry and space-time measurement. Hiroo Kunimori is a world recognised leader in precision orbit determination, laser communications and optical sensing technologies. He has served as a Board Member of the International Laser Ranging Service (ILRS), representative of the Western Laser Tracking Network (WPLTN) and member of Japanese satellite laser ranging committees. Hiroo Kunimori was awarded a BSC from Kyoto University in 1978.



**DR VISA KORKIAKOSKI**  
**POSTDOCTORAL**  
**RESEARCH FELLOW**

**ADAPTIVE OPTICS**  
**ANU**

Dr Visa Korkiakoski obtained his PhD from the Helsinki University of Technology in 2008, after an internship in the European Southern Observatory, on the topic of optimizing the control adaptive optics systems. Since then, he has continued the line of work in international research institutes such as the Institut de Planetologie et d'Astrophysique de Grenoble, Leiden Observatory, Delft University of Technology and the Netherlands Organisation for Applied Scientific Research. Since April 2016, Dr Korkiakoski has worked at the ANU Research School of Astronomy and Astrophysics as a Research Fellow concentrating on the adaptive optics for space situational awareness: improving the tracking of space debris and pushing it with high-power lasers.



**PROF YUE GAO**  
**PRINCIPAL SCIENTIST**  
**& HEAD OF LASER**  
**RESEARCH AND**  
**DEVELOPMENT**

**EOS SPACE SYSTEMS**

Professor Yue Gao is the Principal Scientist and Head of Laser Research & Development Division for EOS Space Systems. Professor Gao is responsible for the research, development, design, and project management of different type of solid state lasers and Electro-Optic devices for scientific and military applications. Prior to joining EOS, Professor Gao held a Postdoctoral Research position at the Australian National University in the Laser and Optical Spectroscopy Group, Research School of Chemistry. Professor Gao was appointed as an Adjunct Professor to the ANU in 2011. Professor Gao received his Bachelor of Engineering degree in laser physics, and laser technologies from Tianjin University, China and his PhD in physics from the University of Strathclyde, Glasgow, UK



**DR FRANCIS BENNET**  
**RESEARCH FELLOW**

**ADAPTIVE OPTICS**  
**ANU**

Dr Francis Bennet obtained a first class honours degree at the Australian National University (ANU) in Physics and was awarded a PhD from the ANU in 2011. Dr Bennet's current research interests include adaptive optics, astrophotonics, laser physics, and optical design. Dr Bennet is developing adaptive optics (AO) for the CRC for Space Environment Management (SERC) to support the remote manoeuvre of space object(s) using ground-based lasers. He is also undertaking research and developing AO to facilitate high performance laser communication.



**DR DORIS GROSSE**  
**POSTDOCTORAL**  
**RESEARCH FELLOW**

**ADAPTIVE OPTICS**  
**ANU**

Dr Doris Grosse is an early career research scientist specialising in adaptive optics with the Advanced Instrumentation and Technology Centre (AITC) at the Australian National University (ANU) Research School of Astronomy and Astrophysics. Dr Grosse was awarded an engineering graduate degree with the Faculty of Electrical Engineering and Information Technology of the Ruhr-University Bochum in Bochum, Germany. On completion of her engineering degree, Dr Grosse was appointed to the Photonics and Terahertz Technology research group at the Ruhr-University Bochum, where she completed a PhD. Doris joined the Adaptive Optics group at the ANU in 2016 as a postdoctoral researcher to develop an adaptive optics system as part of the SERC collision risk mitigation system



**DAVID KOOYMANS**  
**SOFTWARE ENGINEER**

**EOS SPACE SYSTEMS**

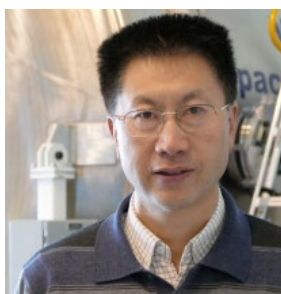
David joined as a software engineer with EOS Space Systems in 2016 and has developed the SERC Space Object Catalogue to store, retrieve and automate the processing of space object observation data. Prior to joining EOSSS, David worked with large scale and start-up organisations working with "big data" such as the cadastre and street address information of Australia. David graduated from the Australian National University with first class honours in software engineering in 2010.



**ALEX POLLARD**  
**SOFTWARE GROUP**  
**MANAGER**

**EOS SPACE SYSTEMS**

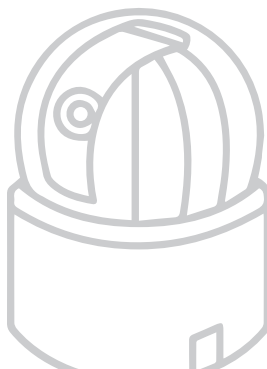
Alex joined EOS Space Systems in 2003, where he developed software for astronomical, satellite and debris laser ranging systems. Alex was appointed Software Group Manager in 2016, and is responsible for overseeing and directing software development including autonomous and remotely operated systems for a number of SERC projects. Alex graduated in Interdisciplinary Systems Engineering (Honours) and IT from the Australian National University in 2002.



**DR YANJIE WANG**  
**SENIOR LASER**  
**SCIENTIST**

**EOS SPACE SYSTEMS**

Dr Yanjie Wang has over 20 years research and development experience in lasers, optics and nonlinear optics. His expertise includes the design, prototyping and manufacture of high power and high energy lasers, mode-locked and Q-switched lasers, single frequency lasers, fiber lasers and nonlinear frequency conversion devices. Dr Wang holds a PhD in laser physics from the Australian National University.



**RESEARCH**  
**PROGRAM**  
**ONE**





**DR ROBERT  
NORMAN**  
**RP2 PROGRAM  
LEADER**

**RMIT  
UNIVERSITY**

Dr Robert Norman is a Senior Research Fellow and member of the Satellite Positioning for Atmosphere, Climate and Environment (SPACE) Research Centre, and the Satellite Positioning and Navigation (SPAN) Laboratory at RMIT University. Prior to joining RMIT, Dr Norman held research positions at La Trobe University before moving on to UK defence research agency QINETIC to work in the area of high frequency beyond line of sight communications. Robert then returned to Australia to take up another research position at La Trobe involving Telstra and Lockheed Martin subsidiary RLM, working on the Jindalee Over the Horizon radar. Dr Norman's current research interests are in laser signal propagation using geometrical optics and atmospheric density modelling using GNSS radio occultation. In addition to leading the SERC research team at RMIT, Robert is primarily responsible for the atmospheric density modelling and ray tracing research streams.



**DR BRETT  
CARTER**  
**POSTDOCTORAL  
RESEARCH  
FELLOW**

**ATMOSPHERIC  
MASS DENSITY  
RMIT  
UNIVERSITY**

Dr Brett Carter received a BSc in Space Physics with First Class Honours from La Trobe University before completing a PhD specialising in high frequency radar backscatter from plasma irregularities in the high-latitude, auroral and sub-auroral latitudes. Dr Carter's main specialisation is in ionospheric plasma instabilities, which is important for many real-world applications. Recently Brett has turned towards understanding the interactions between the charged particles and neutrals in the upper atmosphere due to the important role they play in understanding atmospheric drag on objects in low-Earth orbit.



**DR JÉRÔME  
DAQUIN**  
**POSTDOCTORAL  
RESEARCH  
FELLOW**

**RMIT  
UNIVERSITY**

Dr Jerome Daquin received a Masters Degree in Applied Mathematics from Lille 1 University in 2011 and completed a Masters Degree in Astronomy and Astrophysics at Paris Observatory in 2012. Dr Daquin defended his PhD thesis on the long-term resonant motion of space debris, at Paris Observatory, in 2015. His research interests are macroscopic properties of Earth satellite orbits, especially the presence of resonances and the transition order-chaos in the medium-range. Jerome also research also on model reductions and the establishment of effective equations in the context of highly oscillatory ordinary differential equations. These models are generally more amenable to analytical and/or numerical investigations.

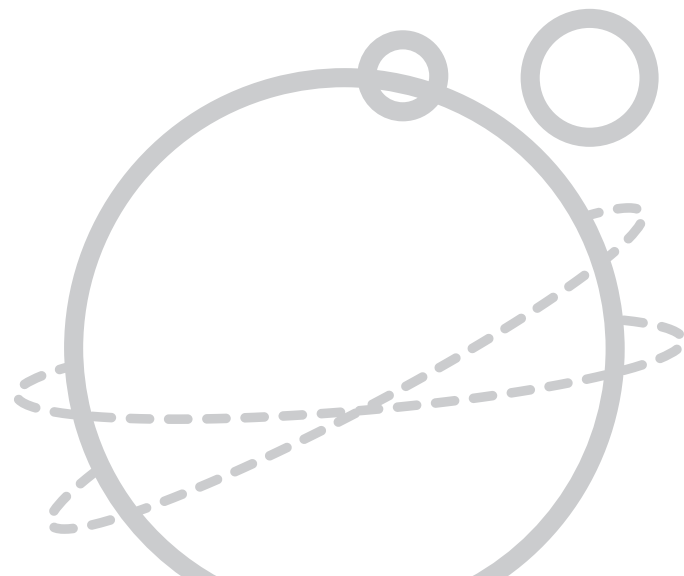


**DR YANG YANG**  
**POSTDOCTORAL  
RESEARCH  
FELLOW**

**RMIT  
UNIVERSITY**

Dr Yang Yang received his PhD from the School of Astronautics, Polytechnical University, China. Dr Yang is leading the Orbit Determination Work Package for Research Program 2 "Orbit Determination and Predicting Behaviours of Space Objects". His current research interests include space debris tracking, orbit determination & prediction, nonlinear and non-Gaussian estimation/filtering, and GNSS-based LEO satellite orbit determination.

**RESEARCH  
PROGRAM  
TWO**







**DR JAMES BENNETT**  
**RP3 PROGRAM LEADER**

**SERC**

Dr James Bennett has over 6 years' experience in Astrodynamics and over 10 years' experience in industrial applied mathematics. Dr Bennett was awarded a PhD in Applied Mathematics from RMIT University in 2008. Dr Bennett is a member of the International Laser Ranging Service (ILRS) Governing Board and a member of the ILRS Western Pacific Laser Tracking Network (WPLTN). Dr Bennett is the SERC Research Program Leader for Research Program 3 and is responsible for the delivery of the SERC Space Object Catalogue and Conjunction Threat Warning Service. His research interests include orbit determination and prediction, conjunction assessments, applied mathematics, debris object characterisation, optical and laser tracking, and singular and regular perturbation methods.



**DR DANIEL KUCHARSKI**  
**RESEARCH FELLOW**

**SATELLITE SPIN DYNAMICS**  
**SERC**

Dr Daniel Kucharski studied mechatronics at Warsaw University of Technology, with a particular focus on the use of laser technology for nano-scale measurements of surface properties. Dr Kucharski went on to study a joint PhD program with the Polish and Austrian Academies of Science, specialising in Satellite Laser Ranging (SLR) and spin determination of artificial satellites. Through his studies at the SLR stations Borowiec (Poland), Graz (Austria), Hitotsubashi University (Japan) and the Korean Astronomy and Space Science Institute (South Korea), Daniel developed new methods for attitude and spin determination of the laser tracked objects. His work at SERC is devoted to the spin analysis and object characterisation from the light curve measurements.



**DR STEVE GEHLY**  
**RESEARCH FELLOW**

**ORBIT DETERMINATION**  
**RMIT UNIVERSITY**

Dr Steve Gehly grew up near Boston, Massachusetts in the USA before moving to Los Angeles to pursue his tertiary studies. Dr Gehly completed his undergraduate degree at the University of Southern California (USC), graduating with a BSc in Aerospace Engineering. Dr Gehly worked at Northrop Grumman for five years while obtaining his Master's degree at USC, and then moved to Colorado to pursue his PhD, specialising in orbit determination and space situational awareness. His dissertation research focused on multi-target estimation for SSA and other related applications such as sensor allocation and initial orbit determination. In 2015 Steve was appointed to a post-doctoral research position at RMIT to undertake research for SERC in the areas of orbit determination and sensor allocation.



**DR MAREK MÖCKEL**  
**RESEARCH FELLOW**

**HIGH PERFORMANCE COMPUTING**  
**SERC**

Dr Marek Möckel studied Computer Science at Braunschweig University of Technology while gaining his first hands-on experience within the Linux and open source software community. Before joining SERC, Dr Möckel worked on space debris environment models and fast orbital propagation at the Institute of Space Systems in Braunschweig. He credits his work in developing video games in the open source community to contributing to the practical skills he now applies to space research. Marek was inspired to work for SERC as it afforded him an opportunity to put his research to practical use whilst working in a field that ensures the safe use of one of the Earth's natural resources.

**RESEARCH  
PROGRAM  
THREE**





**DR SVEN  
FLEGEL  
RESEARCH  
FELLOW**

**NON LINEAR  
COVARIANCE  
PROPAGATION  
SERC**

Dr Sven Flegel studied Mechanical Engineering at the Technische Universität in Braunschweig, Germany, prior to aerospace where he specialised in space studies. Sven's thesis "Multi-Layer Insulation as Contribution to Orbital Debris", studied the mechanisms behind how insulating foils from spacecraft could separate to become part of the debris environment and how their orbits could evolve over time.

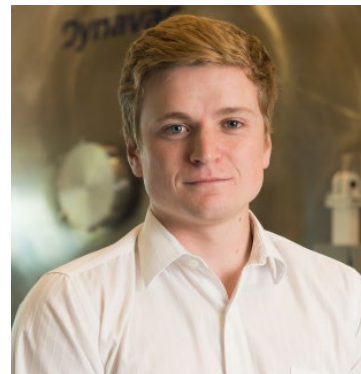
Sven worked at the Institute of Space Systems where he upgraded a suite of space debris cataloguing software for the European Space Agency (ESA). He subsequently worked as a Research Scientist at the Fraunhofer Institute for High Frequency Physics and Radar Techniques, where he developed software for the simulation of radar measurements. Sven also performed an extensive analysis of the potential benefits of performing debris detection campaigns wherein objects with orbit inclinations below 50° could be observed. This led to the first debris detection campaign of the Tracking and Imaging Radar system in December 2015. He is currently working on the prediction of space object state uncertainties and collision risk for the SERC Conjunction and Threat Warning System.



**DR MICHAEL  
LACHUT  
RESEARCH  
FELLOW**

**ORBIT  
DETERMINATION  
& PREDICTION  
SERC**

Dr Michael Lachut completed his PhD in Applied Mathematics at the University of Melbourne, applying numerical and analytical methods to solve differential equations. Dr Lachut has applied his expertise to a broad range of fields, most notably in the field of micro/nano-mechanical sensing devices, and in the last two years in Astrodynamics. He is currently working on improving drag and solar radiation force models in orbit determination and propagation, object characterisation and catalogue maintenance. Michael has played an instrumental role in the development of the SERC Space Object Catalogue which will provide highly accurate ephemeris data (object position/velocity) to facilitate sensor object acquisition, conjunction analysis services to satellite operators and ground-based laser manoeuvres.



**JAMES  
ALLWORTH  
GRADUATE  
RESEARCH  
ASSISTANT**

**SERC**

James Allworth has recently joined EOS Space Systems after undertaking a Summer Research Internship with SERC and the ANU. James achieved first class honours in a combined Bachelor of Aeronautical Space Engineering/Bachelor of Commerce degree at Sydney University in 2016. James has been providing assistance with orbit determination and propagation research for SERC through the data analysis and the development of visualisation tools. James has an interest in machine learning and is considering undertaking further studies in this field.



**JOSEPH  
O'LEARY  
GRADUATE  
RESEARCH  
ASSISTANT &  
SCHOLARSHIP  
STUDENT**

**SERC**

Joseph O'Leary graduated from the Dublin Institute of Technology, Ireland in 2014 with a degree in mathematical sciences. Joseph received the Hamilton Award in Mathematics by Sir Roger Penrose in penultimate year of his undergraduate degree. Joseph was awarded scholarships by the University of South Australia to study relativity in space based satellite systems and a supplementary scholarship with the Space Environment Research Centre (SERC) to research orbit prediction models using the theory of relativity. Joseph's research contributes to SERC's development of highly accurate, long term orbit determination models.

**RESEARCH  
PROGRAM  
THREE**



**MR MATTHEW BOLD**  
**RP4 PROGRAM LEADER**  
**(JULY – DEC 2016)**

**LOCKHEED MARTIN**

Mr Matt Bold is a Principle Researcher with the Lockheed Martin Space Systems Company Advanced Technology Center in Palo Alto, California, USA. His undergraduate studies were in physics and mathematics at the University of Dayton and graduate studies in high energy particle physics at Arizona State University. Since 1996 Matt has been studying the propagation of high energy lasers through the atmosphere with particular interest in the modelling of atmospheric optical turbulence and the performance modelling of adaptive optics systems. For the last ten years Matt has been involved in the space situational awareness research efforts at the UKIRT Telescope in Hawaii and the Lockheed Martin SPOT telescopes in Santa Cruz California. He is involved with the SERC Remote Manoeuvre research project assisting with system engineering and performance modelling and simulation.



**DR BENJAMIN SHEARD**  
**RP4 PROGRAM LEADER**  
**(JAN – JUNE 2017)**

**SERC**

Dr Benjamin Sheard has a Bachelor of Engineering, a Bachelor of Science and a PhD from the Australian National University. After completing his PhD he worked at the Albert-Einstein-Institute in Hanover, Germany for three years as a post-doctoral scientist working on laser interferometry for space based gravitational wave detection and for five years as a research scientist working on next generation geodesy missions, including the GRACE Follow-On Laser Ranging Interferometer. Before joining EOS Space Systems Ben worked for two and half years as a systems engineer on instrument performance and analysis as well as control systems engineering for satellite optical instruments at OHB System AG near Munich, Germany. He is currently developing an instrumented satellite for the SERC remote manoeuvre demonstration.



**MR MIKE PETKOVIC**  
**TEST FACILITIES MANAGER**

**ANU**

Mike Petkovic is the Test Facilities Manager at the ANU Research School of Astronomy and Astrophysics (RSAA) where he is responsible for managing astronomical hardware projects and the development of terrestrial and space instrumentation. Mike has a wealth of space hardware development experience and has held senior positions on the FedSat satellite mission and in the development of focal plane arrays and optics for the advanced along track scanning radiometer (AATSR) and along track scanning radiometer 2 (ATSR2) instrument and the Endeavour Space Telescope.

He also led the mechanical assembly, integration and test (AIT) teams on the Systeme Pour l'Observation de la Terre 3 (SPOT3) and European Remote Sensing Satellite (ERS2) spacecraft, whilst on secondment in Europe, and worked on a number of defence projects whilst with Auspace and earlier with the Commonwealth Aircraft Corporation. Mike was awarded an engineering degree from Deakin University in 1982.



**MR LIAM SMITH**  
**RESEARCH SCIENTIST**

**LOCKHEED MARTIN**

Mr Liam Smith is a Research Scientist with the Lockheed Martin Space Systems Company Advanced Technology Center (ATC) in Palo Alto, California, USA. His studies were in aerospace engineering at California Polytechnic State University San Luis Obispo where he was awarded an undergraduate and graduate degree. Since 2015 Liam has been studying the effects of high energy lasers on perturbing orbital debris in Low Earth Orbit. Liam has been involved in the space situational awareness research efforts at the United Kingdom Infrared Telescope (UKIRT) in Hawaii and the Lockheed Martin Space Object Tracking (SPOT) telescopes in Santa Cruz California. Liam is also involved in trajectory optimization and machine learning research at the ATC. Liam is also involved with the SERC Remote Manoeuvre research project assisting with system engineering and performance modelling and simulation.

**RESEARCH  
 PROGRAM  
 FOUR**





# 1.4. PERFORMANCE AGAINST ACTIVITIES

SERC research is organised around four interdependent research programs, including:



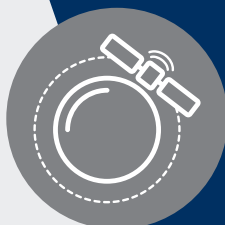
## RP1: TRACKING, CHARACTERISATION & IDENTIFICATION OF SPACE OBJECTS

Development of space debris-tracking hardware and adaptive optics-based solutions for reliable and accurate tracking of space objects



## RP2: ORBIT DETERMINATION & PREDICTING BEHAVIOURS OF SPACE OBJECTS

Developing tools to improve the accuracy and reliability of orbit predictions for Low Earth Orbit (LEO) objects



## RP3: SPACE ASSET MANAGEMENT

Creating algorithms, databases and techniques to improve conjunction prediction and prevent collisions in space



## RP4: SPACE SEGMENT

Apply knowledge gained and technologies developed to manoeuvre space objects using ground-based lasers



EOS researcher calibrating the laser



# RESEARCH PROGRAM **ONE**

## TRACKING, CHARACTERISING AND IDENTIFYING OBJECTS IN ORBIT

**Program Leader:** Professor Craig Smith

This research program is developing innovative techniques of active and passive object tracking to provide sufficient accuracy for orbit propagation and conjunction prediction.

The Active Track in Low Earth Orbit (LEO) research program is investigating and developing non-terminator acquisition and tracking of debris objects. The research is also developing new techniques to detect and provide precision orbit determination for new (currently un-catalogued) objects.

*Innovative  
techniques of  
active and passive  
object tracking to  
provide sufficient  
accuracy for orbit  
propagation and  
conjunction*

### PROJECT PARTICIPANTS

- Australian National University
- EOS Space Systems
- Lockheed Martin
- Optus Satellite Systems
- National Institute for Information and Communications Technology (Japan)

**6 PROJECTS**

**5 PARTICIPANTS**

**28 RESEARCHERS**

**7 STUDENTS**

### RESEARCH SNAPSHOT FOR 2016

- R1.1** Develop Passive and Active Track Sensors
- R1.2** Develop a Database for Historical Recall of Observations and Object Characterisation
- R1.3** Debris Characterisation by High Resolution Imagery
- R1.4** Develop Adaptive Optics
- R1.5** Develop Adaptive Optics Astrometry Capabilities
- R1.6** Develop High Power Lasers and Phased Laser Beam Combining



## R1.1 DEVELOP PASSIVE AND ACTIVE TRACK SENSORS

**Project lead:** EOSSS

**Researchers:** Craig Smith, Ian Richie, Lauren Glina, Mark Blundell, Andrew Gray, Andrew Edwards

**Participants:** EOSSS, ANU, NICT, Optus Satellite Systems

This project will design and develop passive and active track sensors for objects at geostationary (GEO) orbits. This includes technologies for telescopes, beam directors, detectors, lasers, timing systems, optical systems and command and control software.

During the reporting period, the GEO tracker telescope was installed at Mount Stromlo and commissioned for local operation. First light was achieved on 29 May with LAGEOS-1 and Optus C1 satellites being tracked successfully.

Limited manual tracking operations have been performed via remote access, however commissioning works are ongoing and the GEO tracker telescope is expected to be fully automated in the next reporting period. The data collected from the SERC GEO tracker telescope will be fed into the SERC Space Object Catalogue (SOC).

## R1.2 DEVELOP A DATABASE FOR HISTORICAL RECALL OF OBSERVATIONS AND OBJECT CHARACTERISATION

**Project lead:** EOSSS

**Researchers:** David Kooymans, James Bennett, Alex Pollard, Michael Lachut

**Participants:** EOSSS, Lockheed Martin, SERC

The Space Object Database has been developed and the SOC has been upgraded to enable it to cue the station and link back to the data that was used to acquire the target. The improvements in the catalogue, coupled with the nightly operations report has improved the assessment and effectiveness of orbit determination (OD) solutions.

There have also been updates to allow the OD server to improve performance and provide data in a JavaScript object notation (JSON) format. This allows greater sharing of data with other Research Programs

## R1.3 DEBRIS CHARACTERISATION BY HIGH RESOLUTION IMAGERY

**Project lead:** ANU

**Researchers:** Francis Bennett, Michael Copeland

**Participants:** ANU, EOSSS

A critical design review for the adaptive optics imager (AOI) was conducted on 13 June 2017. Significant progress was made on the development of the AOI during the reporting period, including:

- The purchase of all components.
- Resolving issues with the deformable mirror.
- Custom parts have been ordered and are being manufactured and tested.
- The system is being integrated in the lab for alignment and initial testing in early 2018.

**A Scintillation and Detection and Ranging (SCIDAR) system** has been designed and built to enable site testing.

- First light on the Scintillation and Detection and Ranging (SCIDAR) system was achieved in May 2017.
- Initial results were presented at Society of Photographic Instrumentation Engineers (SPIE) Astronomical Telescopes and Instrumentation conference and the Advanced Maui Optical and Space Surveillance Technologies (AMOS) conference in July and September 2017 respectively.
- System risk analysis and schedule were updated on 3 July 2017.

**AO supervisor software** has also been developed with the following notable achievements:

- additional features added (determination of system lag with an expected accuracy of 1%).
- simulation testing undertaken.
- numerous bugs and issues fixed.

## R1.4 DEVELOP ADAPTIVE OPTICS

**Project lead:** EOSSS

**Researchers:** James Webb, Yue Gao, Yanjie Wang, Amy Chan, Phil Musumeci, Francis Bennet, Celine d'Orgeville, Doris Grosse

**Participants:** ANU, EOSSS, Lockheed Martin

This research program will develop leading edge adaptive optics that allow high intensity laser beams to be propagated through the atmosphere. The Adaptive Optics Tracking and Pushing system (AOTP) went through

**From top left:** SERC 0.7m GEO tracker telescope, Mount Stromlo Observatory, Canberra, EOSSS 1.8m telescope, Mount Stromlo, Adaptive Optics alignment, Mount Stromlo



a successful Preliminary Design Review on April 7, 2017. The AOTP optical design is well progressed and is anticipated to be finalised by November 2017 following lab testing in August with a new calibration source. The deformable mirror has undergone extensive testing to determine whether a repolish and recoat is necessary. A new calibration source has been ordered and lab testing will commence in August 2017. In addition repolishing/recoating work has started on the Deformable Mirror (DM).

Significant progress with the Guide Star Laser (GSL) has occurred in the past year with the installation and commissioning of the 1342nm fibre amplifier. The new amplifier and additional control system developments have cleared the final hurdles to achieve the required 589nm wavelength and power output.

Work on stabilising the output frequency is continuing prior to re-packaging the system for installation on the EOS Space Systems telescope at the EOS Space Research Centre, Mount Stromlo, Canberra.

## R1.5 DEVELOP ADAPTIVE OPTICS ASTROMETRY CAPABILITIES

**Project lead:** ANU

**Researchers:** Francois Rigaut, Celine d'Orgeville, Michael Copeland

**Participants:** ANU, EOSSS, Lockheed Martin

The program is developing an adaptive optics system that can reduce the point spread function of stars and targets (diffraction limit) so that higher accuracy astrometric solutions can be made to determine the absolute position on the sky of the GEO target.

This will require developing high performance AO systems, sensors, calibration systems and algorithm development. Lockheed Martin has implemented an AO model into performance modelling tools to provide inputs to astrometric capability primarily through a trade of AO performance vs. blur spot reduction.

Dr Piotr Piatrou has published a paper for Acta Astromica to present the method, concept, and expected performance of the GEO Global Astrometric Interferometer for Astrophysics (GAIA) method. This was also used as the input for the design of the AO imaging system in R1.3.

## R1.6 DEVELOP HIGH POWER LASERS AND PHASED LASER BEAM COMBINING

**Project lead:** EOSSS

**Researchers:** Yue Gao, Yanjie Wang, Amy Chan, James Webb, Daniel Shaddock, Robert Ward, Lyle Roberts, Matt Bold, James Mason, Greg Madsen

**Participants:** EOSSS, ANU, Lockheed Martin

This research program will develop high power laser technologies to be used in photon pressure experiments and also develop techniques to combine and phase multiple lasers for increased power, beam shaping and beam control.

After numerous studies and investigations it was decided that for a successful RP4 manoeuvre, a high beam quality multi kilo-Watt Continuous Wave (CW) laser is required. In the first phase, the RP4 8kW will be obtained through multi-beam combination scheme which requires following key assemblies:

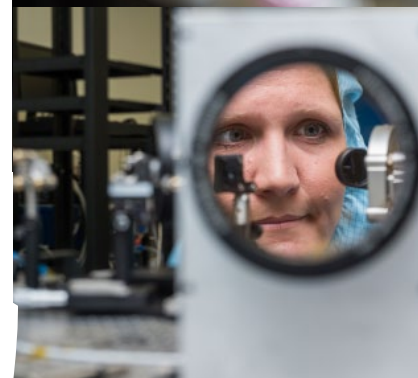
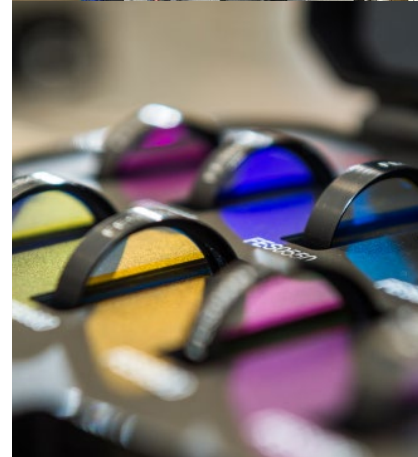
- single frequency seed oscillator
- single mode fibre amplifier
- large dimension Volume Bragg Grating (VBG)

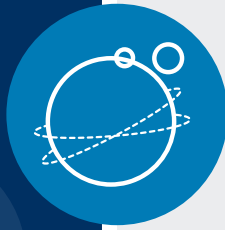
The single frequency seed oscillator and single mode fibre amplifier have been designed and the most expensive and long lead time components have been ordered including:

- 3 YAM-2000-SM fibre amplifier modules
- 3 GEN 80-125-3P400 AC/DC programmable Power Supply Units (PSU).

Analysis of the large dimension VBG has concluded that 25 x 25 mm VBGs will be large enough to achieve 8kW beam combination. Sample VBGs with dimensions 15 x 15 mm have been procured. Investigation and measurement of their diffraction efficiency, and spectroscopic properties are in progress.

Lockheed Martin (LM) is working on a bailment agreement to loan a 10kW laser to SERC. The LM laser will be combined with the SERC developed 8kW laser for the on-sky experiments to move a piece of space debris.





# RESEARCH PROGRAM **TWO**

## ORBIT DETERMINATION AND PREDICTING BEHAVIOURS OF SPACE OBJECTS

### Program Leader:

1 Jul 2016 – 25 Jul 2016 Professor Kefei Zhang  
25 Jul 2016 – 30 June 2017 Dr Robert Norman

To predict future collisions between space objects, the orbit predictions that properly account for the variable space environment, e.g. the Earth's gravity field, atmospheric drag, solar magnetic disturbances and other perturbing forces, are required.

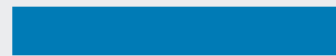
The primary objective of Research Program 2 is to develop advanced high precision orbit propagators.



**2 PROJECTS**



**3 PARTICIPANTS**



**16 RESEARCHERS**



**7 STUDENTS**

*Orbit predictions  
that properly  
account for the  
variable space  
environment are  
required*

## PROJECT PARTICIPANTS

- RMIT University
- Optus Satellite Systems
- National Institute of Information and Communications Technology (Japan)

## RESEARCH SNAPSHOT FOR 2016

**R2.1** Develop Intelligent Systems for Real-Time Precision Orbit Determination (POD) for 'Controlled' Satellites.

**R2.2** Development of Reliable Orbit Determination (ROD) Algorithms and Software

## R2.1 DEVELOP INTELLIGENT SYSTEMS FOR REAL-TIME PRECISION ORBIT DETERMINATION FOR 'CONTROLLED' SATELLITES

**Project lead:** RMIT

**Researchers:** Robert Norman, Yang Yang, Brett Carter

**Participants:** RMIT, Optus Satellite Systems, NICT

This research program is developing real-time POD software platforms for 'controlled' satellites orbiting at a range of altitudes. The program will develop methods to accurately determine Atmospheric Mass Density (AMD) modelling through an improved understanding of the effects of perturbing influences, such as space weather.

Global Navigation Satellite System (GNSS) POD software was completed during the reporting period and is undergoing on-site testing and validation at SERC.

The software has the capability to process Global Positioning System (GPS) two-frequency (L1/L2) pseudo-range and carrier phase measurements for precise orbit determination of low Earth orbit satellites. This software will also provide a platform to validate the new and improved AMD models in terms of orbit prediction.

The AMD software developed includes models for both the neutral and ion densities in the low earth orbit atmosphere. The ion (predominately O+) density and complex dynamics have been included. The ion densities at altitudes of 1000 km can be as high as 15% of the total atmospheric density and this contributes directly to the overall atmospheric drag force on satellites/space debris.

## R2.2 DEVELOPMENT OF RELIABLE ORBIT DETERMINATION ALGORITHMS AND SOFTWARE.

**Project lead:** RMIT

**Researchers:** Yang Yang, Steve Gehly, Jerome Daquin

**Participants:** RMIT, NICT

This program is developing an advanced Reliable Orbit Determination (ROD) platform for 'uncontrolled' space objects. The ROD software platform under development comprises versatile orbit determination algorithms that employ data from a variety of different sources; e.g. two-line element (TLE) and satellite laser ranging data.

ROD is designed to produce accurate state estimates and uncertainty quantification for debris objects using sparse tracking data. This project encompasses many different concepts and estimation techniques. The focus of research over the last 12 months has been on extracting useful information from the publicly available TLE catalogue and computing reliable orbit determination solutions from sparse data that contains outliers.

Algorithm design has been completed for the numerical and semi-analytic ROD software platforms. These platforms have an expected completion date of 30 June 2018.

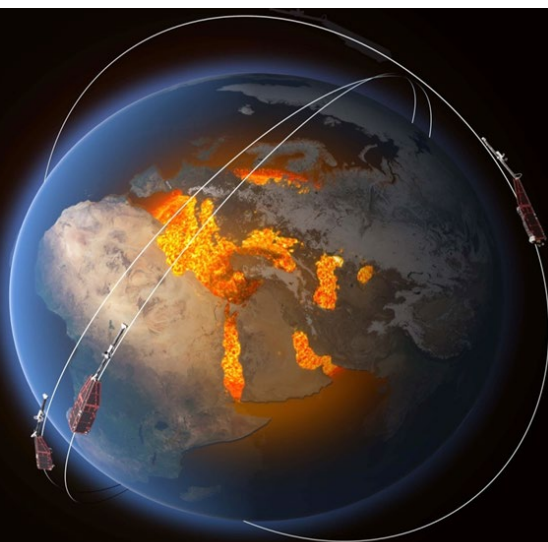


Figure 9: Space weather

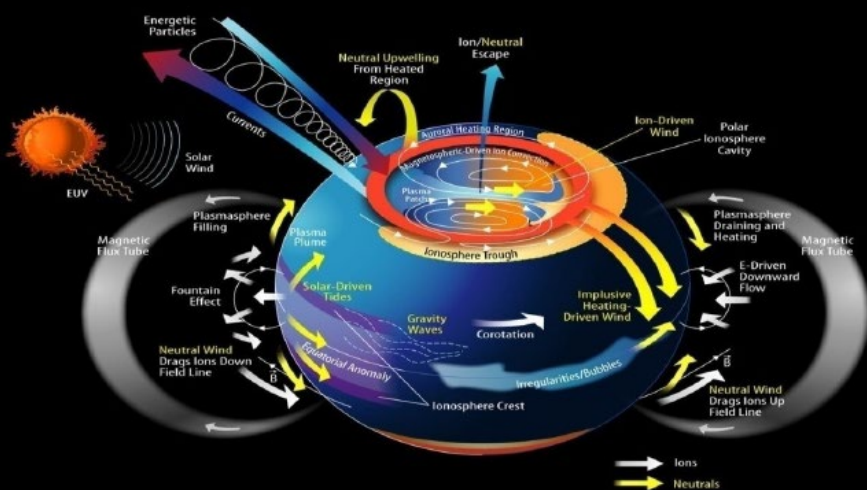


Figure 10: Thermosphere Ionosphere Electrodynamic General Circulation Model (Physics Based model of space weather credit: J Grobowsky NASA OSFC)





# RESEARCH PROGRAM **THREE**

## SPACE ASSET MANAGEMENT

**Program Leader:** Dr James Bennett

This research program is developing techniques, algorithms and databases to predict and avoid potential collisions between space objects. This will provide a transparent and rational means to make decisions about space asset management and how best to optimise assets and preserve the space environment.

A major focus is the development of systems that allow multi-national contributions to space object catalogues and a global distribution of asset management.

*Systems that allow  
multi-national  
contributions  
to space object  
catalogues  
and a global  
distribution of asset  
management*

### PROJECT PARTICIPANTS

- SERC
- EOS Space Systems
- Optus Satellite Systems
- RMIT University

### NON-PARTICIPANT COLLABORATIONS

- University of Arizona
- University of Texas
- Graz Observatory, Austria

### RESEARCH SNAPSHOT FOR 2016

**R3.1** Develop a special Satellite Object Catalogue

**R3.2** Develop Conjunctions Analysis and Threat Warning (CATW) Capability

**2 PROJECTS**

**4 PARTICIPANTS**

**14 RESEARCHERS**

**1 STUDENT**

### R3.1

## DEVELOP A SPECIAL SPACE OBJECT CATALOGUE

**Project lead:** SERC

**Researchers:** James Bennett, Daniel Kucharski, Michael Lachut, Marek Möckel, Sven Flegel, Steve Gehly, Alex Pollard, David Kooymans, James Allworth, Jessica Todd, Ian Bartlett

**Participants:** SERC, Optus Satellite Systems, EOSSS, RMIT

A core function of Research Program 3 is to develop a Space Object Catalogue (SOC). Several tools have been developed to ensure quality data. These include:

- Telescope mount modelling software with new astrometric mount calibration functionality.
- An extensive data post-processor that validates incoming sensor data using probabilistic data association.
- The automation of the orbit determination process. This automation and the previous two software tools are all co-dependent.

A new visualisation platform has been developed for the verification of orbital elements. A graphical user interface (GUI) has been designed to assist analysts investigate the automated orbital solutions that have been quarantined.

Further developments include:

- Data quality summaries are being prepared to allow comparison of Mount Stromlo optical sensor data with SERC generated tracks and cues from TLEs.
- The single-sensor (EOSSS 1.8m telescope) SERC generated orbital elements are performing well and have also been verified as providing successful and more accurate telescope cues during tracking sessions.
- Summary reports have been prepared for tracking session feedback. These contain summary statistics on the residuals of calibration objects, the mount accuracy, and the astrometric corrections.
- The SOC is being populated with new objects of interest through regular tracking.
- State vectors are being generated from the tracking campaigns and are being used to re-cue the EOSSS 1.8m telescope.

- Light-curve generation software has been developed and light-curve generation and processing is now automated.
- A 'satellite body model' (SBM) format which will be used for the force/torque modeling is being developed. A large software package for predicting torques is being developed and will have commercial potential and facilitate many research outcomes.

Work is being done in admissible regions and will be developed to assist with track association and initial orbit determinations.

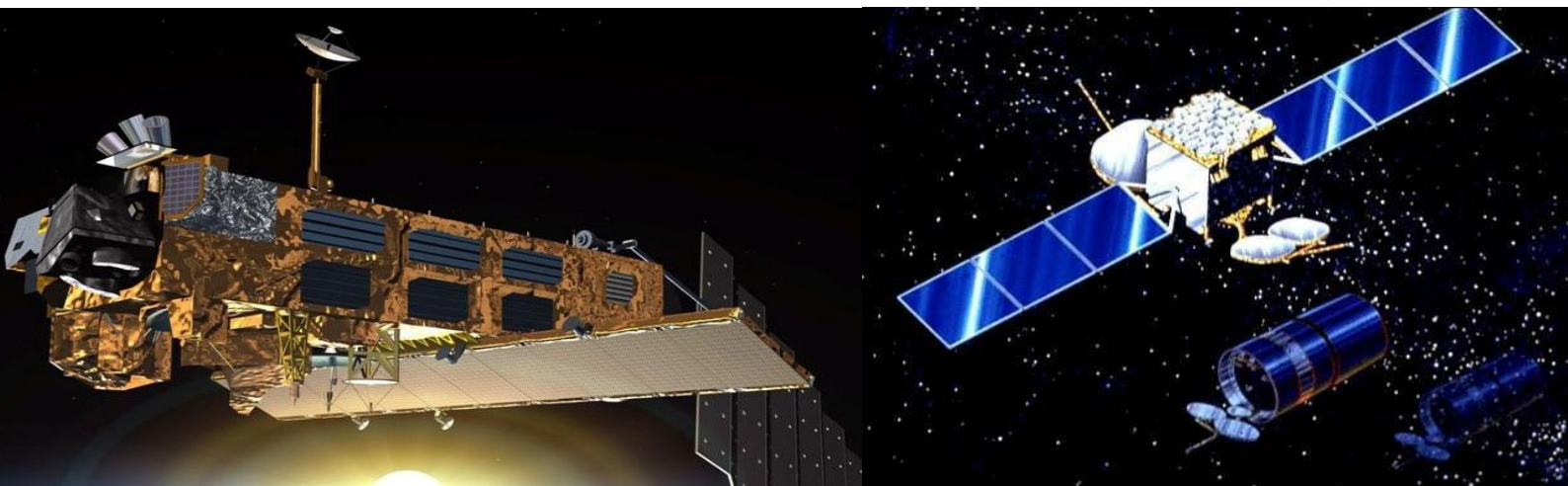
Development work is being done to identify manoeuvres using filtering methods.

A detailed and extensive Torque Analysis Unit (TAU) software platform is being developed. This software models the forces interacting on a space object and has been used to assist the mission planning for Research Program 4. This is a large piece of software that will facilitate many of the research programs in SERC.

One of the areas that the Space Asset Management team are interested in is the support of active debris removal missions and the use of high powered lasers to de-spin objects to assist in the rendezvous missions. The TAU software has been used to model the effects of laser engagements and highlights the necessity of knowing the object's characteristics for the optimal laser engagement.

Several objects have been studied, including the spin-up process of the Optus-B1 satellite. The Glonass-44 and Topex satellites have also been analysed. A macro-model of the ETS-VIII satellite is being developed. The light curves indicate a slow rotation of this satellite and the macro-model will allow us to understand and predict the development of the spin dynamics.

A test will be set up through partner organisations with MOUs with SERC to externally verify the orbital ephemeris data produced. This will be planned for later in 2017 or early 2018 when the additional sensors have been fully integrated.



Envisat, Earth Observation Satellite. Envisat was decommissioned in 2012 and is a candidate for active debris removal mission planned for 2020.

Optus B1 Satellite and Optus A-series Satellite. Both are decommissioned and now space debris.



## R3.2 DEVELOP CONJUNCTION ANALYSIS AND THREAT WARNING (CATW) CAPABILITY

**Project lead:** SERC

**Researchers:** James Bennett, Marek Möckel, Sven Flegel, Daniel Kucharski, Michael Lachut, Steve Gehly

**Participants:** SERC, Optus Satellite Systems, EOSSS, RMIT

SERC is developing a conjunction analysis capability system for all objects (all-on-all conjunction analysis) in the SOC and provide alerts to subscribers. The SERC conjunction system will also distribute priority tasking to sensors in the SOC network to provide increased tracking and updating for serious potential collision prospects.

The compilation of the CATW database is underway. The previous focus has been on TLE vs TLE and now other data sources are being integrated. The conjunction assessment algorithms have been packaged into libraries. A generic propagator interface has been prepared for the integration of other data sources such as satellite ephemerides and observation data. Regular conjunction assessments are performed for Optus and Singtel assets with TLEs; new uncooperative objects which threaten these assets are routinely amended to the SERC SOC. A virtual reality (VR) visualisation of the debris field has also been developed. The visualisation allows the user to view the on-orbit objects immersed in a VR experience. The user can rotate and change views to view from the Earth or any point in the LEO-to-GEO region. Future developments will allow the user to visualise the conjunction scenarios.

Work continues on integrating SERC Catalogue Orbit Prediction and Estimation (SCOPE) software into operations to maintain the SOC and close the operational loop, including:

- Automated orbit determinations (ODs) performed fitting the observations collected. The catalogue now automatically checks for cases which yield non-physical satellite characteristic properties such as the coefficient of drag and solar radiation pressure (SRP). These indicate poor orbit estimations, likely due to data outliers or insufficient data.
- Processes that verify the reliability of predictions from the OD process have been developed.
- The characteristic properties such as coefficient of drag and SRP or ballistic coefficients that results from successful OD processes are now being stored in the catalogue. These will be used to seed subsequent ODs, meaning independence from the TLE catalogue.
- Processes have been developed to improve the reliability of the OD fitting and automation and thus enhancing the overall success rate.

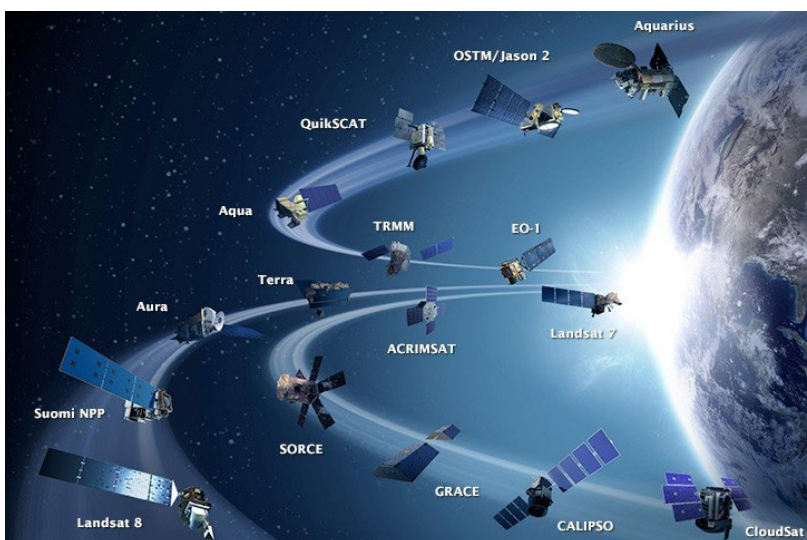
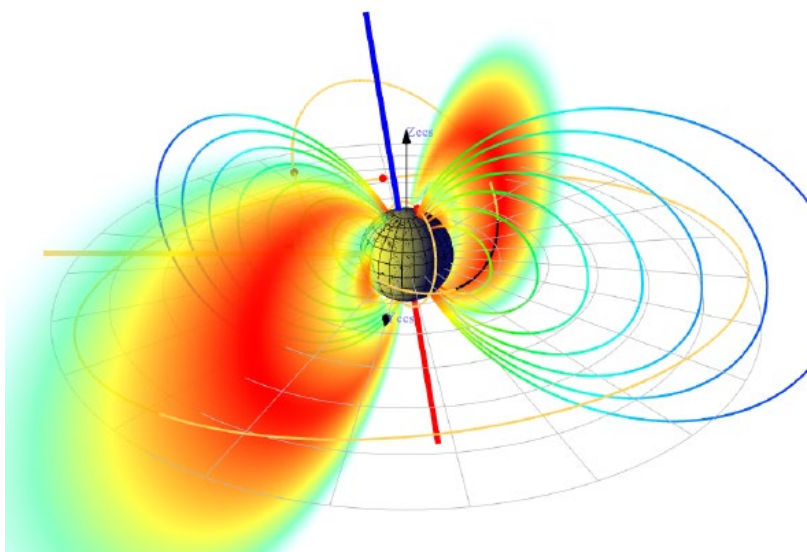
An information gain based sensor scheduler (SERC Scheduler: version 1) has been developed and will now be integrated for testing. The current version automatically schedules (taking into account sensor deconfliction, visibility, etc.) all of the objects on the tracking list and assigns tracking tasks that maximises the information gain for a single sensor. The method also allows for target priority to be included. A “brickpacker” method is employed to handle LEO-to-GEO scheduling. This version is running at Stromlo and is being automated it into regular operations. Work is underway on version two which will be developed for multi-sensor tasking where each sensor can bid for each task and get assigned priority based on the information gain score. The “brickpacker” method will be changed to a single step assignment. Variable track lengths will be facilitated to meet the needs of specific tasks, for example, light curve determination.

A system is being set up which will:

- Provide reliable, high accuracy conjunction assessment for any conjunction type (e.g. GEO, LEO, high relative velocity, low relative velocity) at the cost of high computational burden; and
- Be used as a testing environment for more efficient methods.

The timeframe until the state uncertainty becomes non-Gaussian has been found to rely on the confidence level with which the future position of an object is to be predicted. This relationship has not been found in common publications on the matter. This finding has been presented and published at the 7th European Space Debris Conference.

The applicability of a novel approach to the estimation of the location and epoch of an on-orbit fragmentation has been assessed. The current assessment is that the method has potential to improve a given conjunction estimate if orbit state uncertainties are given. The method could to now only be tested on a case where no orbit state uncertainty was available. The next step will be to implement full force model propagation. The conjunction assessment software now interfaces with orbit determination and mission planning architectures to automatically add critical objects to tracking campaigns. Various methods of automated conjunction data message (CDM) and conjunction warning generation are under development.



**Top:** Space Environment Modelling for space debris orbital and spin dynamics Satellites

**Bottom:** Environmental and Earth observation satellites in orbit



# RESEARCH PROGRAM **FOUR**

## *Preservation of the Space Environment*

### SPACE SEGMENT

#### Program Leader:

1 Jul 2016 – 31 Dec 2016 Dr Matthew Bold  
1 Jan 2017 – 30 Jun 2017 Dr Benjamin Sheard

Apply knowledge gained and technologies developed in research programs 1-3 to manoeuvre an object in space using ground-based lasers.



**5 PROJECTS**



**4 PARTICIPANTS**



**12 RESEARCHERS**



**4 STUDENTS**

### PROJECT PARTICIPANTS

- ANU
- EOS Space Systems
- Lockheed Martin
- Optus Satellite Systems

### NON PARTICIPANT COLLABORATIONS:

- UNSW Canberra
- Georgia Institute of Technology

### RESEARCH SNAPSHOT FOR 2016

- R4.1** System Engineering
- R4.2** Payload Development
- R4.3** Demonstration of Remote Manoeuvre of Space Debris and Photon Pressure
- R4.4** Bus and Payload Integration
- R4.5** Launch and Operations



## R4.1 SYSTEM ENGINEERING

**Project lead:** SERC

**Researchers:** Benjamin Sheard, Liam Smith

**Participants:** EOSSS, Lockheed Martin, ANU, Optus Satellite Systems

A revised proposal for RP4 was presented at a whole of program review which followed the SERC 2017 Research Colloquium. The revised proposal outlined:

- 1) A satellite with a payload to measure laser irradiance as well as a beacon to simplify orbit selection. Payload elements to support a momentum transfer test will be included if assessed to be feasible.
- 2) Near-space test platform consisting of a series of instrumented high altitude balloons to validate the adaptive optics performance by measurement of the laser irradiance profile with AO correction.

RP4 has been focusing on an opportunity to include a secondary payload on an Australian CubeSat with an expected launch date in early 2018. A requirements document and statement of work for this payload has been prepared. This hosted payload is a cost-effective risk mitigation strategy which will negate the necessity for SERC to launch a dedicated satellite to measure laser irradiance on-orbit.

A preliminary requirements document for a dedicated satellite has been prepared and reviewed by Participants. A number of issues have been identified and mitigating controls are in development to enable the manoeuvre to be detectable with high confidence.

Mission definition and preliminary concept of operations was presented at the SERC Colloquium and reviewed at the whole of program review meeting. The top-level requirements of the proposed near-space and satellite projects were presented and workshopped with Participants and end-users.

Trade studies have been performed investigating laser induced target motion from background drag as a function of altitude. Simulations by both SERC and LM have refined SERC's assumptions for orbit prediction capabilities required to resolve a manoeuvre for a 3kg satellite with a  $3 \text{ m}^2$  momentum transfer sail. Further detailed analysis is being undertaken by RP2/3 to support a momentum transfer test with high area to mass ratio (HAMR) objects.

A "capstone" project by a group of Georgia Tech students to develop the satellite design was carried out in collaboration with SERC. The outcome of this student project was a CubeSat Critical Design Review (CDR) which was presented at the 2017 SERC Research Colloquium.

LM continues to assess the impact of an orbital system for completion of the RP4 demonstrations as well as evaluating alternative approaches. The scope of the dedicated satellite has been agreed at the review after the colloquium to support measurement of laser irradiance.

## R4.2 PAYLOAD DEVELOPMENT

**Project lead:** SERC

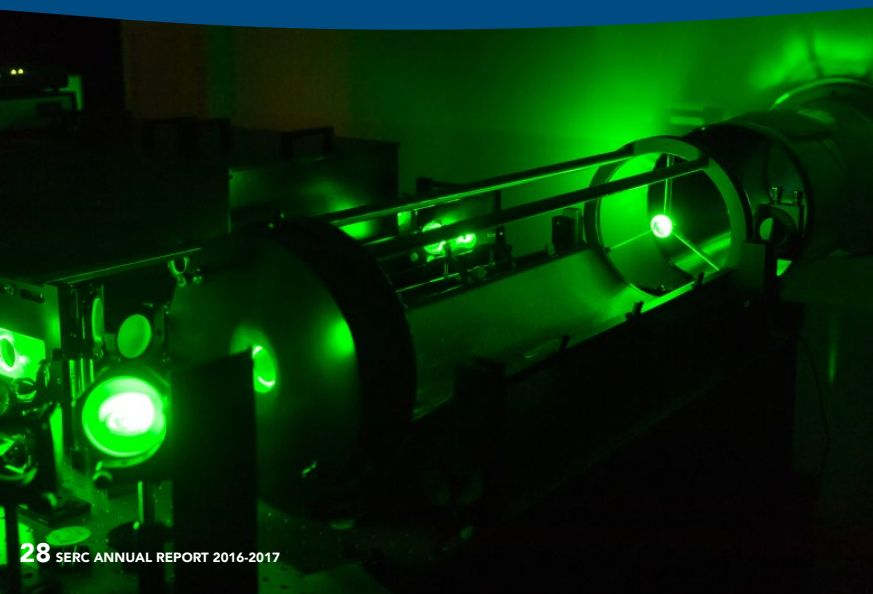
**Researchers:** Benjamin Sheard, Mike Petkovic, Andrew Bish, Gaston Gausachs, Francis Bennet

**Participants:** ANU, Lockheed Martin

RP4 has been focussed on design and development of a hosted payload which has an anticipated launch date in early 2018 and therefore has a challenging development schedule. Software development and payload sub-system design is underway.

The preliminary requirements for the payload elements to support a manoeuvre have been established and documented. The requirement to support the manoeuvre demonstration with a dedicated satellite was de-scoped at the review following the SERC colloquium.

**From left:** EOS Laser at Mount Stromlo, EOS Space Research Centre with laser beam. Source: ANU, Laser calibration, EOS Space Research Centre



RP4 has been focussed on design and development of the hosted payload given the early 2018 anticipated launch date. Software development and payload sub-system design has commenced. LM continues to assess the impact of an orbital system for completion of the RP4 demonstrations and is also evaluating alternative approaches to a dedicated SERC satellite.

### R4.3 DEMONSTRATION OF REMOTE MANOEUVRE OF SPACE DEBRIS AND PHOTON PRESSURE

**Project lead:** SERC

**Researchers:** Benjamin Sheard, Matthew Bold, Craig Smith, Yue Gao

**Participants:** EOSSS, ANU, Lockheed Martin

This program combines the outputs of active tracking, orbit computation and beam propagation through the atmosphere to make small but measureable changes to an orbiting object.

The aim of the project is a demonstration of a practical active collision avoidance system using photon pressure.

Orbit manoeuvre options have been analysed with the view to determine if they are sufficiently large enough to observe an orbit change and confidently demonstrate that the change was due to the laser engagement(s) and not some other perturbing forces acting on the satellite.

The current assessment of the orbit manoeuvre options indicate that a CubeSat using a Commercial off the Shelf (COTS) 3m<sup>2</sup> deployable sail may not yield a reliably observable manoeuvre with sufficient statistical confidence with the current orbit prediction capabilities. Alternative approaches are being analysed as a risk mitigation strategy.

### R4.4 BUS AND PAYLOAD INTEGRATION

**Project lead:** SERC

**Researchers:** Benjamin Sheard, Mike Petkovic

**Participants:** SERC, ANU

**Non-SERC Participants:** UNSW Canberra

Integration, thermal and vibrational testing, and integration of the hosted payload into the satellite is planned for implementation during Q3/Q4 2017 with delivery to the launch provider scheduled for late 2017.

### R4.5 LAUNCH AND OPERATIONS

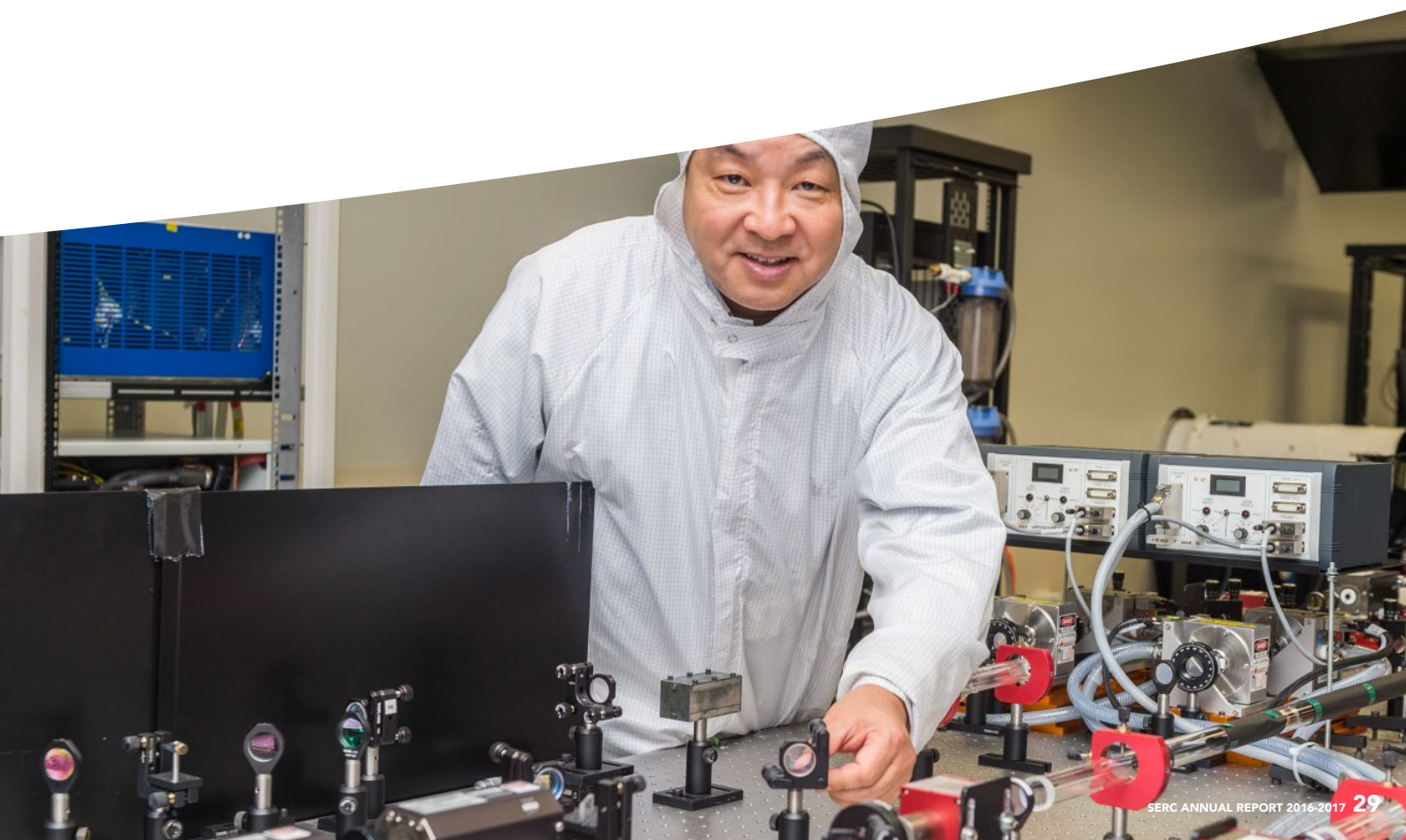
**Project lead:** SERC

**Researchers:** Benjamin Sheard, Mike Petkovic

**Participants:** SERC, ANU

**Non-SERC Participants:** UNSW Canberra

The launch for the hosted payload is scheduled for early 2018. Preparations are underway to work with the host satellite operator to develop SERC's operational requirements.





## 1.5. EDUCATION AND TRAINING

SERC has undertaken to enrol 24 postgraduate students and graduate 10 over the five year funding period. To date, SERC has enrolled 23 postgraduate students and graduated one. In addition, SERC has funded three exceptional undergraduate students during their final year of study, two of whom went on to be funded as SERC PhD scholarship recipients. The third undergraduate student has indicated that he may also apply for a SERC scholarship in the next reporting period.

By 30 June 2019, SERC expects to fund an additional three postgraduate students and graduate a further 14. Funding has not been allocated to support additional undergraduate students. It is anticipated that by 30 June 2019, SERC will exceed the education targets set in the Commonwealth Agreement. SERC expects to enrol 26 postgraduate students and graduate 15 postgraduate and three undergraduate students.

SERC graduate, Lyle Roberts, has secured a position with the ANU Research School of Physics and Engineering as a lecturer and PhD supervisor. Lyle currently provides co-supervision for three SERC PhD students.

### STUDENT INVOLVEMENT IN SERC ACTIVITIES

SERC's education priorities are to build capability and capacity in the space industry sector, provide opportunities to develop the skills of scholarship recipients, build SERC staff capabilities and knowledge transfer. Throughout the reporting period, SERC continued to provide enhanced education and training opportunities for SERC scholarship recipients including participation in the following activities:

**Student Development Day** – SERC students took part in a professional development day at Mount Stromlo in May 2017. Students presented a twenty minute overview of their research project to members of the international Research Management Committee, SERC Executive and Research Program Leaders.

Students were provided the opportunity to discuss any challenges they were experiencing and receive feedback and suggestions for further research from international subject matter experts. As a result of this interaction, Associate Professor Moriba Jah, University of Texas in Austin, undertook to mentor two RMIT students who are undertaking their PhD research in astrodynamics related fields.

SERC graduate, Lyle Roberts (R) with PhD student Paul Sibley (L), Research School of Physics and Engineering, ANU





SERC researcher discussing research concepts with a PhD student at the SERC Research Colloquium 2017

#### **Intellectual Property Identification and Protection Workshop**

An Intellectual Property (IP) workshop was delivered as part of the student professional development day. The workshop was facilitated by Dr Justin Coombs, a registered patent attorney and General Manager of the Cell Therapies CRC. The workshop explored the core concepts of IP including disclosure, novelty, inventive step and utility. Students were introduced to the different types of IP and provided means to identify what is IP and how to record it. Dr Coombs highlighted pitfalls in patent specification and provided practical advice on claims drafting, background IP, Centre IP and how each relate to the commercialisation of SERC Research.

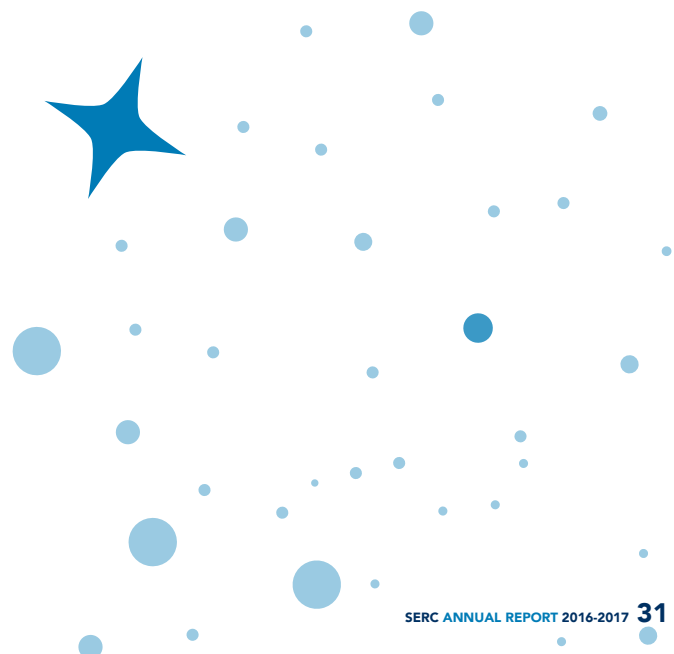
**SERC Research Colloquium** - Students participated in a two day SERC research colloquium at the John Curtin School of Medical Research. The Colloquium was attended by all SERC Participants and end-users and afforded students the opportunity to network and collaborate with senior SERC researchers and potential employers. Students attended presentations covering all SERC research programs and gained a greater understanding of SERC activities and their role in the SERC research program.

**Presentations at International Industry Conferences** - SERC students receive as part of their scholarship award, a discretionary fund of \$3,000 to attend and present at international conferences and industry symposia. This affords students the opportunity to network with international space industry professionals and gain experience presenting to international audiences.

During the 2016-17 reporting period, SERC students presented more than 28 papers at eight international conferences including the Advanced Maui Optical Society (AMOS) conference Hawaii, U.S.A, the European Conference on Space Debris in Darmstadt, Germany and the Adaptive Optics for Extremely Large Telescopes conference in Tenerife, Canary Islands.

**Student Publications** - SERC students were listed as authors on 29 publications during the reporting period. A full list of SERC publications is provided at Appendix 1.

**Research Exchanges** - During the 2017 Research Colloquium, Dr Moriba Jah, Associate Professor, University of Texas in Austin, invited two RMIT students to undertake a research exchange to the University of Texas at Austin in 2018.





# STEM AND COMMUNITY OUTREACH

**STEM X Academy** - SERC sponsored and participated in the Australian Science Teachers Association STEM X Academy for the second consecutive year in 2017. STEM X is a five-day residential professional learning program for primary and secondary teachers of science, technology, engineering and mathematics. This innovative professional development program delivers access to resources, networks and methods and empowers teachers to structure their classrooms as laboratories for STEM-authentic problem solving, creating a portal to the dynamic, multidisciplinary inquiry-driven world of Australia's research community.

**Graceville State School** - Participation in the 2016 STEM X Academy inspired a class of year 5 gifted and talented students at Graceville State School to write a book about SERC CEO, Dr Ben Greene.

**Café Scientifique** - Sandra Davey is now inspiring students in her new role as Queensland Academies Educational Programs Coordinator. Sandra recently hosted Café Scientifique-2017 <https://qasmt.eq.edu.au/qut-cafe-scientifique-2017/> as part of National Science Week.

Dr Greene was the keynote speaker and panellist, and participated in a number of activities including interviews with children in regional Queensland who attended the event virtually, using satellite technology.

**International Baccalaureate Primary Years Programme (PYP)** - SERC General Manager, Dr Steve Gower, was invited to discuss the issue of space debris with Hunter Valley International Baccalaureate (IB) students. The Hunter Valley Grammar School year six IB class interviewed Dr Gower via Skype for their inquiry into space junk. The interview culminated in a PYP exhibition on space debris which was attended by the school community, family and friends.



**STEM INSPIRATION**

After primary school teacher Sandra Davey heard eminent Australian scientist Dr Ben Greene speak at STEM X 2016, she was so inspired by his story that she decided to write a book about it or more accurately, have her students do so.

She knew he would appeal to her students, who were part of the enrichment program and among the brightest at Graceville State School.

"He was an inspirational man who challenged his teachers and was brave enough to stand up for what he believed in," she says. "And the kids in my class got that, so I thought he'd be an excellent role model."

Dr Greene's fierce intellect has seen him become CEO of the Space Environment Research Centre, combating space junk through the world's most sophisticated lasers.

Excited and intrigued by the nature of his work, and with few resources for primary-aged students on Australian scientists, writing a book about Dr Greene and his research seemed an ideal way to explore the concepts, Ms Davey says.

In a case of true inquiry-based student-led learning, students investigated aspects of Dr Greene's work and life according to their interests. Some looked at lasers, others photons, some satellites, others NASA. These subjects were also explored visually through artwork created for the book.

"There were abstract concepts and terminology we didn't initially grasp, but investigating them opened up a whole world of science," she says. **"They had to take some risks to mentally put it all together,**

**but stepping out of their learning comfort zone allowed for beautiful academic growth."**

The students conducted Skype interviews with Dr Greene where they learnt a new set of research skills, as well as taking their book 'beyond the facts' by asking not only about his achievements, but also his schooling and personal life. Dr Greene also met the student who drew his portrait for the book's cover, inspiring her about prospects for women in science.

This personal connection was invaluable for the students, many of whom could identify with his early life and so too came to believe they could one day excel in STEM careers, Ms Davey says. "He has really empowered them and showed them that science is about solving problems relevant in the real world."

Ms Davey, who is now running the Bright Minds and the Young Scholars outreach programs for the Queensland Academies, also learnt an incredible amount through the process of stepping out of the boundaries of the classroom.

STEM X inspired this by introducing her to Dr Greene, and also provided teaching insight into rich hands-on learning and on connecting students with real-world science.

"STEM X broadened my world, my scientific knowledge and my own enthusiasm for what is going on out there and I am now passing that on to the students I teach," she says.



The following artworks were created by the Graceville State School gifted and talented class as illustrations for their book about Dr Ben Greene.



**Top:** QUT Cafe Scientifique 2017 L to R: C Malau, Y Chen, B Greene, C Soans, F Sultanbawa, J Sim

**Bottom:** Hunter Valley PYP Exhibition on Space Debris



## SME ENGAGEMENT

SME representation in the Australian space sector is largely comprised of technology companies and service providers who support international space missions and provide solutions to owners of space based infrastructure.

A further, much broader market segment comprises companies who provide goods or services which rely on satellite technology. This industry sector has much greater SME representation.

SERC supports SME engagement across the space industry sector through the following activities:

**SME Participants** – EOSSS is an SME Participant and represents the interests of SMEs within SERC. Professor Craig Smith, CEO and Technical Director, EOSSS is the leader of RP1. Through leading the RP1 research team, Professor Smith ensures that SME interests are considered through the delivery of SERC research outcomes.

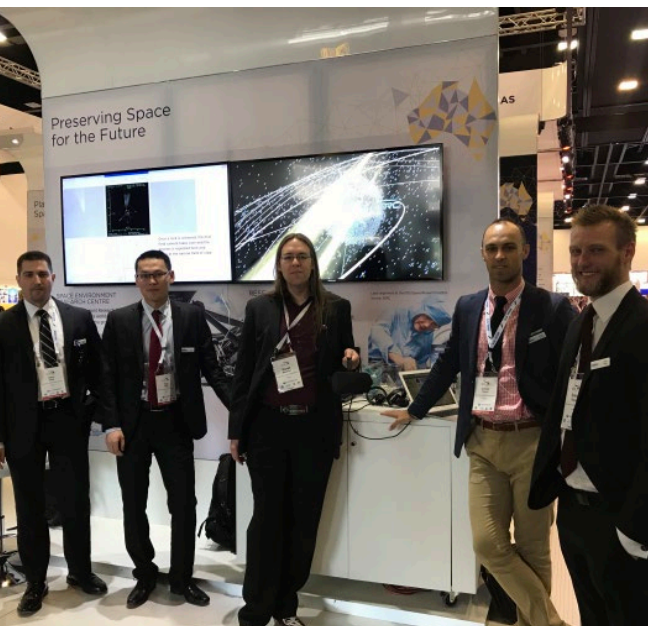
**Board Representation** – Independent Board Member, Mr Brett Biddington AM, is an SME business owner and ensures that SME interests and perspectives are considered at a Board level.

**Research Management Committee Representation** – SME interests are represented at the Research Management Committee (ResMC) level through participation by EOS Group Chief Executive Officer (ResMC Chair) and EOS Space Systems Chief Executive Officer (ResMC Member).

**Conferences and Industry Events** – SME engagement and consultation on a national and international level is achieved through participation at space industry conferences, workshops and symposia. During the reporting period SERC representatives attended over 25 space industry events and held meetings with a broad range of SME space industry professionals.

**International Aeronautical Congress, Adelaide, September 2017** – SERC exhibited at the International Astronautical Congress (IAC) as part of the Department of Industry, Innovation and Science “Big Country, Big Sky, Big Ideas” exhibition stand in Adelaide. IAC is the world’s largest space conference and was attended by 4,500 space industry delegates. SERC representatives engaged with international space industry SMEs during the congress and identified opportunities for further international SME engagement.

**Space Working Group** – SERC is a member of the ACT Government Space Working Group (SWG). The SWG has a number of SME space industry representative members and has recently signed an MOU with the South Australian Government to expand collaborations. The SWG expects to sign additional MOUs with the Northern Territory and other Australian state Governments in 2018. It is therefore anticipated that SME engagement opportunities on a national level will increase through participation in and engagement with SWG members during the next reporting period.



**Above:** SERC booth at IAC. From L to R: Steve Gehly, Yang Yang, Marek Mockel, Jerome Daquin, Sven Flegel



**Right:** The SERC Space Object Catalogue virtual reality experience was demonstrated at the CRC Association Conference at Parliament House in May 2017

## 1.6. UTILISATION AND COMMERCIALISATION

The Space Environment Research Centre (SERC) held regular meetings with end-user Participants during the reporting period, and attended national and international conferences and symposia to promote SERC utilisation and commercialisation objectives.

### Regular Meetings with Participants and Researchers

SERC CEO, Dr Ben Greene, met with senior representatives from each end-user Participant organisation to ensure that SERC research is addressing their needs and requirements. In addition, SERC General Manager, Dr Steve Gower, attended monthly research and technical meetings to ensure that the research is tracking well against commercialisation and utilisation milestones.

### SERC Research Colloquium

The 2017 SERC Research Colloquium was held over 4 days from Tuesday 30 May to Friday 2 June at the John Curtin School of Medical Research, ANU, Canberra and was attended by SERC researchers, students and Participant organisations.

There were 29 presentations including progress reports from each of the SERC research programs and sub-programs. Chief Executive Officer, Dr Ben Greene, presented a whole of organisation overview outlining the technology and componentry requirements and timelines for the on-orbit demonstration (manoeuvre of a space object(s) using ground-based lasers.). Through these presentations, all members of the organisation gained a deeper understanding of program, end-user and commercialisation requirements.

### Design Review Meetings

Design review meetings were conducted for all research programs in accordance with the Commonwealth Agreement utilisation milestones. In addition, a whole of organisation review meeting followed the 2017 SERC colloquium. This enabled an inter-research program and cross-organisation (Participant) review and has informed the development

of a master schedule which tracks the progress and delivery of research and delivery of milestones, including commercialisation and utilisation milestones.

### Industry Liaison and Conference Attendance

SERC continued to build brand awareness and further clarify non-Participant end-user requirements through participation at national and international events and conferences.

During the reporting period, SERC:

- Supported more than 66 researchers and students to participate and deliver technical papers at more than 22 national and international conferences and symposia.
- Essential Participant, RMIT, hosted the 16th Australian Space Research Conference (ASRC) in September 2016 (SPACE/RMIT)

### International Workshop on Laser Ranging

SERC utilisation milestones include delivering an international workshop to communicate SERC research outcomes to an international audience. During the reporting period, SERC was successful in winning a bid to host the 21st International Workshop on Laser Ranging. This event will be held in Canberra from 5-9 November 2018 and is regarded as the world's leading workshop in this field.

It is anticipated the 2018 event will be attended by delegates from international space agencies, space research centres and universities including (but not limited to):

- NASA
- Smithsonian Astrophysical Observatory
- German Research Centre for Geosciences
- European Space Agency (ESA)
- International Laser Ranging Network Stations from around the world including observatories from Europe, USA, China, South Korea and Australia

The SERC Research Colloquium was held at the John Curtin School of Medical Research





SERC is employing industry best practice in the management of Intellectual Property (IP) as detailed in the National Principles of Intellectual Property Management for Publicly Funded Research. In support of IP management, SERC:

- Adheres to the Australian Code for the Responsible Conduct of Research
- Has clear policies and procedures in relation to the ownership and associated rights for all IP generated through Centre activities (Centre IP).
- Has clear policies relating to the exploitation of IP generated through Centre activities.
- Makes all Centre IP openly accessible through licencing arrangements which provide exclusive opportunities to undertake commercial exploitation.
- Provides support to researchers in identifying, developing and protecting Centre IP whilst upholding the academic requirement to publish.
- Provides guidance in relation to potential conflicts concerning IP management, ownership, promotion, dissemination, exploitation and, where appropriate, protection of IP.
- Provides guidance on the licensing of copyright, in particular, the criteria for publishing under the terms of open access licences.

The SERC *Intellectual Property Confidentiality and Disclosure Policy* was reviewed by the SERC governing

Board during the reporting period. This Policy makes clear to all staff their responsibilities in relation to IP management including, where appropriate, the maintenance of research records (including lab books where possible, and field notebooks) and the handling of research results prior to promoting and disseminating the IP or obtaining IP protection.

### IP Awareness and Training

To build awareness of the importance of IP amongst researchers, SERC has implemented a number of initiatives:

- Numbered lab notebooks have been issued to all SERC researchers and students.
- Prior to publication approval being given, all publications and presentations are vetted by SERC for unintentional disclosure of Centre IP.
- Participant Quarterly Reports include a section relating to IP. Information disclosed in these reports is used to populate a comprehensive register of both Participant background IP and Centre IP developed during the quarter.

No registered IP was sold, transferred or licensed for commercialisation during the reporting period, however SERC has been in commercial discussions regarding IP related to methods for measuring atmospheric turbulence and laser light generation at sodium wavelengths.



SERC Researcher, Doris Grosse, discussing her research at the CRC Association Annual Awards Dinner

## 1.7. COMMUNICATIONS

SERC communication activities during the 2016-17 reporting period focused on:

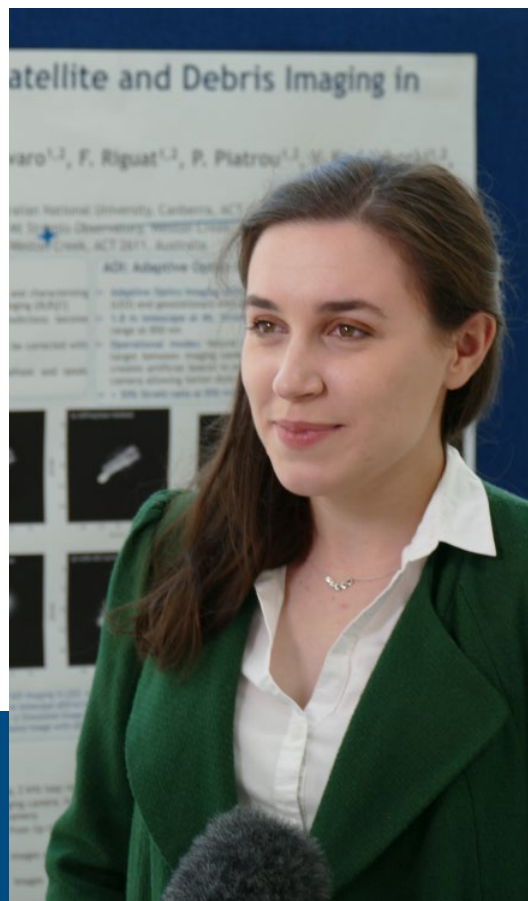
- Strengthening internal communication and collaboration amongst Participants
- Building brand recognition and awareness of SERC activities within the national and international space industry
- In addition, the SERC Communications Strategy was reviewed and updated in line with Commonwealth annual reporting requirements

## INTERNAL COMMUNICATION

**SERC Newsletter** – The SERC newsletter, SERCular, is published quarterly and distributed to Participants, students and stakeholders to strengthen internal communication and collaboration. The newsletter features articles about research progress, publications, awards and accolades, researcher profiles, upcoming events and informs participants about SERC activities.

**Meetings with Participants** – SERC management meet regularly with Participants to foster communication and ensure all aspects of the CRC are running as efficiently as possible.

Television interview with Jessica Todd, SERC Graduate Research Assistant



This is especially important with Participants who are not located in the same physical location.

**Colloquium** – The SERC Research Colloquium is held annually to foster communication and collaboration at a whole of organisation level. The Colloquium is an opportunity to brief all researchers' students, and Research Management Committee members on research progress and success and identify opportunities for further collaboration.



**Quarterly and Annual Reports** – Participants compile reports on their progress against milestones on a quarterly basis. Individual reports are compiled into a whole of organisation progress report which is circulated to Participants twice annually.

## EXTERNAL COMMUNICATION

**Website** – The SERC website informs Participants, students, space industry stakeholders and the public about SERC research and objectives. Content was further developed during the reporting period and traffic to the site has grown significantly.

**Facebook** – The SERC Facebook page continued to gain momentum during the reporting period. Posts have highlighted SERC events and activities as well as space debris stories of interest. SERC maintained an average of three posts or reposts per week which has resulted in 652 likes and 301 visits to the SERC Facebook page.

**LinkedIn** – SERC established a LinkedIn profile to track SERC alumni. This initiative will enable SERC to keep in touch and track the careers of SERC scholarship students and post-doctoral researchers. The SERC LinkedIn profile is gaining recognition in the space industry.

**Press and Radio Coverage** – SERC issued a number of press releases throughout the year which resulted in significant media coverage including:

- one front page newspaper article in The Canberra Times;
- one podcast;
- two magazine feature stories including Nova Science Magazine and the CRC Association Magazine;
- four television interviews including ABC National News;
- eight radio interviews including The ABC Newcastle Morning Show, ABC Radio Canberra, 2UE, ABC National News and ABC Radio Perth; and
- Thirty four web stories about SERC activities including articles in The Daily Mail, The Guardian, The Canberra Times, Mumbai Mirror, Satellite Today and the Scottish Sun.

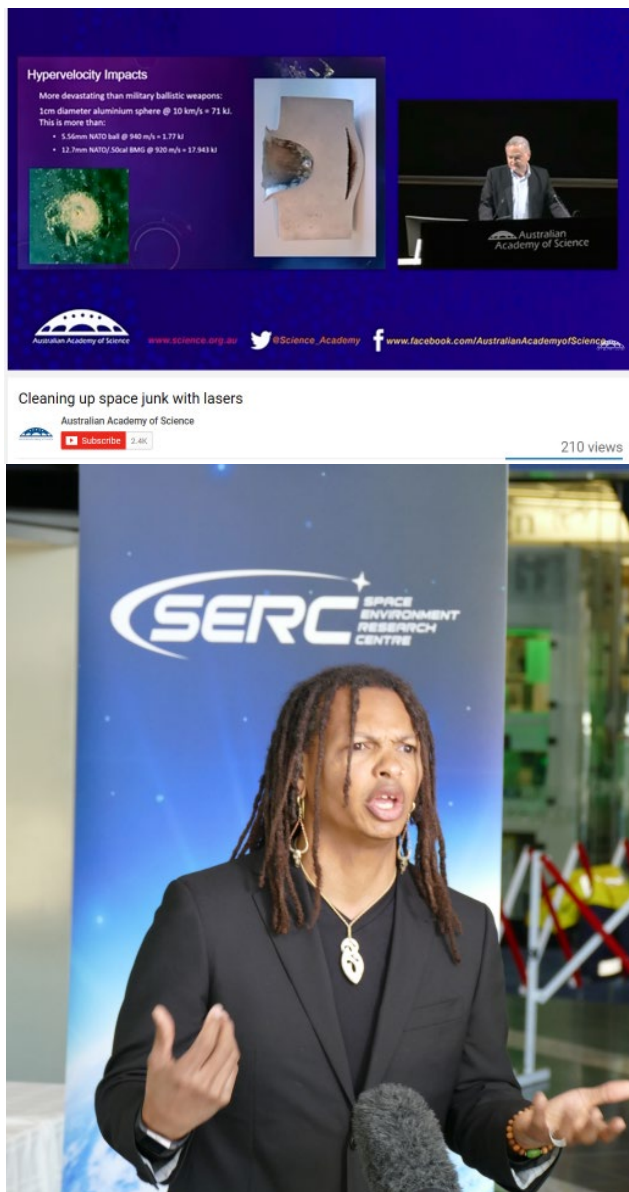
**Conference Attendance** – SERC supported 66 researchers and students to attend and deliver technical papers at a range of national and international space industry conferences and symposia; including the International Laser Ranging Workshop, (Potsdam, Germany) the Advanced Maui Optical and Space Surveillance Technologies Conference, (Maui, USA) and the European Conference on Space Debris, (Darmstadt, Germany). Conference attendance enables SERC researchers and students to network with space industry professionals and communicate SERC research objectives and success to a national and global audience.

**Publications and Citations** – During the reporting period SERC research was presented more than 95 times across formal and other publication categories and the total number of SERC citations reached 123 citations. Through publications and citations, SERC is building brand awareness, developing a reputation for delivering world class research and education and gaining acknowledgement for making a significant contribution towards global space debris management efforts.

**Community Outreach** – SERC has expanded its reach into the community through selective sponsorship and support of STEM activities. During the reporting period, SERC sponsored the Australian Science Teachers Association STEM X Academy for the second consecutive year. STEM X is a five-day residential professional learning program for primary and secondary teachers of science, technology, engineering and mathematics. Through support of this event, SERC communicates its activities in space debris management to a highly motivated group of teachers who in turn enlighten their students about the space debris issue and the research SERC is undertaking to address this issue. Further details about SERC's STEM activities is provided in Section 1.6 Education and Training.

### Invited Presentations

- In December 2016, Dr Robert Norman gave an invited talk at the Australian Bureau of Meteorology during at their annual meeting. Dr Norman provided an overview of SERC activities, objectives and research progress.
- In January and March 2017 respectively, Dr Jerome Daquin gave and invited presentation on "Multiscale Problems; Algorithms, Numerical Analysis and Computation" to the Physics Department of Aristotle University, Thessaloniki, Greece and the Hausdorff Trimester Program in Bonn Germany.
- On 6 June 2017 Dr Ben Greene delivered a presentation at The Shine Dome for the Australian Academy of Science. His presentation informed attendees about the SERC mission to develop and commercialise technologies to reduce the threat to space-based infrastructure from space debris. The presentation has been loaded on YouTube and has received 210 views. To view the presentation please visit <https://www.youtube.com/watch?v=JN8GqveU1Q8>



**Top:** Dr Ben Greene, CEO, SERC presentation at the Shine Dome, June 2017

**Bottom:** ABC Television interview with Professor Moriba Jah, SERC Research Management Committee member

## 1.8. GOVERNANCE – BOARD, COMMITTEES AND KEY STAFF

The Space Environment Research Centre (SERC) is an Australian Public Company, Limited by Guarantee. SERC has been endorsed by the Australian Tax Office as a registered charity, effective 10 April 2014. SERC is exempt from income tax under Subdivision 50-A of the Income Tax Assessment Act 1997.

SERC's Strategic Plan, adopted on 18 March 2015, outlines the mission, vision, core values and strategic objectives for SERC. The strategic objectives include:

- Identification and exploitation of synergies between the research efforts of initial participants so that the research objectives are collectively more advanced than would have been the case without SERC;
- Establishment of efficient, equitable and transparent processes for combining resources from a wide range of collaborating entities; and
- Development of new technologies to preserve the space environment and extend the benefits of space to future generations.

Over this reporting period, SERC has built on the strategic objectives achieved during its first two years. SERC has strengthened its corporate governance and leadership at both the Board and Committee level.

The SERC Board of Directors was established, on 10 April 2014, with three Independent Directors; a Director nominated by research participants and a Director nominated by industry participants.

These Directors were elected to the Board on 18 November 2014. The research Participant Director resigned the position to take up a role as a member of SERC Management on 24 December 2015 and a replacement Director was appointed on 11 December 2015. The research and industry appointments are for a term of two years. These positions will expire at the 2017 Annual General Meeting and new Directors will be elected.

The Board governs SERC through broad policies and objectives and in accordance with the constitution. The SERC Board has adopted and operates within, the Cooperative Research Centre's Programme Principles for CRC Governance.

The Board delegates to committees and management in accordance with the SERC Delegations of Authority Policy, which was adopted in March 2015 and reviewed annually.





# SERC BOARD OF DIRECTORS



**Professor Mary O'Kane AC**  
**Chair**  
**SERC Board**

Professor Mary O'Kane is Principal of O'Kane Associates, a Sydney-based company specialising in major government and research

reviews. She is also the New South Wales Chief Scientist & Engineer and a company director, being Chair of the Cooperative Research Centre for Spatial Information, Chair of the University of Tasmania Institute of Marine and Antarctic Studies Board, Director of Business Events Sydney, the Capital Markets CRC, and the Innovative Manufacturing CRC. She is also a trustee of the New Zealand Antarctic Research Institute. She was Vice-Chancellor of the University of Adelaide from 1996 to 2001. She was formerly Chair of the Australian Centre for Renewable Energy and is a former member of the Australian Research Council, the CRC Committee, the Tax Concession Committee, the board of the CSIRO, and the board of F.H. Faulding & Co Ltd. She is a Fellow of the Academy of Technological Sciences and Engineering and an Honorary Fellow of Engineers Australia.



**Mr Brett Biddington AM**  
**Director**  
**(Independent)**

Mr Brett Biddington is the founder of a Canberra-based consulting firm that focuses on space and cyber-space policy, security and industry development matters. He is presently contracted to

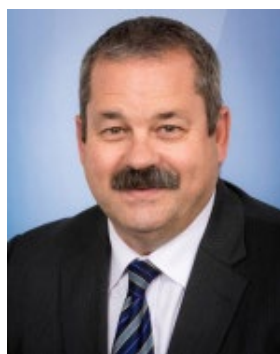
the Space Industry Association of Australia to deliver the world's largest annual space conference, the International Astronautical Congress (IAC2017) in Adelaide in September 2017. Mr Biddington has written two papers for a Canberra-based 'think-tank' ([www.kokodafoundation.org](http://www.kokodafoundation.org)) that discuss the factors Australia needs to consider as it develops its national space policy and capabilities. Between 2002 and 2009 Mr Biddington was a member of the Global Space Team of Cisco Systems. This followed a 23 year career in the Royal Australian Air Force where he specialised in intelligence, security and capability development. Mr Biddington sponsored a wide range of command and control, intelligence, surveillance and reconnaissance projects, including the Jindalee Over the Horizon Radar Project (JORN) and classified space projects.



**Ms Elizabeth Whitelaw**  
**Director**  
**(Independent)**

Ms Elizabeth Whitelaw is a former senior partner of law firm Minter Ellison. She is an experienced board member, having performed both Chair and

non-executive Director roles for government-owned corporations, partnership boards, advisory bodies and not-for-profit organisations. Ms Whitelaw was a member Minter Ellison's National Partnership Board, Canberra, Chair of Partners, a National Government Industry group leader and leader of the Canberra Infrastructure and Finance team. Ms Whitelaw was also Minter Ellison's board representative on the National Risk Assessment and Management Committee.



**Mr Rod Drury CSC**  
**Director**  
**(Industry Participant Director)**

Mr Rod Drury is the Managing Director, Australia and New Zealand for Lockheed

Martin's Space System Company. In this role he is responsible for the execution and growth of Space System's portfolio of products and services across Australia and New Zealand. Mr Drury has significant experience in the global aerospace sector, where he has held various levels of responsibility including strategy, governance, business development, government relations, program management and research and development activities.

Mr Drury is a member of the Board of the Space Industry Association of Australia and a member of the South Australian Space Council.





**Professor Matthew Colless  
(Research Participant Director from Dec 2015)**

Professor Matthew Colless is Director of the Research School of Astronomy

and Astrophysics at the Australian National University (ANU). He was, for nine years previously, the Director of the Australian Astronomical Observatory (AAO). He obtained his BSc at Sydney, his PhD at Cambridge, and has held positions at Durham, Kitt Peak and Cambridge and at AAO and ANU. Professor Colless is a Fellow of the Australian Academy of Science, an Honorary Fellow of the Royal Astronomical Society, an ISI Citation Laureate, a former Vice-President of the International Astronomical Union and the ANU's Founder representative for the Giant Magellan Telescope (GMT) project. He is also a member of the Visiting Committee or Science Advisory Board for the Leibniz Institute for Astrophysics at Potsdam, the Max Planck Institute for Extraterrestrial Physics at Garching and the European Southern Observatory.



**Dr Ben Greene  
Chief Executive Officer**

Dr Ben Greene is the Chief Executive Officer of both Electro Optic Systems (EOS) and the Space Environment Research Centre (SERC).

Dr Greene is internationally recognised for his expertise in space research and the development and commercialisation of innovative solutions in the tracking, monitoring and management of space debris. He is also the author of numerous patents and the architect of a number of international space tracking systems.

## MEETINGS OF DIRECTORS

The number of Directors' meetings and number of meetings attended by each of the Directors of the Company during the reporting period are:

DIRECTOR	BOARD MEETINGS	
	Number Eligible to Attend	Number Attended
Professor Mary O'Kane	5	5
Mr Brett Biddington	5	4
Ms Elizabeth Whitelaw	5	5
Mr Rod Drury	5	4
Professor Matthew Colless	5	5

Table 1: Meetings of Directors 2016-2017 Financial Year

# SERC COMMITTEES

The SERC Board is advised by various Board Committees, including the Audit and Risk Committee, Contracts and Licences Committee, Nominations and Remuneration Committee and the Research Management Committee.

## Audit and Risk Committee

The Audit and Risk Committee has two principle functions;

**Audit** - to ensure that appropriate controls and processes are in place to identify all risks relating to financial reporting and that these risks are being effectively monitored and managed. The Committee also reviews accounting policies affecting SERC and ensures disclosure in the financial statements of the CRC. The Audit Committee meets three times a year at regular intervals.

Synergy was retained as the independent auditor during the reporting period.

**Risk** – to identify, monitor and advise the Board and Executive on potential and actual risks to SERC. A risk register is maintained to monitor and implement risk mitigation strategies. Risks that are considered to have a high impact on, or pose a high risk to, SERC are brought to the attention of the Board.

Ms Jane Tisdall, Financial Controller, Defence Materials Technology Centre (DMTC) is a member of the Audit and Risk Committee. Jane is a member of CPA Australia and the Taxation Institute of Australia.

## Contracts and Licences Committee

This committee meets as required to investigate potential conflicts of interest. A monthly report outlining any contract or expenditure cumulatively over \$10,000 (with any supplier, over a rolling 12-month period) is compiled, checked against the conflicts of interest register and then submitted to the Committee for review. During the reporting period six submissions were considered by the committee.

## Nominations and Remuneration Committee

The Nominations and Remuneration Committee meets as required, but at least once a year to assist the Board in fulfilling its corporate governance responsibilities in regard to the selection and appointment of Board Directors; and in its responsibilities for appointing and reviewing the CEO and DCEO. The Nominations and Remuneration Committee met once during this reporting period.

## NAMES AND SPECIAL RESPONSIBILITIES

## EXPERIENCE AND KEY SKILLS



### MS JANE TISDALL

Audit and Risk Committee  
Financial Controller,  
DMTC Ltd

Ms Jane Tisdall was appointed as an independent member of the Audit and Risk Committee in September 2015. Ms Tisdall has been Financial Controller of DMTC Ltd since September 2011. She was the Company Secretary of DMTC Ltd for 5 years until November 2016. Ms Tisdall has 12 years' experience working in public practice providing accounting, taxation and business services to a diverse range of clients ranging from servicing client public unlisted companies, not for profit entities, small to medium sized private entities, self-managed superannuation funds and individual taxpayers. Ms Tisdall holds a Bachelor of Business/Arts (Japanese) from Swinburne University, is a full member of CPA Australia and Taxpayers Australia.

Table 2: SERC Committee meetings

**A**=Number of meetings held during the time the Committee Member held office  
**B**=Number of meetings attended

COMMITTEE MEMBER	Audit and Risk		Contracts and Licences		Nominations and Remuneration		Research Management	
	A	B	A	B	A	B	A	B
Professor Mary O'Kane			2	2	1	1		
Mr Brett Biddington	4	4	2	2	1	1		
Ms Elizabeth Whitelaw	4	4	2	2	1	1		
Mr Rod Drury	4	4					3	1
Ms Jane Tisdall	4	3						
Dr Ben Greene							3	3
Dr Moriba Jah							3	3
Dr Fumihiko Tomita							3	3
Professor Craig Smith							3	2
Mr Andrew Edwards							3	3
Ms Elaine Sadler							3	2

## Research Management Committee

The Research Management Committee (ResMC) meets as required, but up to four times a year. This committee has been established to advise the Board on decisions relating to the Research Programs, including setting research priorities, identifying education and student development opportunities and providing recommendations to the Board.

The Committee provides expert advice to the Board on the scope and effectiveness of the research activities; whether the program is on target to meet the research objectives; and assists in the review and identification of worldwide developments in relation to space technologies and space debris mitigation.

The principal function of the ResMC is to:

1. evaluate the merits of proposed research;
2. advise the Board on the conduct and nature of research undertaken by SERC;
3. ensure the research undertaken is scientific in nature and is, or may prove to be, of value to Australia; and

4. administer the SERC Research Fund to determine how philanthropic funds are applied to research purposes.

The Committee has representation from international research Participants, end-user Participants, SME Participants and independent researchers with specialist domain knowledge. SERC is currently recruiting additional independent members to augment the considerable skills and expertise already available to SERC through this important committee.

During this reporting period, ResMC members attended the SERC 2017 Research Colloquium. This provided Committee members with an opportunity to assess the progress of each research program, attend technical research meetings and interact with researchers and students. Face to face ResMC meetings were held in conjunction with the Colloquium to review the research program and provide recommendations to management and the Board.

Professor Moriba Jah, independent member of the Committee has agreed to co-supervise two SERC scholarship students and provide invaluable mentoring to these students.

## NAMES AND SPECIAL RESPONSIBILITIES

## EXPERIENCE AND KEY SKILLS



### DR BEN GREENE

Chair of the Research Management Committee

Dr Ben Greene is the Chief Executive Officer of both Electro Optic Systems (EOS) and the Space Environment Research Centre (SERC). Dr Greene is internationally recognised for his expertise in space research and the development and commercialisation of innovative solutions in the tracking, monitoring and management of space debris. He is also the author of numerous patents and the architect of a number of international space tracking systems.

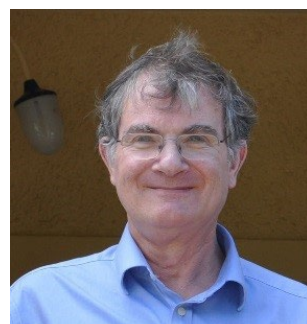


### PROFESSOR MORIBA JAH

Independent member of Research Management Committee  
Associate Professor Aerospace Engineering and Engineering Mechanics  
The University of Texas at Austin

Dr Moriba Jah received his BSc in Aerospace Engineering from Embry-Riddle Aeronautical University, Prescott, Arizona, and his MSc and PhD in Aerospace Engineering Sciences from the University of Colorado specializing in astrodynamics and statistical orbit determination.

While working at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, CA, he was a spacecraft navigator and also the principal investigator of a new approach to determine the position and velocity states of aerobraking spacecraft via the unscented Kalman filtering of inertial measurement unit data. Dr Jah is a world-recognized subject matter expert in astrodynamics-based Space Situational Awareness sciences and technologies.



### MR ANDREW EDWARDS

Member of Research Management Committee  
Manager; Satellite Support, Optus Satellite Systems

Andrew Edwards has over 30 years' experience in Satellite Operations and Orbit Dynamics. He is currently manager of the team which is responsible for the spacecraft engineering, orbit dynamics and computer equipment for current and future Optus operated spacecraft.

Andrew has supported mission analysis, station keeping, propulsion subsystem and fuel life estimation for all five generations of Optus's spacecraft.





**PROFESSOR ELAINE SADLER**

Independent member of Research Management Committee  
Director, Centre of Excellence for All sky Astrophysics (CAASTRO)

Elaine Sadler is Professor of Astrophysics in the School of Physics at The University of Sydney, and Director of the Australian Research Council Centre of Excellence for All-sky Astrophysics (CAASTRO). Professor Sadler was elected as a Fellow of the Australian Academy of Science in 2010, and is currently a member of the Council of the Academy.

She has served as President of Division VIII (Galaxies and the Universe) of the International Astronomical Union (2009-2012) and Chair of the National Committee for Astronomy (2010-2012), and currently chairs the CSIRO ATNF Steering Committee. As CAASTRO Director, Professor Sadler oversees a 180-strong team of scientists and research students across seven Australian university nodes and 11 partner institutions around the world.

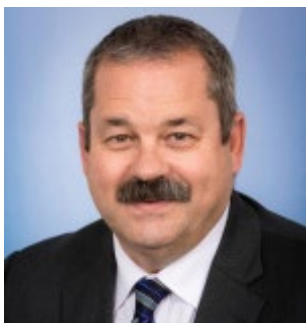


**DR FUMIHIKO TOMITA**

Member of Research Management Committee  
Vice President, Member of the Board  
National Institute of Information and Communications Technology (NICT)  
Japan

Dr Fumihiko "Tom" Tomita is responsible for research strategy at the National Institute of Information and Communications Technology (NICT) Japan. Dr Fumihiko is also a member of the Telecommunication Technology Committee responsible for future inter-industry ICT innovation projects. He was awarded a BS degree in physics and MS and PhD in geophysics by the Tohoku University of Japan.

After an appointment as Assistant Professor of Tohoku University, he joined the Radio Research Laboratory (RRL) which later became NICT. He has been supervising various research strategies and programs in NICT including the Space Weather Forecast Program and is currently the Chief Research and Strategy Officer, Vice President, and Member of the Board of NICT.



**MR ROD DRURY**

Member of Research Management Committee  
Regional Director – Australia, New Zealand & Asia  
Space Systems Company International  
Lockheed Martin Space Systems Company

Mr Rod Drury is the Managing Director, Australia and New Zealand for Lockheed Martin's Space System Company. In this role he is responsible for the execution and growth of Space System's portfolio of products and services across Australia and New Zealand.

Mr Drury has significant experience in the global aerospace sector, where he has held various levels of responsibility including strategy, governance, business development, government relations, program management and research and development activities. Mr Drury is a member of the Board of the Space Industry Association of Australia and a member of the South Australian Space Council.



**PROFESSOR CRAIG SMITH**

Member of Research Management Committee  
CEO and Technical Director, EOS Space Systems

Professor Craig Smith is the CEO and technical director for EOS Space Systems. He leads a multi-disciplinary team of science and engineering innovators developing lasers, beam directors, precision timing systems, sensors, and control systems for the laser tracking products. Professor Smith has also held positions within Electro Optic Systems (EOS) as CEO EOS Technologies (the US subsidiary of EOS) and Head of Research and Development.

Prior to joining EOS Professor Smith was a Senior Research Fellow at the Australian Defence Force Academy where he developed novel techniques for imaging-polarimetry and spectro-polarimetry at thermal IR wavelengths. Professor Smith obtained Bachelors and PhD degrees in Physics from the University of Melbourne.

## KEY STAFF

The SERC team is led by Chief Executive Officer, Dr Ben Greene. In May 2017, Mr David Ball was appointed to the position of Deputy CEO.

### EXPERIENCE AND KEY SKILLS



#### DR BEN GREENE

Chief Executive Officer

Dr Ben Greene is the Chief Executive Officer of both Electro Optic Systems (EOS) and the Space Environment Research Centre (SERC).

Dr Greene is internationally recognised for his expertise in space research and the development and commercialisation of innovative solutions in the tracking, monitoring and management of space debris. He is also the author of numerous patents and the architect of a number of international space tracking systems.



#### MR DAVID BALL

Deputy CEO

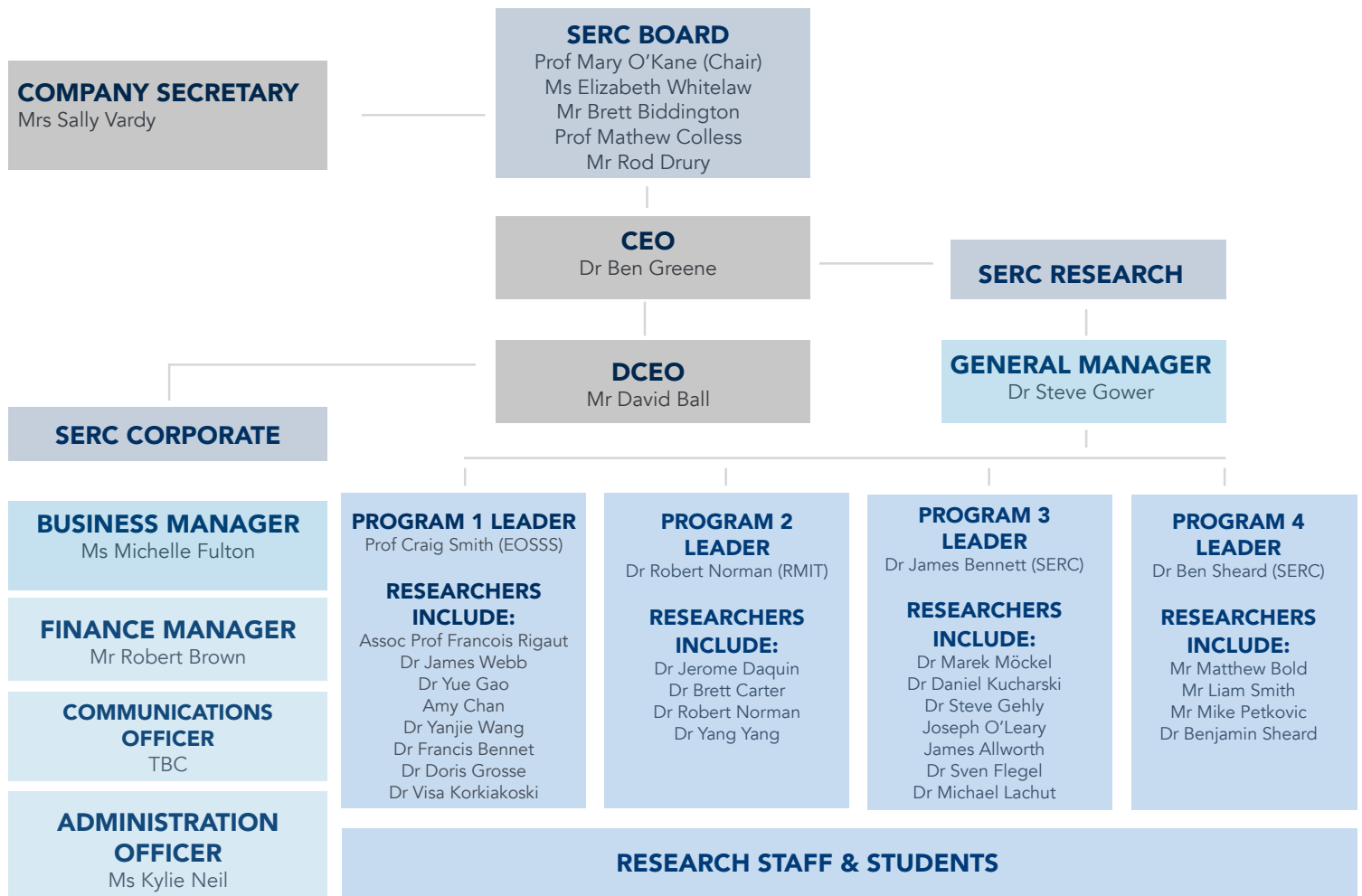
David has 25 years' experience in the telecommunications, media and technology sectors with a significant portion of his career spent specialising in satellite communications and engineering and space systems development. During his time in the satellite communications industry, David has held executive roles with several satellite operations including PanAmSat and Intelsat.

Earlier in his career, David was a commissioned officer in the Royal Australian Air Force. David holds a Bachelor of Engineering degree from the Royal Melbourne Institute of Technology and a Graduate Diploma in Business Management from Deakin University.

NAME	ORGANISATION	CRC POSITION/ROLE	TIME COMMITMENT
Dr Ben Greene	Electro Optic Systems	Chief Executive Officer	65%
Mr David Ball	SERC	Deputy CEO	100%
Dr Steve Gower	SERC	General Manager	100%
Ms Michelle Fulton	SERC	Business Manager	100%
Mr Robert Brown	SERC	Finance Manager	100%
Dr Craig Smith	EOSSS	Research Program Leader	51%
Dr Robert Norman	RMIT	Research Program Leader	100%
Dr James Bennett	SERC	Research Program Leader	100%
Dr Benjamin Sheard	SERC	Research Program Leader	100%

Table 3: SERC Key Staff and Time Commitments

# SERC ORGANISATIONAL STRUCTURE AS AT 30 JUNE 2017



SERC Organisation Chart

## 1.9. PARTICIPANTS

SERC has partnered with world leading organisations and research institutions with strong track records in scientific discovery and space technology development. In light of the limited, five year, funding term, SERC has not recruited additional Participants due to insufficient timeframes to integrate them into SERC research programs.

International collaboration has, however, been expanded through the execution of MOUs with the University of Arizona, USA, The Space Research Institute in Gratz, Austria and the University of Texas, USA.

There were no changes to Essential or Other Participants during the reporting period. The Participants listed in the Commonwealth Agreement were the SERC Participants during the 2016-17 reporting period, including:



**EOS SPACE SYSTEMS**

ABN 11 008 587 451



EOS Space Systems specialises in the design, development and production of satellite and space tracking technologies and the provision of space-based services. EOS Space Systems technologies are applied to a variety of space surveillance applications in the aerospace and defence industries globally and have generated of \$400m in exports for Australia. EOS Space Systems has extensive optical tracking infrastructure and highly regarded expertise in locating and tracking space debris.

Essential Participant  
Publicly listed company  
SME  
End-User Participant

**AUSTRALIAN NATIONAL UNIVERSITY**

ABN 52 234 063 906



The ANU Research School of Astronomy and Astrophysics (RSAA) is internationally recognised in the research and development of astronomical instrumentation and construction of precision instruments for astronomy. In particular, RSAA has considerable expertise in the field of adaptive optics, a technique that corrects the effects of turbulence in the atmosphere to un-blur telescopic images.

Essential Participant  
University Participant

**RMIT UNIVERSITY**

ABN 49 781 030 03



The RMIT SPACE Research Centre is internationally recognised in the areas of astrodynamics, GPS tracking, atmospheric density modelling, space weather and ionospheric research. RMIT SPACE has considerable expertise in developing models for reliably propagating orbits in the variable space environment. In a successful Australian Space Research Program collaboration, RMIT SPACE was instrumental in developing improved orbit determination algorithms, providing a platform for continued SERC research.

Essential Participant  
University participant

**LOCKHEED MARTIN**

Lockheed Martin is one of the world's largest aerospace organisations. It is both a potential end-user for SERC technologies and service provider. Lockheed space business exceeds US\$8 billion annually. Lockheed brings a wealth of technology and space research expertise and international networks to SERC.

Other Participant  
(International)  
Industry and End-User  
Participant

**OPTUS SATELLITE SYSTEMS**

ABN 15 091 789 945



Optus Satellite Systems has been providing satellite services for more than 30 years and is the only network provider in Australia to own and operate a fleet of satellites. Since 1985, Optus has successfully launched ten satellites and operated thirteen spacecraft. The Optus Satellite fleet currently consists of five geostationary satellites providing services across Australia and New Zealand, and to McMurdo Sound in the Antarctic.

Other Participant  
Industry and End-User  
Participant

**NATIONAL INSTITUTE OF INFORMATION AND  
COMMUNICATIONS TECHNOLOGY (NICT)**

NICT is charged with promoting the Japanese ICT sector as well as research and development in ICT, to drive economic growth and create an affluent, safe and secure society. NICT has a strong space mandate because ICT is heavily dependent on space assets. In collaboration with Australia, NICT has deployed multiple optical laser tracking facilities throughout Japan and is considered a global leader in optical space tracking and orbital science relating to high precision orbits.

Other Participant  
(International)  
Research and End-User  
Participant

## MOUs

SERC enhances its international collaboration and global reach through execution of Memoranda of Understanding (MOUs) with strategic research partners.



### Korea Astronomy and Space Science Institute

The Korea Astronomy and Space Science Institute (KASI) is the national research institute in astronomy and space science of South Korea and is funded by the South Korean Government. KASI's areas of research include optical astronomy, radio astronomy, space science, and theoretical astronomy.

KASI is collaborating with SERC in the area of space debris laser ranging and object characterisation.



### The University of Arizona

SERC further strengthened its international collaboration efforts after signing an MOU with the University of Arizona (UA), USA. UA's Space Object Behavioural Sciences (SOBS) mission is to assemble and lead the world's top multi-disciplinary science and technology research and development talent and focus it to solve problems requiring rigorous and comprehensive capabilities in assessing, quantifying, and predicting the behaviour of objects in space, both man-made and natural.

UA SOBS also aims to imagine, identify, develop and deliver new space object behaviour capabilities; make expertise on space object behaviour available to a variety of stakeholders including all branches of government, private industry, academia, and international entities; and help guarantee the University of Arizona's leadership in the area through education, excellence, innovation and practicality in space object behavioural sciences and related fields.

The MOU establishes a framework for scientific collaboration between the two organisations that will result in the combining of the organisations' research expertise to achieve scientific goals whilst developing common specialised knowledge and effective use of facilities. The MOU also opens the door to the exchange of scientific personnel including students in addition to opportunities for joint research and development.



### University of Texas at Austin

SERC signed an MOU with Aerospace Engineering and Engineering Mechanics, Cockrell School of Engineering, The University of Texas at Austin on 14 August 2017.

The school is currently ranked world number eight for graduates and undergraduates in aerospace engineering and the fourth most influential scientific research institution in aerospace from 2004-14.

The school has a research budget of US\$15.2 million and is interested in research and STEM collaboration with SERC.



### The Space Research Institute in Graz

SERC signed a Memorandum of Understanding (MOU) with the Satellite Laser Ranging (SLR) Observatory of the Space Research Institute, Graz, Austria. The MOU signals a marked increase in collaboration efforts between our two organisations.

The Space Research Institute in Graz is one of the largest Institutes of the Austrian Academy of Sciences. The institute focuses on physics and exploration of the solar system, covering the whole chain of research needed in its fields: from developing and building instruments such as the SLR, to analysing and interpreting the data returned by these instruments, with support from theoretical studies.

SERC is excited to be engaging in closer collaboration with the Space Research Institute in Graz, Austria, combining northern and southern hemisphere data on laser and optical observations of space debris including high-area-to-mass ratio objects and defunct satellites, spin dynamics analysis of observed targets, and determination of space debris optical properties for characterisation purposes.

# 1.10. COLLABORATION

SERC's Vision Statement positions SERC as a collaboration vehicle of choice for global efforts to address issues arising from space debris and for SERC's technology to play a key role in the management, mitigation and removal of space debris. This vision, shared by Participants and emphasised in the SERC Strategic Plan, places collaboration at the core of SERC's activities.

SERC research programs are interdependent and foster collaboration between Participants and industry. Research results, including collaborations, are discussed in Section 1.5: Performance against Activities. A cross section of SERC collaboration activities during the reporting period are provided below:

## PROJECT: RP 1.1 - DEVELOP PASSIVE AND ACTIVE TRACK SENSORS

**Collaborators:** EOSSS, ANU, Optus Satellite Systems  
**Results:** During the reporting period, the GEO tracker telescope was installed at Mount Stromlo and commissioned for local operation. First light was achieved on 29 May with LAGEOS-1 and Optus C1 being tracked successfully.

## PROJECT: R2.1 DEVELOP INTELLIGENT SYSTEMS FOR REAL-TIME PRECISION ORBIT DETERMINATION

**Collaborators:** RMIT, Optus Satellite Systems, NICT  
**Results:** Global Navigation Satellite System (GNSS) POD software was completed during the reporting period and is undergoing on-site testing and validation. This software will also provide a platform to validate the improved AMD models in terms of orbit prediction which will be used to support Research Programs 3 and 4.

## PROJECT: RP3.1: DEVELOP A SPECIAL SATELLITE OBJECT CATALOGUE

**Collaborators:** EOSSS, RMIT,  
**External Collaborators:** Space Laser Ranging Observatory, Graz, Austria, Borowiec Space Research Centre, Poland and Korea Astronomy and Space Science Institute (KASI)  
**Results:** Extensive collaboration with Participants and external organisations was undertaken to further the development of the Space Object Catalogue.

These collaborations have afforded access to space object data from a global network of Satellite Laser Ranging stations. The collaborations have also furthered SERC's goal to establish industry credibility and promote SERC technology and research capabilities to an international audience. International collaborations are supported through the signing of Memorandum of Understanding to facilitate the sharing of confidential data and information.

## THE FOLLOWING RP3 COLLABORATIONS WERE UNDERTAKEN DURING THE REPORTING PERIOD:

**Collaborator:** Space Laser Ranging Observatory, Graz, Austria  
**Date:** July-Sept 2016

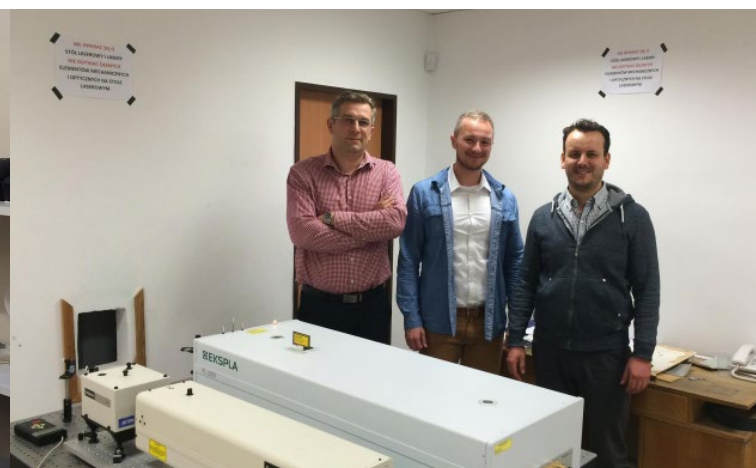
**Collaboration:** Laser and optical observation of space debris and provision of data, including light curves, for SERC research and the SERC space debris catalogue.

**Collaborator:** Borowiec Space Research Centre, Poland  
**Date:** September 2016  
**Collaboration:** Space debris dynamics; observation, analysis and modelling

**Collaborator:** Korea Astronomy and Space Science Institute (KASI)  
**Date:** September 2016  
**Collaboration:** Solar radiation pressure on space debris: observation and modelling

## PROJECT: RP4.1 – SYSTEM ENGINEERING

**Collaborators:** EOSSS, Lockheed Martin, Optus Satellite Systems, RMIT  
**External Collaborator:** Georgia Tech  
**Results:** Collaboration with Lockheed Martin has supported trade studies in the area of laser induced target motion from background drag as a function of altitude. RMIT collaborations have delivered atmospheric density models and reliable orbit determination support to RP4. In addition Georgia Tech has collaborated with RP4 on the development and testing of satellite designs.



July-September 2016 research exchange to Graz SLR Station, Austria. L to R: Franz Koidl, Dr Daniel Kucharski, Dr Georg Kirchner

Borowiec SLR station, Poland R to L: Dr Pawel Lejba, Dr Daniel Kucharski, Tomasz Suchodolski



# 1.11. FINANCIAL MANAGEMENT

SERC continued to implement stringent financial management practices in an aggressive attempt to allow 70% of all cash funds to flow to the SERC research and education programs.

Although administrative costs were slightly higher this financial year, SERC managed to contain administrative costs to 38% of budget.

SERC has continued to improve its financial processes throughout the reporting period, with a number of key achievements:

- Improved functionality and management of accounting and payroll processes
- Enhanced budgeting and forecasting process implemented
- Better financial reporting to the Board, Committees and research programs
- Adherence to stringent budgeting guidelines ensured SERC tracked well against budgets and maintained a strong cash-flow position

There were no significant issues with respect to financial management during the 2016-17 reporting period. Financial management was brought in-house with the appointment of a Finance Manager in October 2016. This change has resulted in an improvement in book-keeping and accounting efficiency and accuracy.

## FUNDS CARRIED FORWARD

SERC carried \$6,686,532 forward at 30 June 2017. These funds are (largely) committed to the purchase of capital items and completing the Research Programs.

## ADMINISTRATIVE COSTS

SERC recruited additional executive and administrative resources during the 2016-17 financial year which accounted for the slight increase in administrative expenditure. A Finance Manager was appointed in October 2016 and a Deputy CEO in May 2017. SERC is now operating with a full complement of administrative resources to support the research program.

## TRAVEL

SERC staff and Participants were invited to deliver papers at a number of key national and international conferences during the reporting period.

In addition SERC Participants, students and members of the Research Management Committee travelled to Canberra for a research colloquium and a SERC research program design review.

## KEY CHANGES FROM 2016

SERC has continued to track well against its aggressively lean cash flow projections. The key changes in 2017 relate directly to developments in research. SERC has been able to secure a hosted payload launch which obviates the need to launch a dedicated satellite mission. This will free up funding for research which will progress SERC's outcomes.

The other key change related to research infrastructure. SERC has been designing and building experimental apparatus to enable on-orbit manoeuvre demonstrations. This expenditure will be capitalised into assets in the following financial year.

## PARTICIPANT CASH CONTRIBUTIONS

During the reporting period, SERC received 100% of pledged cash contributions from Participants. Cash contributions were \$380,000 (in line with Participant Agreements).

## PARTICIPANT IN-KIND CONTRIBUTIONS

SERC is required, under its constitution, to audit all Participant contributions claimed for both quantity (magnitude) and quality.

Aggregate in-kind contributions received from Participants were in excess of 107% of the pledged amounts during the 2016/17 reporting period.

SERC Participants contributed a total of 12.13 FTE which was 95% of the Participants pledged 12.80 FTE.

Non-staff in-kind contributions received from Participants totalled \$3.808 million which was in excess of the \$3.217 million pledged.

SERC expects that Participant contributions will continue to meet or exceed pledged In-kind contributions through to the completion of the program.

## FINANCIAL STATEMENTS

The Annual Financial Statements have been prepared as general purpose accounts in accordance with the Commonwealth Government reporting requirements for Cooperative Research Centres; and in-line with Australian Accounting Standards.

## PROFIT & LOSS

### Space Environment Research Centre Limited for the period 12 months ended 30 June 2017

	2017	2016
	\$	\$
<b><u>Income</u></b>		
Government funding	\$3,065,032	\$1,713,813
Interest Income	\$39,938	\$48,510
Member contributions	\$7,390,512	\$7,313,126
<b>Total income</b>	<b>\$10,495,482</b>	<b>\$9,075,449</b>
<b><u>Less operating expenses</u></b>		
Employee costs	\$656,534	\$371,208
Directors fees & expenses	\$108,570	\$120,502
Operating expenses	\$493,415	\$517,755
Depreciation	\$200,254	\$83,818
Event hosting	\$48,506	\$23,070
Insurance	\$9,673	\$11,668
Legal expenses	-	\$11,564
Research Program - RP1	\$5,384,477	\$3,705,999
Research Program - RP2	\$1,963,824	\$1,075,777
Research Program - RP3	\$971,964	\$701,101
Research Program - RP4	\$403,820	\$2,384,037
Scholarships	\$254,445	\$68,950
<b>Total operating expenses</b>	<b>\$10,495,482</b>	<b>\$9,075,449</b>
<b>Net profit</b>	<b>-</b>	<b>-</b>

## BALANCE SHEET

### Space Environment Research Centre Limited as at 30 June 2017

<b><u>Assets</u></b>	2017	2016
	\$	\$
<b><u>Current assets</u></b>		
Cash and cash equivalents	\$6,686,532	\$5,127,773
Receivables	\$25	\$14,647
Other assets	\$41,801	\$1,950
<b>Total current assets</b>	<b>\$6,728,358</b>	<b>\$5,144,370</b>
<b><u>Non-current assets</u></b>		
Plant and equipment	\$799,432	\$368,438
<b>Total non-current assets</b>	<b>\$799,432</b>	<b>\$368,438</b>
<b>Total assets</b>	<b>\$7,527,790</b>	<b>\$5,512,808</b>
<b><u>Liabilities</u></b>	2017	2016
	\$	\$
<b><u>Current liabilities</u></b>		
Payables	\$860,406	\$292,926
Provisions	\$61,423	\$26,922
Deferred revenue	\$6,578,570	\$5,183,623
<b>Total current liabilities</b>	<b>\$7,500,399</b>	<b>\$5,503,471</b>
<b><u>Non-current liabilities</u></b>		
Provisions	\$27,391	\$9,337
<b>Total non-current liabilities</b>	<b>\$27,391</b>	<b>\$9,337</b>
<b>Total liabilities</b>	<b>\$7,527,790</b>	<b>\$5,512,808</b>
<b>Net assets</b>	<b>-</b>	<b>-</b>

## GLOSSARY OF TERMS

TERM	DEFINITION	TERM	DEFINITION
<b>AAO</b>	Australian Astronomical Observatory	<b>CAASTRO</b>	Council Centre of Excellence for All-sky Astrophysics
<b>AATSR</b>	Advanced Along Track Scanning Radiometer	<b>CDM</b>	Conjunction Data Message
<b>ACNC</b>	Australian Charities and Not-for-profits Commission	<b>Colloquium</b>	An academic conference or seminar
<b>AIT</b>	Assembly, Integration and Test	<b>CDR</b>	Critical Design Review
<b>AITC</b>	The Advanced Instrumentation and Technology Centre located at Mount Stromlo Observatory in ANU, Canberra Australia	<b>Centre IP</b>	Refers to IP held by SERC
<b>AMD</b>	Atmospheric Mass Density	<b>COTS</b>	Commercial off the shelf
<b>AMOS</b>	The Advanced Maui Optical and Space Surveillance Technologies Conference. The premier technical conference devoted to space surveillance	<b>CRC</b>	Cooperative Research Centre
<b>ANU</b>	The Australian National University	<b>CW</b>	Continuous Wave laser refers to a laser that produces a continuous output beam.
<b>AO</b>	Adaptive Optics is a technology used to improve the performance of optical systems by reducing the effect of wavefront distortions: it aims at correcting the deformations of an incoming wavefront by deforming a mirror in order to compensate for the distortion	<b>DM</b>	Deformable Mirror
<b>AOI</b>	Adaptive Optics Imager	<b>DMTC</b>	Defence Materials Technology Centre
<b>AOTP</b>	Adaptive Optics Tracking and Pushing	<b>EIPT</b>	Economic Impact Performance Tool (round 11 onwards)
<b>ARC</b>	Audit and Risk Committee	<b>EOSSS</b>	EOS Space Systems Pty Limited
<b>ASIC</b>	Australian Securities and Investment Commission	<b>ERS2</b>	European Remote Sensing Satellite 2
<b>ASTA</b>	The Australian Science Teachers Association	<b>ESA</b>	European Space Agency
<b>ASRC</b>	Australian Space Research Conference	<b>GAIA</b>	Global Astrometric Interferometer for Astrophysics
<b>ATC</b>	Lockheed Martin Space Systems Company Advanced Technology Center	<b>GEO</b>	Geostationary Earth Orbit
<b>ATO</b>	Australian Taxation Office	<b>GMT</b>	Giant Magellan Telescope
<b>ATSR2</b>	Along Track Scanning Radiometer 2	<b>GNSS</b>	Global Navigation Satellite System, a constellation of satellites providing signals from space transmitting positioning and timing data.
<b>CATW</b>	Conjunctions Analysis and Threat Warning	<b>GPS</b>	Global Positioning System





TERM	DEFINITION	TERM	DEFINITION
<b>GRACE</b>	Refers to the Gravity Recovery and Climate Experiment (GRACE) twin satellites which measure the movement of mass, and hence gravity, around earth every 30 days.	<b>SBM</b>	Satellite Body Model
<b>Graz SLR</b>	The Space Research Institute in Graz, Austria	<b>SCIDAR</b>	Scintillation and Detection and Ranging System
<b>GUI</b>	Graphical User Interface	<b>SCOPE</b>	SERC Catalogue Orbit Prediction and Estimation
<b>HAMR</b>	High Area to Mass Ratio	<b>SERC</b>	Space Environment Research Centre
<b>HDR</b>	Higher Degree by Research	<b>SLR</b>	Satellite laser ranging
<b>IAA</b>	International Academy of Astronautics	<b>SME</b>	Small to Medium Enterprise
<b>IAC</b>	International Aeronautical Congress	<b>SOBS</b>	Space Object Behavioural Sciences
<b>IAF</b>	International Astronautical Federation	<b>SOC</b>	Space Object Catalogue
<b>IB</b>	International Baccalaureate	<b>SPACE</b>	RMIT's Satellite Positioning for Atmosphere, Climate and Environment Research Centre
<b>ILRS</b>	International Laser Ranging Service	<b>SPAN</b>	RMIT's Satellite Positioning and Navigation Laboratory
<b>IP</b>	Intellectual Property	<b>SPIE</b>	Society of Photographic Instrumentation Engineers
<b>JAXA</b>	Japan Aerospace Exploration Agency	<b>SPOT</b>	Space Object Tracking
<b>JORN</b>	Jindalee over the horizon radar project	<b>SPOT3</b>	Système Pour L'Observation de la Terre 3
<b>JPL</b>	NASA's Jet Propulsion Laboratory	<b>SRP</b>	Solar radiation pressure
<b>JSON</b>	JavaScript Object Notation	<b>SSA</b>	Space Situational Awareness is the ability to accurately characterise the space environment and activities in space.
<b>OD</b>	Orbit Determination	<b>STEM</b>	Science, Technology, Engineering and Mathematics
<b>OPTUS</b>	OPTUS Satellite Systems	<b>STEM X</b>	The Australian Science Teachers Association's Science, Technology, Engineering and Mathematics teacher development program.
<b>POD</b>	Precision Orbit Determination	<b>SWG</b>	ACT Government Space Working Group
<b>PSU</b>	Power Supply Unit	<b>TAU</b>	Torque Analysis Unit
<b>PYP</b>	Primary Years Programme	<b>TLE</b>	Two-line element data, a format for distributing orbital elements data.
<b>R&amp;D</b>	Research and development	<b>UKIRT</b>	The United Kingdom Infrared Telescope. Located in Hawai'i
<b>ResMC</b>	Research Management Committee	<b>VBG</b>	Volume Bragg Grating
<b>RMIT</b>	Royal Melbourne Institute of Technology University	<b>VR</b>	Virtual reality
<b>ROD</b>	Reliable orbit determination	<b>WPLTN</b>	Western Pacific Laser Tracking Network (WPLTN)
<b>RP</b>	Research Program		
<b>RRL</b>	Radio Research Laboratory		
<b>RSAA</b>	The Australian National University's Research School of Astronomy and Astrophysics.		

## 4.1. SERC PUBLICATIONS

The following tables provides a list of SERC publications (as defined in the MDQ).

### FORMAL PUBLICATIONS

DATE	PUBLISHED IN / PRESENTED AT	TITLE	AUTHORS	PUBLICATION TYPE
Jul-16	Applied Mechanics and Materials, Vol. 846 (pp. 67-72) (2016)	Validating the k-omega Turbulence Model for 3D Flows within the CFD Solver Eilmer.	S.J. Stennett, W.Y.K.Chan, D.E. Gildfind,& P.A. Jacobs	Journal paper
Aug-16	Proceedings of SPIE - The International Society for Optical Engineering, Volume 9979, 2016, Article number 99790J	Laser remote manoeuvre of space debris at the Space Environment Research Centre	M.Bold.	Conference Presentation
Sep-16	Proceedings Volume 9979, Laser Communication and Propagation through the Atmosphere and Oceans V; 99790L (2016);	Single detector stereo-SCIDAR for Mount Stromlo: data analysis	V. Korkiakoski, J. Osborn, D Grosse, E. Thorn, P. Piatrou, F. Bennet, F. Rigaut	Conference Presentation
Sep-16	2016 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), Cairns, QLD, 2016, pp. 162-165.	An Extremely Wideband Tapered Balun for Application in Tightly Coupled Arrays	A. Bah, P. Qin, & Y. Guo	Conference Presentation
Sep-16	2016 International Conference on Electromagnetics in Advanced Applications (ICEAA), Cairns, QLD, 2016, pp. 852-855.	Characteristics of wideband phased array with two-layer metasurface	X. Yang, G. Zhao, W. Hu, Y. Guo, Y. Yin & A. Bah	Conference Presentation
Oct-16	Journal of Beijing Institute of Technology (English Edition) Volume 25, 1 December 2016, Pages 143-148	An Improved Tracklet Association Method for Initial Orbit Determination of Space Debris	H. Cai, J. Zhang, Y. Yang, S. Gehly, C. He, A. Hu, S. Wu, & K. Zhang	Conference Presentation
Dec-16	ESA 4th Swarm science meeting to be held 20-24 March 2017 Banff, Alberta, Canada	Spatio-temporal variability of thermospheric density using ESA (Swarm mission) Data	A. Yeasmin, R. Norman & K. Zhang	Conference Presentation
Dec-16	20th Australasian Fluid Mechanics Conference. Perth, Western Australia, Australia, 5-8 December 2016.	Extension of the X3 expansion tube capabilities for Mach 12 scramjet testing: flow condition: development and nozzle optimization.	P.Toniato, D.Gildfind, P.Jacobs, & R.Morgan	Conference Presentation
Dec-16	20th Australasian Fluid Mechanics Conference, 5–8 December 2016, Perth	Verification of the Least-Squares Procedure within an Unstructured-Grid Flow Solver	K Damm, R Gollan, P Jacobs,	Conference Presentation
Jan-17	Hausdorff Research Institute for Mathematics Program on "Multiscale Problems: Algorithms, Numerical Analysis and Computation", in Bonn, Germany	Macroscopic Dynamics for Orbital Motions	J. Daquin	Poster Presentation
Jan-17	Earth, Planets and Space EPS Journal: doi: 10.1186/s40623-016-0589-8, pp.1-14.	Laser link experiment with the Hayabusa2 laser altimeter for in flight alignment measurement	H. Noda, H. Kunitomi, et al.	Journal Paper
Mar-17	IEICE: Transactions on Electronics doi: 10.1587/transele.E100.C.274, pp.274-282	Recent progress and application of superconducting nanowire single-photon detectors	T. Yamashita, S. Miki & H. Terai	Journal Paper
Mar-17	Optics Letters doi:10.1364/OL.42.000815, pp.815-818	High-extinction ratio integrated photonic filters for silicon quantum photonics	M. Piekarek, S. Miki, et al.	Journal Paper
Apr-17	Earth, Planets and Space (2017) 69:51	An analysis of the 2016 Hitomi breakup event	S. Flegel, J. Bennett, M. Lachut, M. Möckel & C. Smith	Journal Paper
May-17	Optics Express doi:10.1364/OE.25.012052	Mach-Zehnder interferometer using frequency-domain beamsplitter	T. Kobayashi, S. Miki et al.	Journal Paper

## OTHER PUBLICATIONS

DATE	PUBLISHED IN / PRESENTED AT	TITLE	AUTHORS	PUBLICATION TYPE
Jul-16	"Feast of Facts" RSAA Colloquia at ANU	Analysis of the ASTRO-H breakup and its impact on the collision risk of intact objects	S Flegel	Presentation
Aug-16	Satellite Laser Ranging observatory Borowiec (Space Research Institute, Polish Academy of Science), Poland.	Space debris dynamics: observation, analysis and modelling	D Kucharski	Seminar
Sep-16	Australian Space Research Conference, 26-28 September 2016, Melbourne	An analysis of short-arc orbit determination for Low Earth Orbit objects comparing batch and Kalman Filter methods	A Harris, S Gehly, K Zhang	Conference Abstract
Sep-16	Australian Space Research Conference, 26-28 September 2016, Melbourne	Space Object Characterisation- A Case for Ballistic Coefficient	M Afful, S Gehly, K Zhang	Conference Abstract
Sep-16	Australian Space Research Conference, 26-28 September 2016, Melbourne	Comparison of atmospheric mass density models and their impact on the orbit propagation of low Earth orbit satellites	C He, Y Yang, B Carter, S Wu, T Kodikara, S Gehly, K Zhang	Conference Abstract
Sep-16	Australian Space Research Conference, 26-28 September 2016, Melbourne	Heterogeneous Multiscale Methods for the mean orbital motion: a discussion	J Daquin, J Perez, F Deleflie, K Zhang	Conference Abstract
Sep-16	Australian Space Research Conference, 26-28 September 2016, Melbourne	RMIT SPACE Research Centre – overview of past and present research endeavours	R Norman, K Zhang, J Le Marshall, B Carter, S Gehly, Y Yang, J Daquin	Conference Abstract
Sep-16	Australian Space Research Conference, 26-28 September 2016, Melbourne	Schmidt-Kalman Filter and Its Applications to Orbit Determination of Space Objects	Y Yang, K Zhang	Conference Abstract
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Satellite Imaging with Adaptive Optics on a 1-m Telescope	F Bennet, I Price, F Rigaut, M Copeland	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Site Testing for Space Situational Awareness with Single-Detector Stereo Scidar	E Thorn, D Grosse, F Bennet, F Rigaut	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Adaptive Optics for Satellite and Debris Imaging in LEO and GEO	M Copeland, F Bennet, A Zovaro, F Rigaut, P Piatrou, V Korkiakoski, C Smith	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Towards Relaxing the Spherical Solar Radiation Pressure Model for Accurate Orbit Predictions	M Lachut, J Bennett	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Extracting more information from passive optical tracking observations for reliable orbit element generation	J Bennett, S Gehly	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	High Performance Orbital Propagation Using a Generic Software Architecture	M Möckel, J Bennett, E Stoll, K Zhang	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Incorporating Target Priorities in the Sensor Tasking Reward Function	S Gehly, J Bennett	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Laser remote manoeuvre of space debris at the Space Environment Research Centre	M Bold	Conference Presentation



## OTHER PUBLICATIONS

DATE	PUBLISHED IN / PRESENTED AT	TITLE	AUTHORS	PUBLICATION TYPE
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Incorporating Target Priorities in the Sensor Tasking Reward Function	S Gehly, J Bennett	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Schmidt-Kalman Filter with Polynomial Chaos Expansion for Orbit Determination of Space Objects	Y Yang, H Cai, K Zhang	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	High Performance Orbital Propagation Using a Generic Software Architecture	M Moeckel, J Bennett, E Stoll, K Zhang	Conference Presentation
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Pixel-remapping waveguide addition to an internally sensed optical phased array	P Sibley, R Ward, L Roberts, S Francis, S Gross, D Shaddock.	Conference Presentation
Sep-16	Korea Astronomy and Space Science Institute, KASI, Daejeon, South Korea	Solar radiation pressure on space debris: observation and modelling	D Kucharski	Seminar
Sep-16	Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference, 20-23 September 2016, Maui, Hawaii	Laser de-spin manoeuvre for an active debris removal mission – a realistic scenario for Envisat	D Kucharski, J Bennett, G Kirchner	Poster Presentation
Sep-16	AIAA/AAS Astrodynamics Specialist Conference, 2016	Ballistic Coefficient Estimation for Low Altitude Debris Objects from Two-Line Element Data	M Afful, S Gehly, K Zhang	Conference Presentation
Sep-16	AIAA/AAS Astrodynamics Specialist Conference, 2016	Lp-Norm Batch Estimation as Applied to Orbit Determination	S. Gehly, J. Bennett, M. Afful	Conference Presentation
Sep-16	AIAA/AAS Astrodynamics Specialist Conference, 2016	Relative State Estimation of Space Debris Based on the Stereo-vision Measurement System	H Cai, Y Yang, S Gehly, S Wu, M Afful, K Zhang	Conference Presentation
Oct-16	20th International Workshop on Laser Ranging. 10-14 October 2016, Potsdam	Application of adaptive optics in Space Debris tracking	F Bennet, C d’Orgeville, I Price, F Rigaut	Proceedings
Oct-16	20th International Workshop on Laser Ranging. 10-14 October 2016, Potsdam	The scientific results of the optional laser tracking campaigns to the defunct satellites Envisat and Topex	D Kucharski, G Kirchner, J Bennett, F Koidl	Conference Paper
Oct-16	20th International Workshop on Laser Ranging. 10-14 October 2016, Potsdam	A method for sampling debris laser ranging data to generate range rates for orbit determination	J Bennett	Conference Paper
Dec-16	Invited oral presentation at the annual R&D workshop at the BoM: on data assimilation	First-Principles-Based Analysis of Thermosphere Using Swarm-C Accelerometer Derived Neutral Densities	T Kodikara, B Carter, K Zhang	Conference abstract
Dec-16	Australian Institute of Physics conference, 4-8 December 2016, Brisbane	Adaptive Optics for Object Characterisation in Low Earth Orbit	F. Bennet	Conference Presentation
Dec-16	Australian Institute of Physics conference, 4-8 December 2016, Brisbane	Resolving satellite in Low Earth Orbit with Adaptive Optics	F. Bennet	Conference Presentation
Dec-16	Australian Institute of Physics conference, 4-8 December 2016, Brisbane	Site testing for space situational awareness with single-detector stereo-SCIDAR	E. Thorn	Conference Presentation

DATE	PUBLISHED IN / PRESENTED AT	TITLE	AUTHORS	PUBLICATION TYPE
Jan-17	Hausdorff Research Institute for Mathematics Program on "Multiscale Problems: Algorithms, Numerical Analysis and Computation", in Bonn, Germany	Macroscopic Dynamics for Orbital Motions	J. Daquin	Poster Presentation
Feb-17	Precise Time and Time Interval Meeting (PTTI 2017)	Domestic Time Transfer with Digital Broadcast Satellite Signals	T Gotoh, T Kubooka, et al.	Conference
Feb-17	Directed Energy Professional Society (DEPS) 19th Annual Symposium, 13-17 February 2017, Huntsville, Alabama	Directed Energy Application to Orbital Debris Mitigation	S Gower & E Montgomery	Conference presentation
Mar-17	IEICE 2017 Annual Meeting, 22-25 March 2017, Nagoyo	Optical Detection for Small Optical Transponder(SOTA) Downlink Experiment using SSPD	H Kunimori, M Toyoshima, et al.	Conference
Mar-17	ITU Journal, Vol.47, No.3. pp.36-40	The newest trend of Space Communication Technologies	M Toyoshima	Journal
Apr-17	7th European Conference on Space Debris, 17-21 April 2017, Darmstadt, Germany	Covariance Size and the Breakdown of Gaussianity in GEO Uncertainty Predictions	S Flegel, M Moeckel, J Bennett	Presentation
Apr-17	7th European Conference on Space Debris, 17-21 April 2017, Darmstadt, Germany	Spin-up of space debris caused by solar radiation pressure	D Kucharski, G Kirchner, J Bennett, F Koidl, M Steindorfer, P Wang	Poster Presentation
Apr-17	7th European conference on Space Debris, Darmstadt, Germany	Adaptive Optics for Satellite Imaging and Earth Based Space Debris Manoeuvres	D. Grosse, F.Bennet, C. Dorgeville, F. Rigaut, M.Copeland, E. Thorn, V.Korkiakoski	Conference Presentation
May-17	Space Comm.Seminar in NICT	Status report of development HICALI	T Kubooka, H Kunimori, T Fuse, M Toyoshima et al.	Seminar
May-17	SERC Research Colloquium 2017, Canberra	NICT activities and planning project for SERC	H Kunimori, T Fuse, Kubo-oka and M Toyoshima	Presentation
Jun-17	26th International Symposium on Space Flight Dynamics ISSFD	Generalised Polynomial Chaos Based Particle Filter for Orbit Determination	Y Yang	Conference Proceedings
Jun-17	26th International Symposium on Space Flight Dynamics ISSFD	Nonlinear Uncertainty Propagation of Orbital Mechanics Subject to Stochastic Error in Atmospheric Mass Density Models	C He, Y Yang, B Carter, H Cai, S Wu, & K Zhang	Conference Proceedings
Jun-17	SERC Research Colloquium 2017, Canberra	Space Asset Management Update: Achievements, Highlights and Progress	J Bennett	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Application of the batch least squares method in maintaining the SERC Catalogue	M Lachut	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Space debris spin dynamics	D Kucharski	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	General Relativity in Global Navigation Satellite Systems	J O'Leary	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Optimised Scheduling for a network of tracking sensors	S Gehly	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Towards actionable collision risk warnings for spacecraft operators	S Flegel	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	An Update on SERC's Conjunction Assessment Capabilities	M Moeckel	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Charming ICT for the Future	F Tomita	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	RP1 Update: Achievements, Highlights and Progress	C Smith	Presentation

## OTHER PUBLICATIONS

DATE	PUBLISHED IN / PRESENTED AT	TITLE	AUTHORS	PUBLICATION TYPE
Jun-17	SERC Research Colloquium 2017, Canberra	Multi-Beam Combination for High Beam Quality Multi kW CW Laser	Y Gao	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Developments with the Sum Frequency Sodium Guidestar Laser	J Webb	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	An Overview of LM iSpace	M Bold	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Adaptive Optics System for Space Debris Manoeuvre Demonstration	D Grosse	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Overview of AO Imaging System for Object Characterisation and Tracking	M Copeland	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Site Characterisation at Mount Stromlo Observatory	V Korkiakoski	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Developments in Scaling the Optical Phased Array	P Sibley	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Space Debris Catalogue and Automating Orbit Determinations	D Kooymans	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	NICT Activities and Planning Project	H Kunimori	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	RP2 Update: Achievements, Highlights and Progress	R Norman	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Physics-based Modelling and Ionospheric Data Assimilation for Characterising the Atmospheric Mass Density in LEO	B Carter	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	General Orbit Determination Techniques for Space Objects	Y Yang	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Macroscopic Orbital Propagators	J Daquin	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Deorbit of Optus B3 and Current GEO Operator Issues	A Edwards	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Overview of the Space Segment for Demonstration of Remote Manoeuvre by Photon Pressure	B Sheard	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Instrumented Stratospheric Test Target	M Petkovic	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Preliminary Design Considerations for SERC CubeSat	L Smith	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	Lockheed Martin RP4 Mission Modelling Update	L Smith	Presentation
Jun-17	SERC Research Colloquium 2017, Canberra	SERC Future Directions	B Greene	Presentation
Jun-17	Adaptive Optics for Extremely Large Telescopes 5 (AOELT5), 25-30 June, 2017, Tenerife, Canary Islands	Evaluation of statistical turbulence models for use in the Distributed Kalman Filter	J Cranney, P Piatrou, J De Dona, V Korkiakoski, F Rigaut.	Conference presentation
Jun-17	Adaptive Optics for Extremely Large Telescopes 5 (AOELT5), 25-30 June, 2017, Tenerife, Canary Islands	SPOOF: Spot Packing Optimisation on Optical Frames	F Rigaut, J Cranney, B Neichel, T Fusco, O Fauvarque.	Conference presentation
Jun-17	International Workshop on Superconducting Quantum Technology, 18-21 June 2017, Freyburg/Unstrut Germany	Cryogenic digital signal processing for superconducting single-photon detector	H Terai, S Miki et al.	Conference presentation
Jun-17	ISTS2017: International Symposium on Space technology and Science, 3-9 June 2017	Environmental-data Collection System for Satellite-to-Ground Optical Communications	K. Suzuki, M. Toyoshima, et al.	Conference Presentation
Jun-17	16th International Superconductive Electronics Conference (ISEC2017), Japan	High Performance Fiber-coupled NbTiN Superconducting Nanowire Avalanche Photon Detector	S. Miki et al.	Conference Presentation



## 4.2. SERC SCHOLARSHIP STUDENTS

The following table provides a list of all SERC scholarship students.

NAME OF STUDENT	RP	HOST RESEARCH INSTITUTION	TYPE	COUNTRY OF ORIGIN	PROJECT TITLE
Elliott Thorn	RP1	ANU	HDR	Australia	Design of SERC Adaptive Optics Laser Guide Star Facility
Michael Copeland	RP1	ANU	HDR	Australia	Advanced Imaging and Wavefront Sensing for Satellite Laser Ranging and Tracking
Paul Sibley	RP1	ANU	HDR	Australia	Laser Written Waveguides for an Optical Phased Array Head
Shasidran Raj	RP1	ANU	HDR	Malaysia	Space Debris Tracking using Continuous Wave Laser
Samuel Francis	RP4	ANU	HDR	Australia	A Robust Laser Interferometer for Multiplexed Measurements of Optical Path Lengths
Richard Samuel	RP2	ANU	HDR	Australia	A method for determining near-earth object characteristics and behaviour using iterative orbital refinement and convergence
Jesse Cranney	RP1	Newcastle	HDR	Australia	Predictive Control of Adaptive Optics Systems for Observations and Tracking of Space Objects and Debris
Adam Harris	RP2	RMIT	HDR	USA	Precise Orbit Determination and Advanced Astrodynamics Research for Application in Satellite Positioning and Tracking.
Alea Yeasmin	RP2	RMIT	HDR	Bangladesh	Monitoring, Mapping and Modelling Atmospheric Density Using the Swarm Mission
Changyong He	RP2	RMIT	HDR	China	Precise Thermospheric Density Correction for Robust Orbit Determination and Prediction of Low-Earth-Orbit Objects
Han Cai	RP2	RMIT	HDR	China	Tracklet Correlation and Multi-target Tracking Of Space Debris Initial Orbit Determination for Enhanced Catalogue Maintenance and Conjunction Analysis
Samantha Le May	RP2	RMIT	HDR	Australia	NLP as a Sensor of Soft (human based) Inputs to Support SSA an Space Traffic Management Activities
Michael Afful	RP2	RMIT	HDR	Ghana	Space Debris Characterisation for Reliable Orbit Determination and Prediction
Timothy Kodikara	RP2	RMIT	HDR	Sri Lanka	Enhancing Atmospheric Mass Density Modelling for Space Situational Awareness
Joseph O'Leary	RP3	UniSA	HDR	Ireland	GPS Application of General Relativity
Pierpaolo Toniato	RP4	UQ	HDR	Italy	Mach 12 Scramjet Testing in X3 Expansion Tube
Samuel Stennett	RP4	UQ	HDR	Australia	Flow Condition Optimisation and Characterisation for a New Large Scale Reflected Shock Tunnel
Timothy Cullen	RP3	UQ	HDR	Australia	Re-entry Shock Layer Thermography
Kyle Damm	RP4	UQ	HDR	Australia	Multipoint, Multi-objective Geometric Optimisation of a Hypersonic Launch Vehicle
Alpha Bah	RP1	UTS	HDR	Sierra Leone Australian citizen	Reconfigurable Ultrawideband Tightly Coupled Arrays.
GRADUATED STUDENTS					
L. Roberts	RP2	ANU	HDR	Australia	Development of a High-power Optical Phased Array for Space Debris Tracking and Manoeuvring
Anna Zovaro	RP1	ANU	U/grad	Australia	Simpler Adaptive Optics using a Single Device for Processing and Control
Samantha Le May	RP4	RMIT	U/grad	Australia	Modelling the Future Evolution of the Orbital Debris Population
Alexander Stuchbery	RP1	ANU	U/grad	Australia	Design, Construction & Testing of a Camera Latency Measurement Device
FORMER STUDENTS					
Anna Zovaro	RP1	ANU	HDR	Australia	Adaptive Optics for Space Debris Manoeuvring and Astronomy
Yang Zhao	RP1	RMIT	HDR	China	Two-line Element Data Quality Control and its Application in Space Situational Awareness

The background of the entire page is a deep blue space filled with numerous white stars of varying sizes. Some stars are simple dots, while others are larger, multi-pointed shapes. At the bottom of the image, the curved horizon of the Earth is visible, showing a blue sky and white clouds. The text 'PRESERVING SPACE FOR THE FUTURE' is centered in the lower half of the image in a light blue, bold, sans-serif font.

PRESERVING  
**SPACE**  
FOR THE  
**FUTURE**



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