PROJECT TITLE: Semiconductor Laser for Adaptive Optics in Astronomy and Space Awareness

EXECUTIVE SUMMARY: This project aims to procure a new and innovative *Semiconductor Laser* to support existing, and enable critically-needed, future research in ground-based **Adaptive Optics (AO) instrumentation**, **astronomy**, and **Space Situational Awareness (SSA)**. **Sodium Laser Guide Stars (LGS)** are an essential component of modern AO for astronomy, **satellite tracking/imaging,** and **space debris tracking/pushing** at **Low Earth Orbits (LEO)** and **Geostationary Orbits (GEO)**. Past and current generations of sodium lasers are expensive, unreliable, bulky, and inefficient. With this proposal we will deliver a *cost-effective*, *reliable, shoe-box-size* and *efficient* alternative system based on proven *semiconductor laser technology*. We will:

- Design, fabricate, and test the Semiconductor Laser, on telescope and in operational conditions;
- Create *the first sodium LGS in Australian skies* and use it to achieve major scientific breakthroughs;
- Establish the Semiconductor Laser as the long-awaited, enabling laser technology for widespread adoption of LGS AO on small, large, and extremely large telescopes (ELTs) around the world.

Such a laser system is: (i) essential to support existing and future Australian research projects and commercial opportunities for instrumentation on astronomical telescopes, satellite imaging and space debris tracking stations; (ii) critical to meet the *Space Environment Management Cooperative Research Centre* (CRC) objectives to improve sensitivity of orbital tracking in the short term, and mitigate the threat of space debris in the long-term; and (iii) fundamental for the success of the Australian-supported *Giant Magellan Telescope* (GMT – Figure 1).

The project brings together internationally recognised science, instrumentation and technology experts in astronomy and SSA, from the public, private, civil and defence sectors, in Australia and in the United States. The Semiconductor Laser will support large-scale national and international cooperative initiatives by providing the academic and industry investigators and their teams with access to the first LGS AO system ever built in Australia.

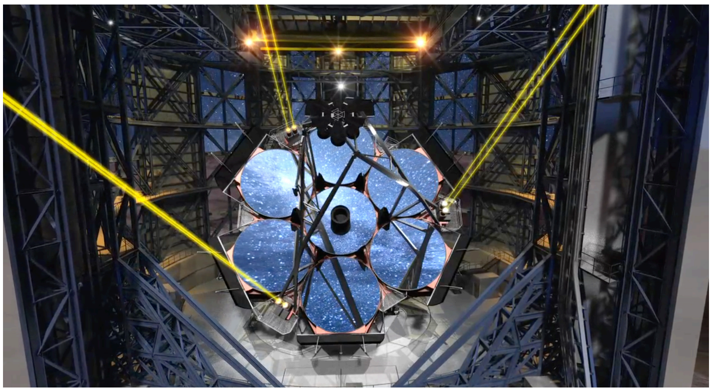

Figure 1: Giant Magellan Telescope (Credit: GMTO)

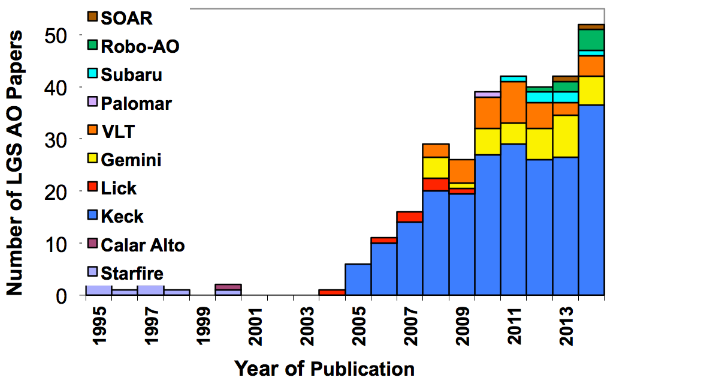

Figure 2: Number of LGS AO science papers published per observatory (Wizinowich 2013).

1. STATEMENT ADDRESSING THE SELECTION CRITERIA

1.1 Significance of Research to be Supported with the Proposed Infrastructure

LGS AO in general and sodium lasers in particular are at the heart of the project investigators' present and future research activities in **LGS AO instrumentation** (CIs/PIs d'Orgeville, Rigaut, Lambert, Goodwin), **astronomy** (CI/PIs Sharp, Ryder, Bouchez), **satellite tracking/imaging**, and **space debris tracking/pushing** (PIs Gao, Mason). Australian universities ANU and UNSW, the Australian Astronomical Observatory (AAO), and Australian company EOS Space Systems are prominent research and innovation leaders in these fields. They are key participants in large, international cooperative research initiatives such as GMT and the Space Environment Management CRC, which Lockheed Martin (LM) also participates in. However the lack of a *cost-effective*, *reliable, shoe-box-size* and *efficient* sodium laser *in Australia* is a critically limiting factor for the investigators and their organisations' existing and future research, innovation, and commercial activities. The Semiconductor Laser project will overcome this limitation.

Nature, Aims and Significance of Research:

- **Adaptive Optics:** CIs/PI d'Orgeville, Rigaut, Lambert, and Goodwin's research focuses on the science, technology development, and use of AO, a technique described as "*the most revolutionary technological breakthrough in astronomy since Galileo pointed his telescope skyward to explore the heavens 400 years ago*" (Duffner 2009). The use of AO was first proposed in 1953 as a means to correct for optical wavefront distortions caused by atmospheric turbulence. Practical implementation of the technique however was delayed until the relatively recent development of deformable mirrors, high-speed computers, and lasers. *Natural guide star* AO, the original technique whereby the object of interest is bright enough to provide adequate wavefront sensor signal-to-noise ratio and deliver optimum AO correction, is in routine operation on telescopes around the world but has limited application. Artificial guide stars are required to enable AO correction for observation of fainter sources (thereby providing extended sky coverage in astronomy) or uncooperative targets such as fast moving satellites and space debris. *Laser guide star* (LGS) systems employing Rayleigh scattering at UV/optical wavelengths provide an inexpensive solution but only enable probing of the atmosphere close to the ground (<20 km), thus delivering limited AO correction. LGS AO systems accessing the high altitude sodium layer at ~90 km enable significantly improved correction but are in limited operation today due to the high procurement, operation, and maintenance costs of sodium lasers and sodium LGS facilities.

- **Sodium Lasers:** Sodium laser technology is central to CI d'Orgeville's research at ANU (d'Orgeville 2015). The first sodium guide star lasers to be used routinely in astronomy were exceedingly bulky and messy systems based on dye laser technology developed in the 1990's. A second generation of sodium lasers was developed in the 2000's based on solid-state laser technology, resulting in improved power efficiency and clean operation, but such systems remain prohibitively expensive for widespread adoption, and have proven exceedingly difficult and costly to operate and maintain. A third generation of sodium guide star lasers based on Raman fibre technology has been developed over the past ten years and is now being fielded on telescopes. Raman fibre-based sodium lasers can be procured from German laser manufacturer Toptica with a unit price upward of AU$1.3M. These systems are still expensive to purchase and continue to require significant power and cooling capacity. Additionally, the laser head remains too large to be optimally located on the telescope, and so complex and lossy relay optics are still required in most cases, further degrading LGS AO performance and reliability. Because Toptica has indicated limited ability to maintain their product line into the future, there is also significant community risk in relying on a sole source supplier to provide this key component of LGS AO systems.

CI d'Orgeville and her co-investigators will deliver *the fourth generation of sodium guide star lasers* based on proven *semiconductor laser technology,* tailored specifically for emission at the sodium D2a and D2b lines at a wavelength of 589nm, with output power levels and spectro-temporal laser formats comparable or superior to the Toptica laser and other fielded sodium laser systems. Optically-Pumped Semiconductor Lasers (OPSL) have been commercially available for a few years with thousands of units currently used in the field, albeit at wavelengths other than 589nm. OPSLs are affordable, efficient and compact systems which can enable reliable, 24/7, hands-off operation in challenging environments such as high altitude, remote astronomical telescopes and fully-automated laser tracking stations with unusually high acceleration rates. Power outputs higher than 50W are required for the most demanding AO applications, a power level that has been demonstrated in shoe-box-size semiconductor laser packages (Berger 2012). It will therefore be possible to install the Semiconductor Laser at the optimal location on any size telescope, removing relay optic losses and allowing both side and centre launch for sodium LGS AO use in astronomy and ground-based SSA applications.

- **Astronomy with LGS AO:** CI Sharp, PI Bouchez and PI Ryder are specialist users, developers, and access providers of LGS AO on large and extremely-large telescopes. Since 2011 all major astronomical research telescopes used by Australian astronomers and their collaborators worldwide have been equipped with sodium LGS AO, including most of the 8-10 metre-class telescopes (Keck, Gemini, Subaru, VLT) and many of the 4 metre-class telescopes (Lick, Palomar) (Figure 2). LGS AO enables angular resolutions for observations at near-infrared wavelengths ($\lambda \sim$ 1-2.4μm) with 8-10m telescopes on the ground that are comparable or superior to angular resolutions achieved with the orbiting 2.4m diameter Hubble Space Telescope at shorter wavelengths ($\lambda \sim$ 0.3-1.0μm). With the pending launch of the 6.5m diameter James Webb Space Telescope (JWST) slated for 2018, this powerful observational synergy will only be repeated in the next decade if the ground-based 25-40m diameter ELTs can achieve diffraction-limited observations through the use of LGS AO. Consequently all ELTs will be equipped with sodium LGS, including six LGS for the Australian-supported GMT, nine LGS for the Thirty Meter Telescope, and six or more LGS for the European ELT. ANU CIs d'Orgeville, Rigaut, and Sharp are leading the GMT LGS AO instrumentation effort in Australia, with support from PI Bouchez at GMT. Meanwhile the Keck, Gemini, Subaru, Gran Telescopio Canarias, and the Large Binocular Telescope observatories have indicated their strong interest in the Semiconductor Laser and offered their telescopes as future additional test platforms and possible early adopters of this extremely promising, and relatively inexpensive technology.
- **Space Situational Awareness:** Industry PIs Gao and Mason, in collaboration with CIs d'Orgeville, Rigaut, and Lambert, are leading innovative SSA research using AO-enhanced satellite tracking/imaging and space debris laser tracking stations. *Accurate positioning data* and *collision predictions with space debris* are of vital importance to modern telecommunication infrastructure and the remote sensing industry multi-billion dollar space assets. Originating from an isolated portion of the southern hemisphere, observations from the EOS laser tracking station situated at ANU's Mount Stromlo campus and the US Air Force Academy Falcon Telescope situated at UNSW's Canberra campus provide unique and valuable information to a wide range of public and private customers. High performance sodium LGS AO is key to tracking the smallest, faintest debris, which are still a threat to operational on-orbit systems despite their small size, and to developing precision orbits in the first place, so that highly reliable conjunction analyses can be performed. ANU, EOS, Lockheed Martin (LM) and other academic and industry organisations involved in the Space Environment Management CRC are also seeking to demonstrate the NASA LightForce concept for *mitigation of space debris collisions* through use of photon pressure. A key requirement of

this innovative SSA research area is uplink LGS AO compensation to provide the highest efficiency in the transfer of laser power to apply force on an object in orbit.

Relevance: The Semiconductor Laser initiative builds on previous investment and intellectual capacity within the partnership, including: Australia's AU$88M participation in GMT through ANU and Astronomy Australia Ltd; ANU and AAO involvement in the GMT instrumentation program (McGregor 2012, D'Orgeville 2013, Bouchez 2014, Lawrence 2014); and ANU, UNSW, EOS, and LM's active research in satellite imaging, space debris tracking, and other SSA programs such as those pursued by the Space Environment Management CRC (AU$19.8M federal funding over 5 years -- D'Orgeville 2014, Shivitz 2014).

The degree of investment required to deliver this project is well matched to the ARC LIEF program objectives. The proposed approach to develop a sodium guide star Semiconductor Laser in collaboration with industry is typical of technological developments for astronomy and space science, which have a targeted market coupled with high technology demands. As a result, innovative manufacturers collaborate with international research groups who have the expertise and motivation to utilise their product in a scientific development, eventually benefiting all academic and industry partners, in Australia and abroad. *The common but erroneous belief that developing sodium laser technology is "a problem that will be solved naturally in due course" has in the past considerably delayed the advent of sodium LGS AO in mainstream astronomy, and still prevents deployment of the technique in SSA applications today.* The research and development (R&D) costs associated with tailoring any new laser technology, however promising, are beyond what any university, observatory or private company can afford. Considerable past investments by US and European funding agencies have enabled the current generations of sodium lasers for astronomy, including the >AU$1.3M Toptica Raman fibre laser which, as the only commercial laser available today, remains prohibitively expensive for most would-be LGS AO users. ARC support to the Semiconductor Laser project will be the first, albeit crucial step to produce a competing system based on *vastly superior laser technology, that will be demonstrated and used in Australia, and later commercialised by Australian academic and industry partners at a third or half of the Toptica laser purchase price*. For these reasons, the Semiconductor Laser project is also well aligned with the National Innovation and Science Agenda (http://www.innovation.gov.au/page/agenda).

***Existing and Emerging Research Strength*:** The astronomy and space ground-based instrumentation community in Australia has a world class reputation, partly built on Australia's timely investment in emerging new technologies. The development program supported by this proposal ensures Australia continues to capitalise on past investments while safeguarding future returns by removing sole source supplier risk for infrastructure critical to the success of GMT and the Space Environment Management CRC.

The Semiconductor Laser project also lays the foundation for future technology transfers and parallel development programs in Australia. LGS AO-enhanced satellite imaging and debris tracking will result in immediate commercial opportunities, such as the existing EOS/ANU contract for the Korean Astronomy and Space Science Institute (KASI), and the EOS/LM space object tracking joint venture in Western Australia. In astronomy, the Semiconductor Laser will form the foundation of a new generation of AO instrumentation for existing medium- and large-size telescopes in the 2-5 year time frame, not only leveraging Australia's investment in its flagship national facility at Siding Spring Observatory and in the major international observatories (e.g. Gemini, Keck, Subaru), but also providing new opportunities for competitive tender for future instrumentation at all international facilities. As a specific example we are currently exploring how such a program could form a significant component of the proposed US$40M Keck Next Generation AO facility, attracting funding from the US National Science Foundation and/or providing the Australian community with increased access to the two 10m Keck telescopes.

1.2 Need and Use of the Proposed Research Infrastructure

Following delivery to the ANU, the Semiconductor Laser will be installed on the EOS 1.8m telescope located at the ANU Mount Stromlo Observatory where it will be used as a sodium guide star laser for *a minimum period of six months*. The EOS telescope is currently being equipped by ANU with two state-of-the-art AO systems for the Space Environment Management CRC research projects #1 (Satellite and Debris Tracking at LEO and GEO) and #4 (Debris Manoeuvring). When the Semiconductor Laser becomes operational, it will be *the first time that a LGS AO system is used on the Australian continent.* This will usher *a new era of LGS AO-enhanced astronomy and SSA observations in Australia*. Use of the Laser Semiconductor beyond the initial six month demonstration period on the EOS telescope and/or other Australian and international telescope facilities will be negotiated between ANU and their partners based on relative research priorities, project schedules and telescope availability constraints.

Immediate Use for Astronomy: The Semiconductor Laser will be used by AO scientists and astronomers on the EOS 1.8m telescope to show-case the fourth generation sodium guide star laser performance in real operating conditions and its potential as the ideal laser source for existing and future sodium LGS AO systems in *astronomy*. More specifically, the LGS AO campaign on the EOS telescope will inform: (i) the ANU Laser Tomography AO (LTAO) project for GMT using six sodium LGS, led by **CIs Rigaut** and **d'Orgeville**, and managed by **PI Bouchez** on GMT's behalf; (ii) the LTAO-fed GMT Integral Field Spectrograph (GMTIFS) project led by **CI Sharp**; (iii) the

AAO AO program development led by **PI Goodwin** for the Anglo-Australian Telescope (AAT) and GMT; and (iv) the AO development programs at the Keck and Gemini telescopes in Hawaii and Chile whose access by the Australian astronomy community is managed by **PI Ryder** at the AAO.

Immediate Use for SSA: The Semiconductor Laser is absolutely essential to completing the LGS AO infrastructure at the EOS laser tracking station and to fulfilling the partners' research objectives in ground-based SSA science, instrumentation and technology. **CIs d'Orgeville**, **Rigaut**, and **Lambert**, and **PIs Gao** and **Mason** will demonstrate LGS AO-enhanced laser tracking of cooperative, and more importantly, uncooperative targets (satellites and space debris) at LEO and GEO while breaking established records in terms of positioning accuracy, space debris altitude, and system efficiency. Extensive use of the Semiconductor Laser in challenging operational conditions (tracking speed and telescope acceleration will be higher than when tracking astronomical objects) will also prove the technology's potential for existing and future sodium LGS AO systems in ground-based SSA applications. **CIs d'Orgeville** and **Lambert,** and **PI Goodwin** will also characterise the photon return from the sodium laser guide star created by the Semiconductor Laser, as well as temporal variations of the mesospheric sodium column density above Canberra. These will inform current and future LGS AO projects at Mount Stromlo and UNSW Canberra.

Future Need in Astronomy: This program will lead to the deployment of technology demonstrator instruments at Australia's premier mainland optical astronomy observatory, Siding Spring Observatory (SSO). For example, **CI Sharp** is leading a 2015 Linkage Project (LP150100620) to develop the next generation near-infrared wavefront sensor technology using ultra low readout noise avalanche photodiode detectors, and **CI Rigaut** is leading a laboratory investigation to characterise cooled deformable mirror technology. Like sodium semiconductor lasers, both of these technologies are also essential components of the GMT instrumentation program. Once the new sodium guide star has been demonstrated on the EOS 1.8m telescope, **CIs Sharp**, **d'Orgeville** and **Rigaut**, and **PIs Ryder** and **Goodwin** will seek to combine these three technologies to provide an on-sky demonstration of a composite system at the ANU 2.3m telescope and/or the AAO 3.9m AAT at SSO. In addition to delivering some niche scientific observations, the principal value of this instrument resides in capitalising on Australian investment in the technology from the past decade to develop the technology of the future in a timely and cost-effective manner. Technology deployment at existing on-shore facilities at which there is less access pressure minimises time lost on expensive high value facilities (8-10m telescopes) at ideal, but remote, observatory sites. **PI Goodwin** and **CI Lambert** have previously demonstrated that the turbulence characteristics at SSO are ideal for this purpose (Goodwin 2013). **PI Goodwin** and colleagues have already initiated a preliminary AO test campaign on the AAT using a laboratory AO system developed at AAO to explore innovative Multi-Object AO (MOAO) concepts relevant to the GMT and other astronomy instrumentation programs (Goodwin 2013b).

Australian astronomy access to high angular resolution AO facilities such as the Keck, Gemini, and Magellan 6-10m telescopes is currently extremely limited. A well developed next generation AO facility, with demonstrated on-sky heritage, would provide a powerful in-kind component for new instrumentation on existing 6-10m class facilities, with guaranteed nights of access for Australia as a reward. Hence, a modest investment in the new laser technology at this time could be fundamental to addressing the first recommendation listed in "Australia in the era of global astronomy: The decadal plan for Australian astronomy 2016–2025" (https://www.science.org.au/node/389) and to helping secure cost-effective access for the Australian community to 6-10m telescope facilities, the workhorses of modern astronomy, into the future.

Realising the full scientific potential at an angular resolution approaching the diffraction limit of any ELT, and in particular that of the Australian-supported GMT, also requires affordable, reliable, and efficient sodium guide star lasers. LGS constellations are essential to achieving the high sky-coverage (>90%) necessary to access legacy survey fields such as the Hubble Deep and Ultra-Deep Fields. These predetermined survey regions of the sky have by design few stars bright enough to be suitable natural guide stars. The flexibility provided by laser beacons is essential to ensuring the exquisite angular resolution of ELTs can be focused on the most important targets identified by the powerful survey modes of the smaller observatories such as the 6.5m JWST to be launched in 2018.

Future Need in SSA: SSA industry leaders **PIs Gao** and **Mason** also recognise LGS AO as a key enabling technology in several ground-based SSA sensing modalities. In many cases, modest 1-2m telescope apertures with LGS AO are sufficient to meet sensor performance requirements. Additionally, to meet mission needs, it is frequently preferable for SSA sensors to be distributed globally. Hence a low SWaP (Size, Weight, and Power), low cost sodium laser solution is a key enabler to advancing SSA capability. In one example, LM has invested in the Space Object Tracking facility (SPOT), which has three 1m telescopes used for R&D in SSA applications (Shivitz 2014). Current work includes installation of three Rayleigh beacon AO systems to extend the capability of this observatory. The possibility of an affordable upgrade to the superior performance provided by a sodium LGS is a key motivation for LM's participation in the Semiconductor Laser effort. In another example, LM has been executing the Galileo program for the US Defense Advanced Research Projects Agency, which seeks to achieve high resolution (<milli-arcsecond) imaging of satellites at GEO, using interferometric sparse aperture techniques. One limiting factor is the interferometric efficiency through turbulence; hence LGS AO is required to achieve fringes on fainter objects. In a

third example, LGS AO provides better imaging resolution at LEO and better sensitivity for dim object detection and tracking in general. Better resolution will make it possible to troubleshoot anomalies of satellites in orbit, attribute collisions with debris or break-up events, and enable higher sensitivity for detection and tracking of smaller objects in space. In all three examples, the benefits of sodium LGS AO in SSA applications are clear, motivating the need for affordable, reliable, scalable, and commercially available sodium guide star lasers on a global scale.

1.3 Nature of the Alliance and Commitment Between the Organisations Named on the Proposal

Strategic Alliance: As illustrated in sections 1.1 and 1.2 above, the academic and industry partners' strategic research priorities are well aligned and their coordinated efforts to develop LGS AO instrumentation for astronomy and SSA applications are already underway under a number of pre-existing cooperative agreements.

The Semiconductor Laser project will support the ANU Advanced Instrumentation and Technology Centre (AITC) business model, including: delivering world-class, cutting-edge AO instrumentation to ELTs (e.g. GMT LTAO and GMTIFS); developing new capabilities for existing 8-10m telescope AO infrastructure (e.g. Gemini South Multi-Conjugate AO upgrade under LIEF grant LE140100013); supporting innovative AO concepts at Australian national facilities (e.g. AAO Multi-Object AO for the AAT and GMT); transitioning LGS AO capabilities to industry (e.g. participation in the Space Environment Management CRC); as well as building commercial LGS AO systems for international customers (e.g. ANU/EOS contract to deliver an AO-equipped surveillance telescope to KASI). It will further confirm ANU as a leader in AO instrumentation in general and in sodium LGS technologies in particular, strengthen ANU's position as an unmatched provider of integrated, turn-key sodium LGS AO systems, and enhance opportunities for multi-million dollar contracts with current and prospective customers such as GMT, KASI, and the Japanese National Institute of Information and Communications Technology (NICT).

The development of an affordable sodium laser source will also support Astronomy partners AAO and GMT's extensive instrumentation programs. The Australian and international astronomy communities will greatly benefit from lower procurement, operational and maintenance costs, optimum AO performance, and ultimately scientific output of their astronomical observatories. ANU and AAO jointly operate telescopes at Siding Spring Observatory, and actively collaborate in a number of astronomy instrumentation programs for other observatories such as Gemini (e.g. Gemini South AO upgrade, GHOST optical spectrograph) and GMT.

Finally, access to innovative laser technology will increase the productivity of ground-based SSA missions by SSA partners UNSW, EOS and LM in Australia and abroad, and open new areas for research collaborations with ANU as well as new commercial opportunities. Development of the Semiconductor Laser will further strengthen on-going collaborations between ANU, EOS and LM within the Space Environment Management CRC.

Commitment: All partners are strongly committed to the success of the Semiconductor Laser project for which they will provide significant cash ($532,405) and in-kind ($635,961) contributions. ANU as the lead organisation will provide 60% of the non-ARC cash contributions and 21% of the total in-kind contribution, including 0.41 FTE in laser/AO/instrument scientist resources. Although EOS does not provide cash to the project, they will take a leading role among partners contributing over half (55%) of the total project in-kind. This includes 0.6 FTE in laser scientist and engineer resources to install the Semiconductor Laser on the EOS laser tracking station, as well as $134k in access to the EOS laser tracking station to test the Semiconductor Laser on the sky. The remaining cash and in-kind contributions will be provided by UNSW ($40k, 0.1 FTE), AAO ($25k, 0.08 FTE), GMT ($66k, 0.05 FTE), and LM ($79k, 0.1 FTE), including resources from leading astronomers and instrumentation scientists to participate in the Semiconductor Laser requirement definition phase, design, performance and final acceptance reviews.

Please refer to section 2 for details on the cooperative arrangements related to the Semiconductor Laser.

1.4 Investigators

CI d'Orgeville (ANU) is a leading sodium laser expert with over 18 years of experience in the field of LGS AO, who *has been involved in the design, installation and on-sky commissioning of more sodium LGS than anyone else in the world*. She led the Gemini laser program to equip the twin 8m diameter telescopes with state-of-the-art, second generation sodium solid state lasers (14W laser worth US$2.9M at Gemini North in 2005, and 50W laser worth US$3.7M at Gemini South in 2011). Spanning two hemispheres and multiple time zones, she successfully managed the large (25+) international, multidisciplinary team of scientists and engineers who created the first and so far unique sodium LGS constellation for use with GeMS, the Gemini South Multi-Conjugate AO system pioneered by CI Rigaut. D'Orgeville was also instrumental in bringing sodium LGS to other astronomical telescopes. She managed the contract to procure a second generation, 20W solid-state laser for Keck I (2010) under US National Science Foundation award #0100845 (US$3.3M). She has also been invited to review the LGS AO programs for the 8m Subaru telescope (one LGS, solid-state laser technology) and for the European Southern Observatory Very Large Telescope (one LGS, dye laser technology, now being upgraded to four LGS, fibre laser technology). D'Orgeville's current research activities at the ANU include the design and expected fabrication contract for the US$20M GMT LGS facility overseen by PI Bouchez, and the use of sodium LGS AO for space debris tracking and manoeuvring of interest to UNSW CI Lambert and industry PIs Gao and Mason. D'Orgeville regularly participates in scientific organising committees for AO conference (e.g. SPIE 2016, 2014, 2010, 2008), and as an invited speaker at international venues (e.g. SPIE 2014, 2002; US Center for Adaptive Optics 2015, 2010, 2007; Australian Academy of Science *Frontiers in Science* 2014). D'Orgeville has published over 65 papers in refereed journals and conference proceedings. As of March 2016, her Google Scholar h-index is 15 and her i10-index is 23, placing her among the most cited authors in her field of expertise.

CI Rigaut (ANU) is the adaptive optics group lead at the ANU, bringing over 28 years of experience to the project, including COME-ON, the first successful AO system for astronomy (Rousset 1989), and GeMS, the first and only LGS Multi-Conjugate AO system in the world (Rigaut 2013). Rigaut has been a key player in AO investment totalling in excess of US$50M in 2015 dollars. As an AO theorist, Rigaut initially proposed the concept of Ground Layer Adaptive Optics (GLAO), implemented or being planned on most large telescopes (MMT, VLT, Subaru, E-ELT and GMT). He is the author of YAO, a Monte Carlo AO simulation code that is used around the world to estimate the performance of LGS AO systems, and is directly applicable to the proposed work. Rigaut is a regular member of AO conference organising committees, including but not limited to SPIE 2014, 2012, 2010, 2004, 2000, 1998, 1997, and AO4ELT 2011. He has authored over 275 papers, mostly in adaptive optics or astronomical instrumentation, with over 5300 citations. In March 2016 his Google Scholar h-index is 39 and his i-10 index is 101.

CI Sharp (ANU) is project scientist for the AU$25M GMTIFS instrument selected as the first-light adaptive-optics instrument for the GMT scheduled for commissioning in 2023. The science case for GMTIFS relies on the availability of high-power sodium laser guide star constellations; hence Sharp will provide the scientific motivation for the Semiconductor Laser future deployment on ELTs via simulation of performance of the GMTIFS system. This ensures the program will focus on delivering a pathway to realise the full scientific potential of adaptive optics on the GMT and other ELTs. Sharp is CI for Linkage Project LP150100620 to develop the next generation near-infrared wavefront sensor technology, using ultra low readout noise avalanche photodiode technology. This technology is a key parallel component of next generation AO systems. As of March 2016, Sharp's total citation count is 6384, leading to a personal h-index of 42, m-index of 3.2, and g-index of 75.

CI Lambert (UNSW) is an expert in applied and adaptive optics, for astronomy, surveillance and ophthalmology (Lambert 2013). He has assisted PI Goodwin in the turbulence characterisation campaigns at sites in Australia (Goodwin 2013) and at the GMT site in Chile. He currently operates an AO system at the UNSW Canberra node of the US Air Force Academy Falcon Telescope Network for space debris tracking. Access to an affordable, reliable sodium laser guide star system will revolutionise the UNSW AO operations, significantly improving performance for debris tracking and securing Australian involvement in this important program into the next decade. Lambert's work parallels that of CI d'Orgeville, CI Rigaut and PI Gao in Canberra and allows access to a second local platform for AO operations during development, mitigating access conflicts with commercial operations at EOS.

PI Ryder (AAO) heads the International Telescopes Support Office at the AAO. In this role, he is responsible for supporting Australian astronomical community access to the leading 6-10m class telescopes in Hawaii and Chile. He oversees operational issues associated with development of community proposals to use the telescopes, providing and supporting the tools to process data generated at the telescopes. As such Ryder is an Australian expert in the community needs for current and future astronomical instrumentation. Ryder will work with CI/PIs d'Orgeville, Rigaut, Goodwin and Sharp to identify the key opportunities to leverage past and current investment to access the next generation of facilities. Ryder has been an active user of natural and laser guide star systems for supernova and starburst galaxy research on both the Gemini North and South telescopes, as well as on the Very Large Telescope, since 2007. He is a PI on LIEF grant LE140100013 to upgrade the existing wavefront sensors on the Gemini South Multi-Conjugate AO system for which CIs Rigaut and d'Orgeville are also active and essential contributors. Ryder has published over 100 refereed papers and has an h-index of 34, and an i10-index of 78.

PI Goodwin (AAO) is an instrument scientist at the Australian Astronomical Observatory, a recognised centre of excellence for innovative astronomical instrumentation. Goodwin has over 10 years of experience in engineering and research, having worked in industries including telecommunications, data acquisition and control systems, software development, and astronomical instrumentation R&D. Goodwin's research interests include astronomical site-testing, adaptive optics, robotic fibre positioning technologies and fibre technologies. With CI Lambert, Goodwin performed key atmospheric site testing measurement for both Siding Spring Observatory in Australia and GMT in Chile. Goodwin brings to the project specific expertise in atmospheric modelling. He will focus on future exploitation of the Semiconductor Laser as part of next generation astronomical instrumentation on the 3.9m AAT, the Gemini and Keck telescopes, and the GMT.

PI Bouchez (GMT) is leading the design of the GMT AO systems in partnership with premier groups around the world, including that of CI Rigaut at ANU. He previously participated in the development of the first-generation LGS AO systems at the Keck and Palomar observatories. The GMT LTAO system requires six high power sodium laser guide stars. Bouchez will ensure development of the Semiconductor Laser is optimised for the performance requirements of ELTs, such as the GMT, since these facilities represent major future customers. Bouchez's early involvement in the program allows many potential problems associated with future ELT deployment to be "designed out" of the laser system at the prototype stage. This significantly mitigates risk associated with Australia's substantial ongoing investment in this critical component of the US$35M LTAO system for GMT.

PI Gao (EOS) is the head of research and development at EOS Space Systems Pty Ltd., based in Canberra, and a long-standing partner with ANU. For 30 years he has been leading research, design, development, and project management for a range of high energy (many Joules per pulse), and high power (thousands of Watts) solid state lasers. Gao has been working with solid-state lasers since 2000 and will actively engage with Areté Associates particularly in the area of laser frequency locking to the sodium D2 line where he has significant prior experience. Gao will also coordinate on-sky testing at the EOS laser tracking station in Canberra.

PI Mason (LM) is the chief scientist for Lockheed Martin Space Systems Company's ground based situational awareness research area. He has worked on a wide range of electro-optical sensors during his 15 years in the aerospace industry, including metrology, spectroscopy, optical filters, imaging, target tracking, and active and passive remote sensing. Mason is an expert in all aspects of use of laser systems for ranging/tracking operations and will focus on characterisation of the performance and reliability of the LGS AO system. LM's significant early investment in this project reflects the high demand for a reliable, cost effective and compact LGS AO system; hence Mason will undertake extensive systems engineering trade studies and mission analysis to develop cost estimates for the Semiconductor Laser as a future marketable technology.

2. RESEARCH INFRASTRUCTURE ARRANGEMENTS

Laser Manufacturer: **CI d'Orgeville** has researched OPSL laser developers and commercial vendors who have the background IP and expertise required to build a cost effective Semiconductor Laser tailored for the sodium guide star application. Over the past couple of years she has established a strong collaboration with Colorado-based laser company Areté Associates whose demonstrated expertise and business model are both consistent with the guide star OPSL market for LGS AO applications in astronomy and space debris tracking (D'Orgeville 2015). Areté Associates is an innovative R&D company with over 250 employees and a 40 year-long proven track record in laser and instrumentation development for remote sensing US defence applications. Areté has been developing OPSLs for over 10 years focusing on applications requiring high power, continuous wave, narrow linewidth, UV and visible band lasers, including OPSLs producing high-power yellow light at or near sodium D_2 resonances (Alford 2013, Leinonen 2013, Ranta 2013). Areté's commitment to the success of the Semiconductor Laser program is made evident by the sizable (18%) discount included in Areté's quote to design and fabricate the Semiconductor Laser with input and assistance from ANU and their partners.

Design and Fabrication Contract: **CI d'Orgeville**, who has considerable experience leading sodium laser development efforts, will manage the contract between ANU and Areté Associates on behalf of the partnership. *CI d'Orgeville, PIs Gao and Mason, EOS laser scientists and engineers, and ANU students will be closely involved in the Semiconductor Laser design, fabrication and testing in Colorado and in Australia*. All CIs/PIs will participate in the project requirement definition, project reviews, factory and post-delivery testing at the ANU. Laboratory testing results will be shared among all partners. Budget and work scope information is provided in Part E of this proposal.

Intellectual Property Agreement: The IP agreement under discussion for the Semiconductor Laser project aims to enable the academic and industry partners to access Areté Associates' background IP as well as share the project IP for future use. It is expected that licensing agreements will enable joint commercialisation by Areté and Australian partners ANU, EOS and/or LM. Preferential access and pricing for all project partners will be provided as well.

Cooperative Access Arrangements: Following delivery and successful post-shipment testing of the Semiconductor Laser in the ANU AITC laboratory at Mount Stromlo Observatory, ANU and EOS will initially install the ANU-owned sodium guide star laser on the EOS 1.8m telescope (also located on the ANU Mount Stromlo campus) for a minimum duration of six months. In this early phase EOS has committed to providing access to their telescope for a minimum average of one five-night LGS AO run per month over six months (six runs in total).

Three runs will be dedicated to LGS AO use in ground-based SSA applications. The EOS laser tracking station will be equipped with a LGS facility and a couple of AO systems (being built by ANU for the Space Environment Management CRC) in time for the Semiconductor Laser to provide *the first LGS AO-enhanced satellite and space debris tracking/imaging at LEO and GEO in Australia*. Assuming 10 hours/night, *a total of 150 hours* of LGS AO operation will be available to **CIs d'Orgeville**, **Rigaut** and **Lambert,** and **PIs Gao** and **Mason** and/or their collaborators. Time on the LGS AO-enhanced laser tracking station will be provided to interested researchers by ANU **CI d'Orgeville,** with logistical support from EOS **PI Gao**, in the following order of priority: (i) CIs and PIs named on this proposal (or their team/students), (ii) researchers/students from organisations listed on this proposal, and (iii) researchers/students from organisations which are involved in the Space Environment Management CRC.

Three more runs, corresponding to about *150 hours of on-sky LGS AO operations*, will be dedicated to LGS AO use on astronomical targets by **CIs d'Orgeville**, **Rigaut,** and **Lambert** (3 runs), and by **CI/PIs Sharp**, **Goodwin**, **Ryder** and **Bouchez** and/or their collaborators (1 run each). LGS AO observation time on the EOS 1.8m telescope will be provided to interested researchers by ANU **CI d'Orgeville** with logistical support from AAO **PI Ryder**, in the following order of priority: (i) CIs and PIs named on this proposal (or their team/students), (ii) researchers/students from organisations listed on this proposal, and (iii) researchers/students from other astronomy institutions. This arrangement will provide instrumentation scientists, astronomers, and students *the opportunity to operate and gather data from the first, and only sodium LGS AO facility in Australia.*

Future Use: Depending on the EOS 1.8m telescope availability, the desire to use the Semiconductor laser for other projects, and the availability of future funding to transition the Semiconductor Laser into a commercial product, the ANU-owned laser may either remain on the EOS telescope, be provided to one or more of the partners for installation at another location (e.g. UNSW Canberra, SSO, LM's SPOT facility in California), or be returned to the ANU AITC laboratory. Additional uses of the Semiconductor Laser will be devised by ANU, their partners, and other interested parties depending on future funding availability. **PI Goodwin** would for instance be interested in following up with an on-sky test of the Semiconductor Laser on the AAT at Siding Spring Observatory, although this experiment would be conditional on AAO resource availability to support the test.

Cost Management: While the Semiconductor Laser is being used by the LIEF partners over the nominal six month period discussed above, all laser-specific operational costs will be borne by ANU, including laser operator resources. All infrastructure costs associated with installing the laser on the EOS telescope, and personnel required to operate and maintain the EOS laser tracking station during LGS AO operations will be borne by EOS. Any unexpected laser maintenance cost will be borne by ANU during the first 6 months, and by whichever organisation may be using the Semiconductor Laser after that time.

3. ROLE OF PERSONNEL

Investigator Managers: **CI d'Orgeville** will lead the Semiconductor Laser project on behalf of the LIEF partnership. She will negotiate final contractual arrangements with Areté Associates, manage the laser development contract, ensure delivery of a laser system that conforms to the user requirements defined at the beginning of the project, and lead all on-sky laser operations. **CI Lambert** will define the laser specifications as they relate to use in space surveillance applications, attend design reviews and acceptance testing, and participate in all on-sky laser runs to derive LGS photon return and sodium column density variations. **PI Ryder** will oversee aspects of this project to do with scientific use of LGS AO on the AAT and on international 8-10m class telescopes. **PI Bouchez** will assist in the development of the laser technical requirements for ELTs, and focus on issues of reliability and ease of operability during on-sky testing of the laser system. **PI Gao** will actively engage in laser technology R&D with Areté Associates staff, particularly in the area of laser frequency locking where he has significant prior experience. He will also be responsible for coordinating access to the EOS laser tracking station. **PI Mason** will characterise the performance and reliability of the Semiconductor Laser for use in a broad range of SSA applications.

Other Named Investigators: **CI Rigaut** will bring his unique experience in designing, integrating and operating AO with LGS to this project. He will also assist in planning and executing on-sky LGS AO operations. **CI Sharp**'s involvement ensures the necessary cross fertilisation of concepts between development of instrumentation for the GMT project and the specific requirements of the sodium laser system. **PI Goodwin** will work with CI Lambert to monitor the sodium photon return flux and, with CI Rigaut to model the predicted performance for the AAT. With CI Sharp and PI Ryder, he will investigate the feasibility and design of integrating the LGS device into an on-sky demonstrator or conceptual instrument for the AAT, and look at concepts of using multiple LGS to implement Multi-Object AO (MOAO) on existing telescopes.

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