PhD Research Proposal

Coherent optical free-space frequency dissemination

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A Project Summary

The stabilised distribution of reference frequencies is a vital tool in many areas of modern physics. These signals were traditionally transmitted through the use of microwave frequencies. Optical frequencies are now predominantly used in applications requiring high performance, due to their improved stability. Most of the work in this field has been focused on sending these signals through optical fibres. While these fibre links have excellent performance, there are some applications where laying an optical fibre is impossible. For this reason there has recently been research directed at transmitting these references over free space. So far these links have required highly sensitive and expensive equipment, or have only been demonstrated over short distances (less than 500m). The aim of this project is to develop systems capable of the stabilised coherent dissemination of frequency references over free-space laser links from ground to space using robust and affordable equipment. The turbulence expected in a link of this size is approximately equivalent to a 10 km horizontal link. This project will identify, model and overcome the challenges associated with creating these long free-space links.

B Research Project

The stabilised dissemination of reference frequencies is a vital requirement for many areas in modern physics, including radio astronomy, geodesy, Doppler ranging and tests of fundamental physics [1]–[6]. In the past decade, the stability of optical clocks has rapidly improved [7], which allows for improvements across these applications. However in order to utilise these ultra-stable optical clocks, the generated reference signal must be transmitted to a location of interest. Traditional microwaves techniques of disseminating these reference signals are unable to match the exceptional stability of these new optical clocks [6], [7]. This means that the performance of the frequency dissemination as a whole is severely limited by the distribution of the signal.

In order to overcome this issue, stabilised transmissions can be performed in the optical domain [6]. The higher carrier frequencies in the optical domain makes it easier to achieve high stability quickly [6]. The prevalence of optical fibres in the communications industry, as well as the many advantages in terms of power-loss and flexibility, has resulted in most optical reference frequency dissemination being performed over optical fibres.

Thermal, acoustic and mechanical fluctuations in the fibres introduce phase noise into the transmitted signal, thus degrading the quality of the reference [7]. This phase noise may be suppressed by a feedback loop. The system measures the error in phase or frequency that the link introduces and then uses an actuator on the Input/Output of the local terminal to pre-compensate for this effect. An underlying assumption here is that the forward and backward paths through the link are reciprocal, thus knowledge of the error on the return signal can be used to stabilise the forward pass of the link [8]. Fluctuations occurring at time scales less than the round trip time can not be compensated, as the stabilisation requires the return signal.

There are two main classes of actuation used for active stabilisation systems. The first is to directly operate on the group delay of the signal, for example using a fibre stretcher [9]. The second is to act on the frequency of the signal, such as with an Acousto-Optic Modulator (AOM) [10]. Ma et al. pioneered a technique which uses an unbalanced Michelson interferometer where the long arm travels over the link that is being stabilised and the short arm provides a local reference [10]. The signal from the long and short arm form a heterodyne beat which contains the error in frequency between the two. This error signal is then used to control the AOM and thus drive this error to zero.

The three common optical reference signals are direct continuous wave (CW) [11]–[14], modulated continuous wave [15]–[17] and the a frequency comb [18], [19]. For direct CW stabilisation the phase and frequency of the optical carrier are stabilised. For modulated CW stabilisation the phase and frequency of the modulation (typically a micro-wave or radio-wave) is stabilised. A frequency comb produces a signal consisting of many very narrow spectral lines which are all evenly spaced at a specific frequency offset [5]. These combs can be overlapped with an optical signal, and then a beat signal can be used to accurately determine the frequency of the optical signal [5]. However, the current size and complexity of the hardware required to produce these optical combs, make them inappropriate for some applications [8].

The stability of these clock signals are generally measured in fractional frequency (or "Allan Deviation") for a certain integration time (τ) [6]. This is the absolute frequency deviation divided by the carrier frequency when integrated over a certain amount of time (τ).

While there has been a lot of work into the stabilised distribution of references via fibre optics in the last decade [13]–[18], for applications such as ground-space clock comparisons, optical Doppler orbitography [4] the use of optical fibres is not possible. Optical ground-space clock comparisons could aid in the Atomic Clock Ensemble in Space (ACES) mission, which plans to send a cold atomic caesium clock and a hydrogen maser to the International Space Station [6].

Another interesting application not suited to the use of optical fibres is chronometric geodesy [5]. This involves the extremely accurate comparisons between a local clock and a remote clock for direct measurements of differences in gravitational potential at remote locations [5]. Modern day optical clocks are approaching fractional frequencies around 1×10^{-18} [5]. This stability would be enough to detect the changes in time corresponding to the gravitational potential difference variation between clocks that have a 1 cm height difference [5]. For this technique to be useful for geodetic purposes, it would require the remote clock be moved spatially to sample the gravitational potential at different locations. It is thus not feasible to to run a fibre to each of these locations.

For these applications, free-space optical links must be used. Free space links deliver advantages in terms of cost, versatility and flexibility [19]. There are however some major challenges associated with free-space transfer.

Atmospheric turbulence causes spatial and temporal variations in the refractive index of the atmosphere [8]. These in turn effect the propagation of the optical beam. Piston-action atmospheric fluctuations result in longitudinal delay variations, and thus added phase noise [8]. This has a similar effect on the reference signal as thermal, acoustic and mechanical fluctuations in an optical fibre. Thus the phase noise can be removed using a system like those that have already shown so much success at performing the same function for fibre-optic links. Our research group recently published a paper demonstrating this over a 500 m link [8]. In the opening months of this PhD project we managed to extend this to 2 km. Previous studies suggest a 5 km link is subject to similar amounts of longitudinal phase variations as a ground to satellite link [3]. Our 2 km stabilised link is an important step towards the realisation of ground to space frequency transfer.

Atmospheric turbulence can also effect the spatial profile of the beam. A first order effect is causing the beam to deviate its path. A gradient across the optical path will result in the beam being deflected laterally [20]. This is referred to as beam wander. As the beam wanders, it may move off the far terminal thus resulting in a loss of signal [21]. Beam wander can be corrected using tip-tilt control. Tip-tilt control uses a mirror in the optical terminal to automatically alter the pointing of the outgoing or incoming beam by small amounts in order to keep the beam centred [22].

A second order effect is variations in the wave-front of the beam caused by small scale variations in the atmosphere. This causes scintillation which can cause amplitude modulations of the incoming beam [3]. Scintillation effects can be corrected using Adaptive Optics, which distort the wave-front of the outgoing beam so that in the far-field the variations are removed [23]. Djerroud et al. suggests that for applications, such as the distribution of clocks (where the phase stability is of paramount importance), amplitude variations are acceptable [3]. Thus a simple tip-tilt control system to ensure consistent alignment of the beam may be sufficient [22].

Another challenge associated with free-space transfer is that sufficiently accurate pointing is required in order to physically hit the target. This is exceedingly difficult when the exact location of the remote terminal is not known precisely or when the terminals are moving. This becomes more difficult when there is an object that is moving rapidly. This is the case for orbital bodies. The outgoing beam must be aimed ahead of the object to account for the signal time of flight. The incoming beam will be from a point further back in it's path. Beyond making it more difficult in terms of pointing accuracy, this also means that the forward and reverse paths pass through slightly different parts of the atmosphere [22]. The closed loop phase stabilisation techniques mentioned above work under the assumption that the link is reciprocal. This point ahead effect makes the link less reciprocal and thus reduces the effectiveness of the phase stabilisation methods [22]. There is simulation based research to suggest that the link is still sufficiently reciprocal to allow for stabilisation down to fractional frequencies at the level of 2×10^{-17} [22].

This project will aim to overcome the issues associated with the free-space optical communication in order to develop a system capable of transmitting highly stable coherent reference signals over distances with turbulence equivalent to a ground to space link. This system would advance what is currently possible in free-space optics and be extremely significant in many areas of modern physics.

B.1 Related Work

While there are many research groups looking into stabilised optical reference signal dissemination using fibres, there are far fewer research groups looking at the use of free space laser links. I will outline the work of the three research groups with the most similar objectives.

The first research group is SYstèmes de Référence Temps Espace (SYRTE) at Observatoire de Paris. They have been looking into the possibility of coherent ground to space bi-directional optical transfers for use in Doppler orbitography or ground-space clock comparisons. In 2009 they created a 5 km optical link through turbulence and measured the uncompensated stability [3]. They concluded that according to their uncompensated results, the use of long distance free space optical transfers would be viable for use in Doppler ranging and frequency transfer. In 2013 they described an experimental realisation of a system that could potentially be used for Doppler orbitography [4]. This system had good stability (at a few parts in 10^{-14}) and was able to perform well controlled frequency sweeps of $\pm$12GHz. The large dynamic frequency is required when performing Doppler orbitography. This system did not however account for the effects of atmospheric turbulence and was unable to hit any celestial targets. In 2016 they simulated the effect that the turbulent atmosphere would have on a ground to satellite two-way coherent optical link [22]. They concluded that tip-tilt control would be mandatory, and that the stability could exceed 2×10^{-17}. In 2017 they released a paper that simulated how current geodetic mapping could be improved through the use of accurate atomic clock comparisons [24]. This is referred to as chronometric geodesy, and is a promising application for coherent optical free-space links.

The second research group is out of the National Institute of Standards and Technology (NIST) in the USA. This group developed a technique that can perform time-frequency transfer through the two-way exchange of frequency combs, each locked to a local oscillator [25]. In this case the optical link is not coherent. They dubbed this technique Optical Two-Way Time-Frequency Transfer (OTWTFT). This system has proven very successful, and they have managed to demonstrate a stabilised transfer of a 12 km horizontal link [18]. Our coherent system is fundamentally different to this technique, and requires far less expensive or complex infrastructure.

The third research group is a far smaller, but more closely related research effort based at the University of Electronic Science and Technology of China. This group has been attempting to perform the stabilised transfer of microwave [26] and radiowave [27] modulation on a coherent optical carrier. They use a phase shifter for their actuation and have demonstrated reasonable results (10^{-13} to 10^{-12} at 1s of integration) over 100m. While it is worth mentioning this group, our preliminary results have shown equal or better performance over six times the distance.

B.2 Research problem

The goal of this PhD is to develop world first systems capable of the stabilised coherent dissemination of frequency references from ground to space using robust and affordable equipment. The turbulence expected in a link of this size is equivalent to a 10 km horizontal link. The following challenges associated with free-space optical frequency transfer will have to be addressed:

1. Spatial variations in the beam (beam wander and scintillation) caused by turbulence
2. Longitudinal phase variations caused by turbulence
3. System power loss caused by beam divergence, fibre coupling, etc.
4. The high degree of pointing accuracy required

B.3 Methods and direction

The challenges identified above are exacerbated when the transmission distance is increased. Work into solving these challenges will be conducted at progressively longer distances up to our target maximum distance of 10 km. Progress at short distances will inform the techniques used at the longer distances.

An additional degree of complexity is associated with the nature of the signal being transmitted. The signals of interested are defined below in order of increasing complexity. Success in transmission of the simple signals will inform techniques used at the more complicated.

1. Continuous wave optical (193 THz)
2. Microwave modulated optical (193 THz + 8 GHz)
3. Data modulated system (193 THz + Data)

For each of these signals, the four challenges identified in Section B.2 will have to be addressed. Specific experiments to be completed are identified in Section C.10.

C Research Project Details

C.1 Confidential and sensitive information

There is no foreseeable issue regarding any confidential or sensitive information.

C.2 Intellectual property

There is no foreseeable issue regarding intellectual property. The standard regulations regarding PhD intellectual property at the University of Western Australia will be sufficient.

C.3 Fieldwork

There is likely to be fieldwork in this project at the Yarragadee Geodetic Observatory. I am aware of the UWA travel policy, student travel insurance policy and fieldwork procedures. There is no foreseeable issue regarding obtaining permission from the facility. As it is within Australia there is no visa requirements.

C.4 Facilities

All facilities required for this research are currently present at UWA within the ICRAR or EQUS groups and are available for my use.

C.5 Statistical component

Only minor statistical work will be required for this research (eg, regarding the calculations of the Allan Deviation). The UWA EQUS group has macros implemented in the science analysis software *Igor Pro* which they have used been using for a number of years that I am now experienced with.

C.6 Skills audit

Skill	**Personal Rating**				**Evidence**
	None	Basic	Competent	Proficient	
Understanding and application of relevant data collection and analysis methods			✓		During the opening months of this project I have gained experience in obtaining, processing and analysing the data that I will be relying on for the remainder of my PhD. This has included the use of *Igor Pro* macros produced within the EQUS group, and custom Python based programs I developed.

Skill	**Personal Rating**				**Evidence**
	None	Basic	Competent	Proficient	
Identifying and accessing appropriate bibliographic resources				✓	During my Masters of Professional Engineering I received extensive experience in utilising the reference resources that UWA provide. In the opening months of this PhD I have obtained a large amount of relevant material and also attended a HDR Library induction session.
Use of information technology relevant for the research				✓	During my Masters of Professional Engineering I received extensive experience in various relevant information technologies (such as Mendeley, LaTeX, Excel, MATLAB, Python).
Familiar with the principles and conventions of academic writing			✓		I obtained a basic understanding of academic writing in my Masters. I also wrote a paper for an international conference which gave me experience in the process of getting work peer reviewed and published. I have also attended a GRS Journal Paper workshop, which gave me additional information about the processes involved with writing and publishing a journal paper.

Skill	Personal Rating				Evidence
	None	Basic	Competent	Proficient	
Ability to constructively defend research outcomes at seminars and conferences		✓			I have some experience in presenting and defending my own research through masters. I will gain experience in this area throughout my PhD.
Operation of equipment for this project			✓		I have experience working with most of the equipment I will require. My supervisor will aid with additional equipment.

C.7 Research project communication

I am aiming to produce 4 journal articles throughout the course of my research. My final thesis will be formatted as a series of papers.

Communication type	Planned Journal	Estimated submission date	Subject
Journal paper	Journal of Geodesy	March 2019	Optical Doppler Orbitography
Journal paper	Physical Review Applied	September 2019	Coherent transmission of microwave modulated optical carrier
Journal paper	Optics Letters	May 2020	Demonstration of pointing and tip-tilt control system
Journal paper	Nature Photonics	March 2021	Demonstration of robust optical reference dissemination system over ground-space equivalent distance

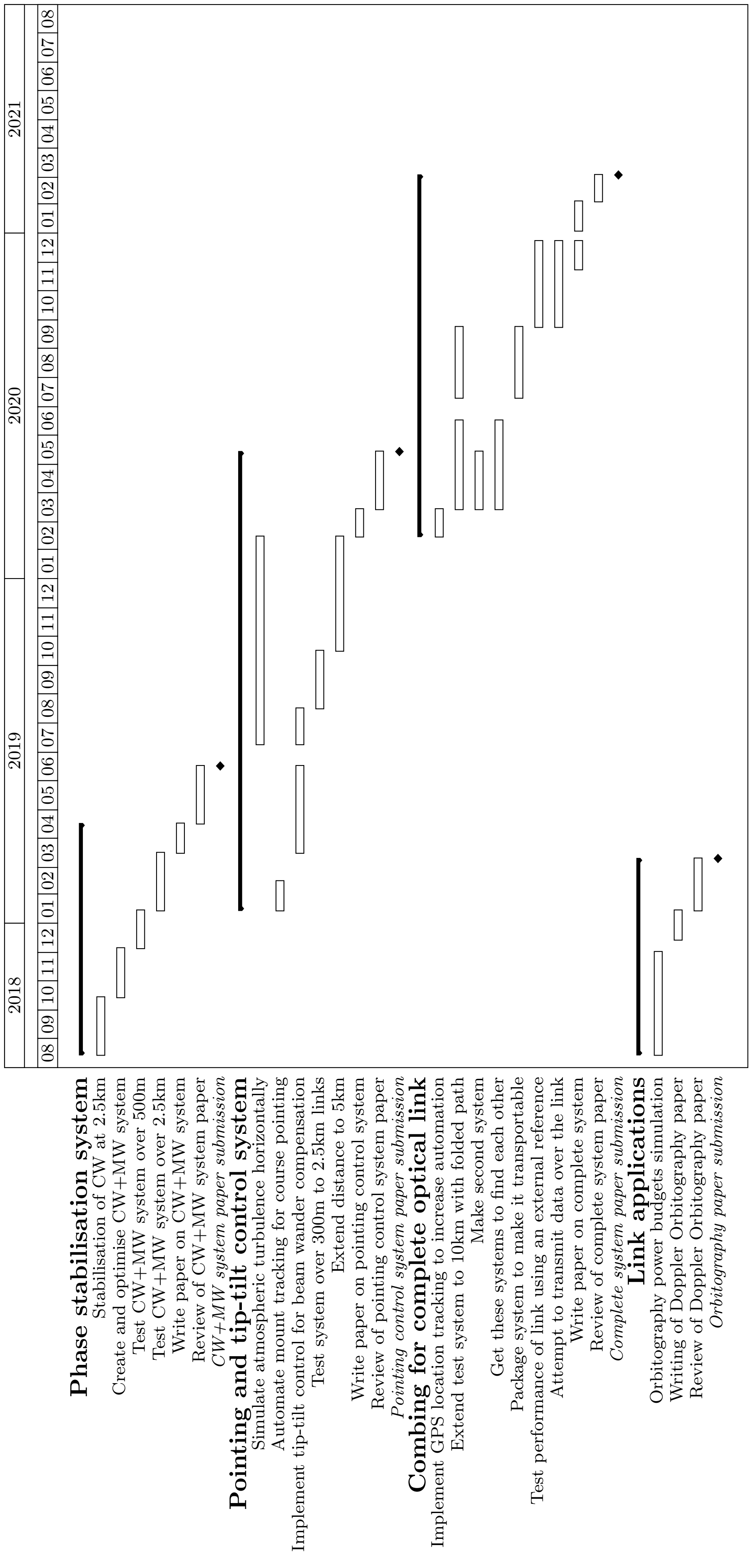
C.8 Approvals

No special approvals are required for this research.

C.9 Data management

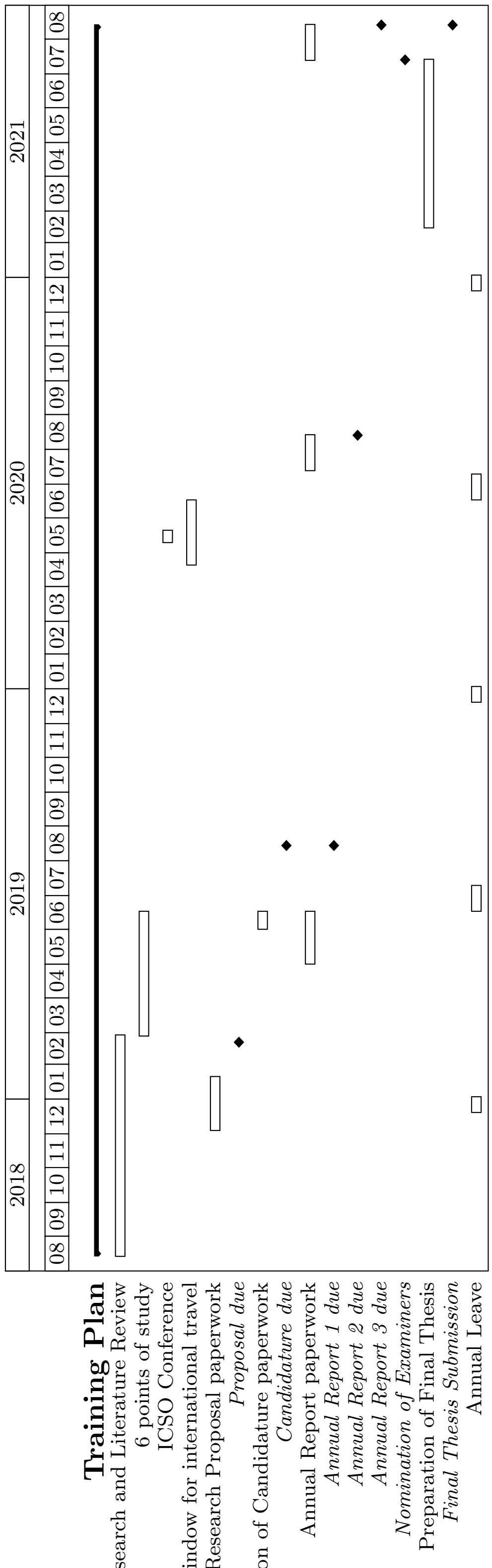
The UWA Astrophotonics group in ICRAR has a shared online drive. Lab data will be stored in this drive and on the Lab data acquisition computer. Personal documents will be stored on my student drive and my university computer.

C.10 Research project plan



D Research Training

D.1 Research Training Plan



D.2 Confirmation of Candidature

Designated Task	Proposed completion date
AACE1000 (Essential Unit)	Completed in undergraduate studies
Research proposal approval	February 2019
Substantial piece of writing: Draft of Optical Doppler Orbitography paper	March 2019
6 credit points of coursework	June 2019
Presentation to ICRAR on proposed research	February 2019
HDR library induction session	September 2018
Laser safety course	February 2019
Workshop safety course	February 2019

D.3 Working Hours

Work will be conducted from 9am - 5pm from Monday to Friday.

E Budget

Description	Year cost incurred			Source
	Year 1	Year 2	Year 3	
Administrative costs				
New Student Computer	$1250			ECM Faculty
Office space				ICRAR (inkind)
Printing, desk supplies, etc.	$100	$100	$100	ICRAR
Printing and binding of thesis			$200	ICRAR
Research costs				
Various lab consumables	$1000	$1000	$1000	Supervisor's PG
Training costs				
Laser safety training	$50			Supervisor's PG
Travel costs				
ICRAR Radio School Registration	$300			ICRAR
ICRAR Radio School Accom, food and travel	$500			Supervisor's PG
AIP Conference	$500			Supervisor's PG
Yarragadee field work		$650	$700	ICRAR
International Conference on Space Optics (ICSO)		$1850		UWA Graduate Research School
ICSO additional costs		$1000		ICRAR
Sub-totals	$3700	$4700	$2000	
			ECM Faculty Total:	$1250
			ICRAR Total:	$3250
			UWA Graduate Research School:	$1850
			Supervisor's PG:	$4050
			TOTAL:	**$10400**

F Supervision

Coordinating supervisor: Prof. Sascha W. Schediwy (70%)

Dr Schediwy is an expert in ultra-stable frequency transfer over optical fibre and leads the development of the SKA's frequency synchronisation system. As coordinating and primary supervisor, Dr Schediwy will be the key correspondent for the Graduate Research School. Dr Schediwy will be responsible for ensuring that administration and reporting requirements are met. Dr Schediwy will be available to provide assistance to the project at weekly meetings, and will often be available in the lab during the week. Dr Schediwy will review thesis chapters and the final thesis draft.

Co-supervisor supervisor: Prof. Michael E. Tobar (15%)

Prof. Tobar is the director of the Frequency and Quantum Metrology Research Group, and has published over 200 refereed journal publications. He is the UWA Node Manager of the 2014 and 2017 ARC-funded Centre of Excellence for Engineered Quantum Systems (EQuS). As co-supervisor supervisor, Prof. Tobar will provide a key link to the frequency metrology applications associated with this project as well as a link to the ARC Centre of Excellence for Engineered Quantum Systems (EQUS). Prof. Tobar will be available at weekly meetings where progress will be discussed. Prof. Tobar will review thesis chapters and the final thesis draft.

Co-supervisor supervisor: Prof. Simon Driver (15%)

Prof. Simon Driver leads the Multi-Wavelength science program at ICRAR and has over 175 publications. As co-supervisor supervisor, Prof. Driver will provide insight into potential applications of the project in the astrophysics field and will be a key link to ICRAR. Prof. Simon Driver will review thesis chapters and the final thesis draft.

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