PhD Proposal: Coherent Free Space Optical Communications

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A Project Summary

Free-space optical (FSO) communications between ground and space promises to overcome challenges facing contemporary free space radio frequency (RF) communications including bandwidth limitations, spectrum crowding, transmitter size, and probability of interception. Owing to these benefits, development of FSO communication technologies will significantly aid future human space exploration. A major limitation, however, is the significant phase and amplitude noise incurred when unguided optical signals propagate through the Earth's turbulent atmosphere. The Astrophotonics group at The University of Western Australia (UWA) develops atmospheric stabilisation systems to suppress such noise, aiming to provide fibre-like data rates between the Earth and satellites in orbit.

My proposed PhD project will contribute to the group's body of work by investigating phase stabilisation in communication systems and developing hardware for an amplitude stabilisation system. Metrology-style phase stabilisation systems in communications have been demonstrated in only one published article, and no investigation into potential use cases has been published. I will demonstrate phase and amplitude stabilised high-speed FSO communications over challenging horizontal and vertical laser links, in a series of likely firsts for Australia, and therefore novel outcomes in demonstrating FSO communications capability in the Southern Hemisphere.

B Research Project

B.1 Motivation and Background

FSO communications links, utilising lasers as optical frequency carriers for data, pose physical advantages over comparatively lower frequency RF links for terrestrial and space-based communications [1]. These advantages may be readily exploited by established practices in communications engineering. Transmission between ground and space is made possible with atmospheric stabilisation systems, deployed on mobile optical terminals or on an optical ground station (OGS).

Advantage 1: Bandwidth

Fundamentally, optical frequencies offer more bandwidth than RF frequencies because more oscillations occur in a given time interval, so opportunities to transmit information-carrying symbols are more frequent. Increasing bandwidth between space and ground is motivated by both commercial and public interest. Case in point, space-to-ground communication capability is useful to disseminating high resolution Earth observation data, an industry from which Australia receives significant economic value [2].

*supported by the SmartSat Cooperative Research Centre and the International Centre for Radio Astronomy Research, UWA

Advantage 2: Beam Divergence

Furthermore, at the hundreds of terrahertz, optical beam divergence is extremely narrow, resulting in lower geometric losses compared to RF communications and easing size requirements on transmitter apertures, and therefore total payload size. This property makes FSO communications well-suited for the predicted future trend, in Australia, of constellations of small satellites launched more frequently [2]. The limited divergence is also of interest as a security feature, reducing the probability of intercept from the ground for secure transmissions. Of note are FSO communications terminals for horizontal links intended for secure point-to-point connection between sites when it is inconvenient or impossible to install fibre optic cable, such as ship-to-shore maritime communication.

Communications Background

Communication between a transmitter and receiver can be classified as involving *direct detection*, with a single oscillator at the transmitter site, or *coherent detection*, with phase-locked oscillators at both the transmitter and receiver sites [3]. In direct detection, a transmitter is limited to modulating only phase or amplitude, therefore only having one degree of freedom to encode information.

Direct detection, in the form of pulse-position modulation (PPM), is the current recommended physical standard for FSO communications systems by the Consultative Committee for Space Data Systems (CCSDS) on the basis of its high photon efficiency [4]. The PPM format is seeing use in deep space communications such as the upcoming NASA Artemis mission [5]. UWA has research funding to demonstrate PPM capability over free-space in order to support the NASA Artemis mission.

Coherent detection, on the other hand, is based on coherent reception of the transmitted signal with a local oscillator (LO) at the receiver, providing frequency and spatial selectivity, as well as measuring both phase and amplitude [6]. This means a coherent detection scheme can reject background light and encode information in at least two degrees of freedom, phase and amplitude, with the possibility of adding additional data channels in orthogonal polarisations or spatial modes, therefore offering much higher potential data rates than direct detection schemes. This comes at the cost of additional complexity.

Experimental coherent communication standards are available from the CCSDS and indicate a future industrial shift to coherent modulation techniques for space-ground and inter-satellite communication [7]. Coherent communication is the primary focus of UWA's activities with the SmartSat Cooperative Research Centre (SmartSat CRC).

Atmospheric Noise and Stabilisation

At optical frequencies, turbulence in the Earth's atmosphere poses challenges to FSO communications for both horizontal and vertical links of all appreciable distances. Temperature and humidity variation in the atmosphere disturb the optical beam from a straight path, leading to path length (zeroth order) changes and angular (first order) deviations.

Zeroth order movement of the atmosphere adds phase noise to an optical carrier, effectively increasing its linewidth, and is a hindrance to coherent FSO communications in particular. First order deviations steer optical beams off-target, reducing the signal-to-noise ratio (SNR) and causing complete loss of signal when the beam is steered off the receiver.

In links with high enough turbulence, the turbulent "cells" of the atmosphere are spatially comparable to the propagating beam's wavefront and can excite the ideally Gaussian wavefront shape into a random linear combination of higher order modes in a process known as scintillation. Scintillation is an issue because transmit and receive devices in FSO communications are often fibre-coupled at the end-points with single mode fibre (SMF) that only accepts single Gaussian modes. Therefore, scintillation further reduces SNR because light excited into higher order modes is discarded when coupling from free space back into fibre. SNR degradation due to angular disturbances and scintillation are collectively referred to as amplitude noise.

Measurement and stabilisation of these deleterious effects is an enabling technology for FSO communications and the Astrophotonics group is a world leader in atmospheric stabilisation systems to suppress phase noise and amplitude noise. The deployment of combined phase and ampli-

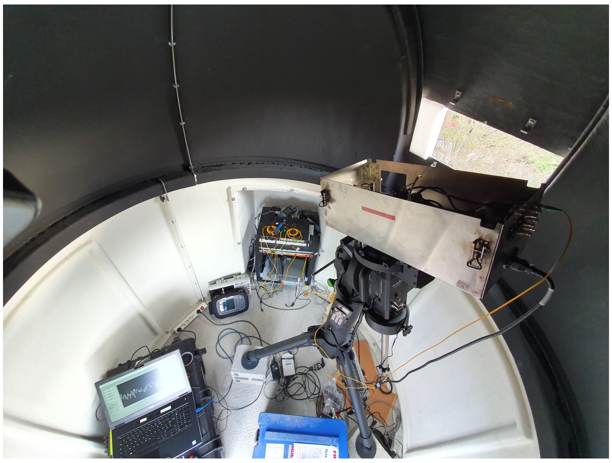


Figure 1: First-generation amplitude stabilisation system and phase stabilisation system inside an observatory dome in Toulouse, France

tude stabilisation is highly novel, with only one or two other research groups publishing research describing similar systems [8, 9].

Atmospheric phase-noise suppression involves closed loop feedback control to a fiberised actuator, before the optical beam is launched into free space. The Astrophotonics group has deployed both group delay and Doppler actuation to suppress phase noise in fibre and in free space to disseminate highly coherent timing signals for frequency metrology, holding a world record in FSO frequency transfer [10, 11]. Of relevance to FSO communications, such a system has been demonstrated to be able to suppress atmospheric phase noise across the entire 1550 nm optical C band, using a single pilot beam [1]. This system has also been utilised in folded and point-to-point timing links in parallel with a first-order angular stabilisation system, based on a fast-steering mirror (FSM) [10, 11].

Mobile Optical Terminals

These experimental campaigns required field-deployable mobile optical terminals, such as the terminal shown in Figure 1, containing sensors and actuators such as a quadrant photodetector (QPD) and FSM. Mobile optical terminals will continue to be necessary in the future in order to provide spatial diversity, especially in locations with non-ideal weather for optical transmission, and are therefore an ongoing area of research and development for industry and space agencies such as the German space agency, DLR [12]. Being field-deployable, mobile optical terminals are also applicable to point-to-point terrestrial communication.

Optical Ground Stations

Fixed OGS installations are planned as the primary backbone of FSO communications networks because permanent installations are likely to have the infrastructure required for high-speed communications, and also the specialised optical components required for deep space communications. UWA is currently in the process of commissioning an OGS on-campus, based on the 0.7 m modified Dall-Kirkham telescope shown in Figure 2.

Other Applications

Additionally, the phase coherence of optical carriers is a useful characteristic for other satellite-based techniques including highly precise geodesy measurements [13], optical phased arrays for satellite de-orbiting [14], and emerging continuously-variable and twin-field quantum key distribution technology [15, 16]. UWA's phase and amplitude stabilisation technology therefore also bears relevance to these fields of study.

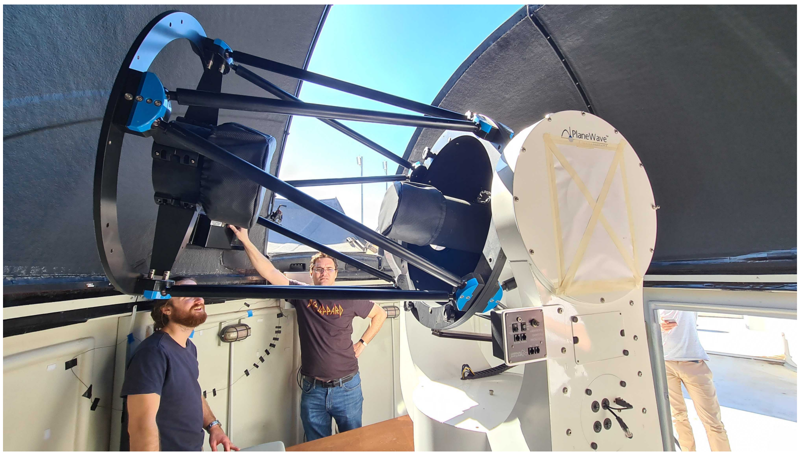


Figure 2: Modified Dall-Kirkham telescope for optical ground station installed within an observatory dome on campus in Perth, Western Australia

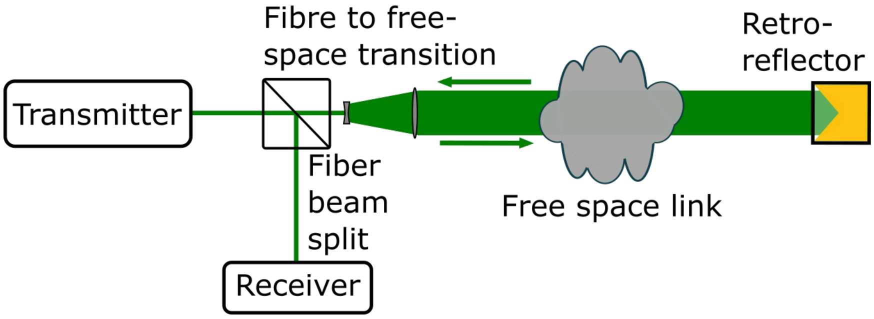


Figure 3: Generic representation of a monostatic laser range for loopback communications testing

B.2 Methodology

The following tasks have been identified as addressing or adding to the state-of-the-art outlined above, with each task intended to demonstrate some novel outcome. The project is primarily demonstration-based, and therefore uses mostly experimental methods common in frequency metrology and communications engineering. Mathematical modelling and digital system development will supplement the experimental work, particularly where a lack of in-house capability has been identified.

Resources available at UWA include optics and electronics laboratories and free-space laser ranges. Both laboratories are equipped with fibre and free-space optical hardware shared between both facilities. For demonstrating coherent communications, a fibre-based digital coherent optics (DCO) module has been procured. Such modules utilise phase, amplitude and polarisation to encode data at rates in the hundreds of gigabits per wavelength, and form the backbone of long-haul terrestrial internet.

The laser ranges used in this project are best described as monostatic, with the transmitter and receiver components co-located, and the range embodied in a folded link with a retroreflector at the midway point, as illustrated in Figure 3. Co-locating the transmitter and receiver hardware in the experiments means the same laser can be used as signal carrier and receiver LO, reducing an element of complexity.

PhD Task 1: NASA Artemis Communications

The Astrophotonics group has received a Moon to Mars Initiative Demonstrator Feasibility Grant (M2M) from the Australian Space Agency (ASA) to establish optical communications support for the upcoming NASA Artemis mission. I will design a surrogate communications system based on the NASA software-defined radio (SDR) [17] to be deployed in a monostatic (Figure 3) vertical link arrangement over the UWA OGS, such as shown in Figure 4. This task will comprise optical transmitter design, digital firmware development, and offline processing using a commercial off-the-shelf (COTS) data acquisition device. The novelty of this work is contingent on UWA's current status hosting the first OGS on-sky in the Southern Hemisphere, and therefore likely being the first institute in the Southern Hemisphere to demonstrate capability to support Artemis.

PhD Task 2: CRC Milestone 2

The SmartSat CRC Milestone 2 (due before CRC Milestone 1) is to demonstrate coherent FSO communications over a 1 km vertical link, again using the UWA OGS as in Figure 4. Towards this goal I will be responsible for commissioning the DCO module and adapting it for use on the ground station telescope, in parallel with the acquisition and tracking optics developed by my colleagues.

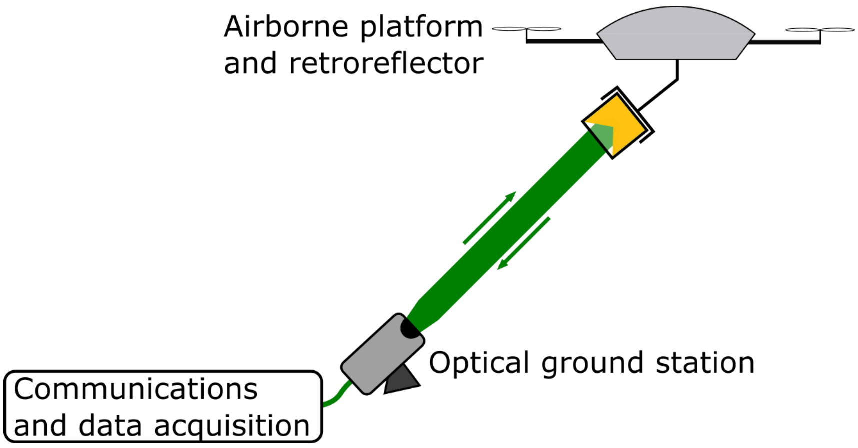


Figure 4: Schematic representation of a monostatic vertical free-space optical communications link using an optical ground station and airborne retroreflector

PhD Task 3: CRC Milestone 1

SmartSat CRC Milestone 1 is to demonstrate coherent FSO communications over a 10 km horizontal laser range. At this distance, this path is theorised to exhibit integrated atmospheric turbulence exceeding, the turbulence of a worst-case ground-to-space link [8]. It is the experience of the group, that a shorter 2 km link can exhibit equivalent turbulence to a ground-to-space segment [11, 18], and establishing a carrier-only link over 10 km has proved challenging for the current experimental setup, involving independent control over two mechanical degrees of freedom (x and y axes of a FSM). I have been undertaking skills development with digital system design with a view to consolidating control of various actuators in the optical assembly into one digital controller, such as embodied in Figure 5. At the same time, analytical work is being carried out by my colleagues to characterise the dynamics of this long distance monostatic arrangement. I intend for this analytical modelling to feed back into the controller design in order to exploit the optical design's maximum potential.

Data collected through this task may yield novel results by quantifying the capability of first-order stabilisation in the far field, with a retroreflector.

PhD Task 4: Photonic Lantern

In FSO communications, high-order amplitude stabilisation, in order to mitigate scintillation effects, is carried out using adaptive optics (AO), a technique involving a wavefront sensor and deformable mirror with many micro-mechanical actuators for feedback stabilisation of the incoming wavefront [19]. AO systems are used in optical astronomy to correct images and for signal gain in spectroscopy, on instruments placed at high altitudes above the majority of atmospheric turbulence. Mode-converting photonic devices have emerged recently as alternatives to AO for single-pixel applications including spectroscopy [20] and FSO communications [21]. These devices convert a scintillated wavefront composed of many modes into several first-order mode outputs suitable for conventional single mode fibre, as shown in Figure 6. This technology dovetails conveniently with spatial diversity techniques proposed for ground stations composed of spatially-separated optical terminals [22, 23, 24]. Digitally combining the outputs of a free-space-based mode-converting device was demonstrated by DLR in conjunction with the company, Cailabs, in 2020 [21]. However, all-fibre photonic lanterns, developed at The University of Sydney [25], may be a significantly cheaper alternative to the Cailabs product. Lab benchtop-scale free-space demonstrations of photonic lanterns for coherent optical communications have indicated the usefulness of this technology for high-order amplitude stabilisation [26, 27], and I propose to continue on this work by demonstrating this technology over either the 10 km horizontal link, or vertical laser range.

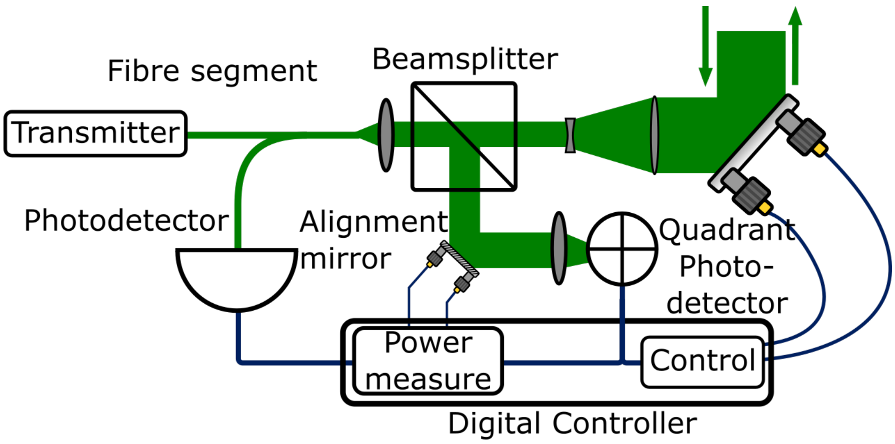


Figure 5: Schematic representation of a first-order amplitude stabilisation system with consolidated digital control of x and y axes and axial alignment of fibre and free-space segments

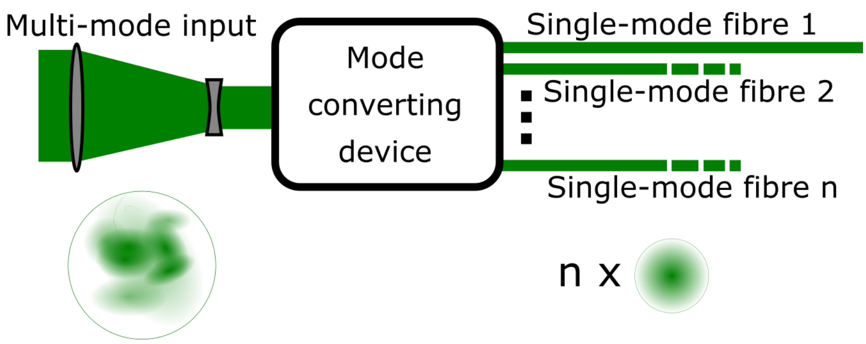


Figure 6: Representation of n Gaussian outputs extracted from a mode-converting photonic device, with a scintillated multi-mode input wavefront

PhD Task 5: Phase Stabilisation

An open research question in UWA's SmartSat CRC project is the applicability of phase stabilisation to enhance coherent FSO communications. This approach may be described as bottom-up in seeking a need for a specific technology, rather than a technology to satisfy a need. The outcome of this task therefore, is to use numerical modelling to determine a realistic use-case for phase stabilisation in communications, as a follow-up to earlier work from the group [1]. Currently is it believed phase stabilisation will be most applicable to ground-to-space or space-to-ground links in which the power budget is tight and low, albeit reliable, data throughput (e.g. on the order of tens of Mb/s) is desired.

On UWA's 2 km horizontal free-space range, a DCO has shown no noticeable improvement when operated in parallel with the phase stabilisation system. This is attributed to the effectiveness of phase recovery algorithms carried out inside the digital signal processors inside the DCO. The correction bandwidth of such algorithms are typically related to the symbol rate of the modems [28] and as such the DCO signalling at 28 GS/s is insensitive to the comparatively slower phase fluctuations of the atmosphere. A caveat to this is that the effectiveness of phase recovery is degraded at low SNR [29], and therefore more sensitive to phase noise when the power budget is tight. For space-to-ground links, the receiver amplitude sensitivity is crucial because of the distances involved and geometric power losses incurred, as well as practical limitations to stored energy available on a satellite for digital signal processing and transmission. For example, transmitting and receiving with 10 cm optics along a 500 km path to LEO will incur a maximum 58 dB one-way loss at 60° off the zenith. Our DCO specifies a minimum -18 dBm of received power, requiring an impractically high 40 dBm transmit power or amplification at the receiver, after the signal has already been exposed to significant amplitude noise, further degrading SNR.

For completeness, in this task I will consider and model a variety of potential applicable technologies and scenarios. For example, beyond digital phase recovery, analog phase-locking techniques for coherent communications are known [30] and may suit low SNR scenarios and therefore also benefit from phase stabilisation.

PhD Task 6: CRC Milestone 3

Optical transmissions between Earth and a satellite in Low Earth Orbit (LEO) are predicted to exhibit a high rate-of-change Doppler frequency shift on the order of 18-28 GHz. This Doppler shift is a relevant limitation to the applicability of COTS networking fibre-based communication equipment to LEO satellite communications, as these devices were not designed to track high-rate frequency sweeps.

The objective of CRC Milestone 3 is to establish a coherent carrier link to an moving, high altitude (>5 km) airborne platform as a stepping stone towards Doppler shift compensation. The platform will pass over an OGS so as to the angular velocity of a satellite pass, but with a relatively smaller Doppler shift due to the proportionally lower tangential velocity component. This demonstration will test our ability to compensate for Doppler shifts as well as track a fast-moving target. An altitude around 15 km, achievable with a light aircraft, would be comparable to previous FSO communications demonstrations by Facebook [31].

This milestone leads directly into the subsequent CRC Milestone 4, and, if successful, the pair are intended to form the basis of a research publication.

PhD Task 7: CRC Milestone 4

After a coherent link is successfully established during CRC Milestone 3, I will attempt to integrate the COTS DCO into the Doppler-compensating, target-tracking OGS, demonstrating high-altitude, high-speed FSO communications. This milestone will rely on the expertise and techniques gained from completing PhD tasks 2, 3, and 6.

In the event of an incompatibility between the DCO and Doppler compensation system, it is highly likely the outcome of PhD task 5 could apply to developing a more suitable SDR-style apparatus for completing this milestone.

Successful completion of this milestone along with CRC Milestone 3 will be a novel result, suitable for publication, as the high relative velocity and point-ahead angle, required, will extend on the most similar previous work [31].

Project Risks

The project comprises seven tasks with multiple overlapping delivery dates, particularly in 2022, introducing uncertainty in delivering the expected research outputs. The SmartSat CRC and NASA Artemis tasks (1-3, 6 and 7) have fixed end dates based on contractual agreements. The end dates of tasks 4 and 5 are not subject to contracts and, if necessary, can be delayed until the first or second quarters of 2023, when there are fewer concurrent activities. If the time involved in completing tasks 2 and 3 delay the start dates of tasks 4 and 5, the proposed timeline can therefore accommodate this delay. This comes at the cost of reduced time for thesis writing and compilation towards the end of the project.

B.3 Summary of Work Completed

Activity Description	**Associated PhD or Confirmation of Candidature Task(s)**
Background research into communications techniques and hardware. Through this I have become familiarised with the state of the art in optical communication and have been able to discuss concepts with collaborating subject matter experts.	All PhD tasks
Procure high data rate coherent communications modem. This device will be used for coherent communications demonstrations.	PhD tasks 2, 3, 7
Learning to use digital system design software to develop firmware for programmable real-time digital controllers.	PhD Tasks 3, 4, 5
Visit SmartSat CRC colleagues at the University of South Australia and Defence Science Technology Group for knowledge exchange.	Confirmation of candidature - written research proposal
Applied for and received Andy Thomas Space Foundation research award for an abridged version of my research proposal.	Confirmation of candidature - written research proposal
Enrolled in coursework unit ELEC4406 Digital System Design.	Confirmation of candidature - complete 6 points of study

C Research project Details

C.1 Intellectural property and confidentiality

The proposed project falls within UWA's work with the SmartSat CRC and therefore intellectual property obligations between the two entities are subject to the terms as outlined in the SmartSat CRC grant agreement.

C.2 Approvals

The Australia Communications and Media Authority (ACMA) regulates electromagnetic emissions up to and including the wavelengths including the 1550 nm C-band telecommunications wavelengths being used. In the course of this project, the Astrophotonics group will observe and comply with ACMA requirements and licensing fees for 1550 nm emissions. Similarly, for drone flight, and flights over 120 m altitude, the Civil Aviation and Standards Authority provides guidelines and exemptions to be observed during flights. The regulator also provides approval for laser emission into Australian airspace. UWA is also to provide approval for drone flight over university land. This drone flight approval has been previously obtained on multiple occasions.

C.3 Fieldwork

This project will involve experimental work using facilities on-campus at UWA. The facilities have safety controls in place, set up within the larger context of the Astrophotonics group's activities.

C.4 Research Outputs

The tasks detailed in **Section B** are intended to be communicated in a series of five journal papers, and three milestone reports for the SmartSat CRC. The thesis will be formatted from the collected journal papers, with expected submission dates and corresponding research tasks outlined in the table below. I anticipate the final journal paper to be *in preparation* when the thesis is submitted.

Communication Type	Planned Journal	Submission Date	Corresponding Task
Journal Paper	Optics Letters	Apr. 2022	Task 1
CRC Milestone Report	N/A	Apr. 2022	Task 2
Journal Paper	IEEE Communications Letters	Jun. 2022	Task 2
CRC Milestone Report	N/A	Sep. 2022	Task 3
Journal Paper	Nature Photonics	Jan. 2023	Task 4
Journal Paper	IEEE Transactions on Wireless Communications	May 2023	Task 5
CRC Milestone Report	N/A	Jul. 2023	Task 6
CRC Milestone Report	N/A	Mar. 2024	Task 7
Journal Paper	Journal of Lightwave Technology	Mar. 2024	Task 6 & 7

C.5 Data Management

Data collected in the course of this project will be stored on a cloud based service such as Microsoft OneDrive, provided by UWA. If required, the institutional research data store will be utilised for long term storage.

D Training and Development

D.1 Skills Audit

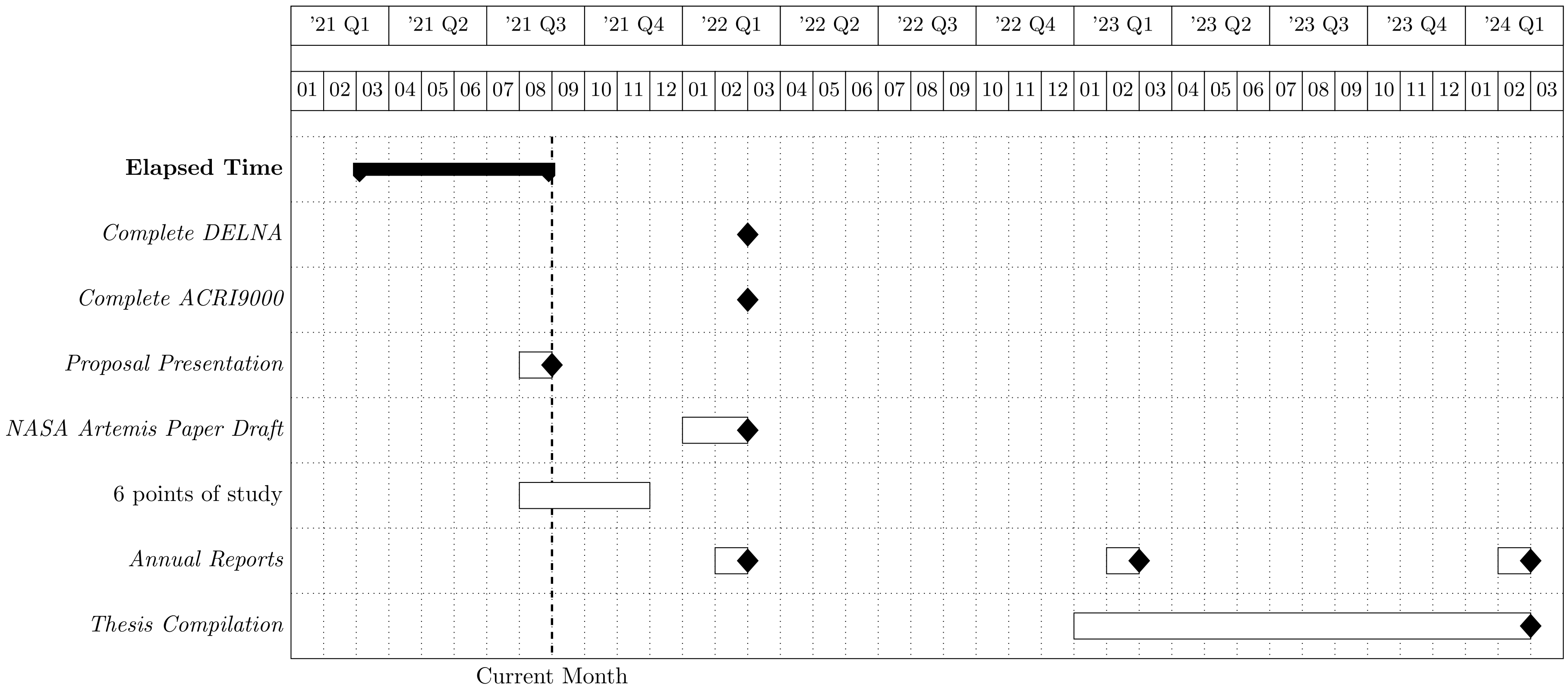
Skill	Personal Rating				Evidence
	None	Basic	Competent	Proficient	
Evaluate and synthesise existing disciplinary knowledge				✓	Ability to do this is the outcome of my engineering education, work experience, and mentorship from colleagues at advanced stages in their careers.
Collect, analyse and present data			✓		Practical assessment items throughout university have taught me this to some degree. I will be refining these skills during the course of this PhD project.
Relevant software applications				✓	Through university and work I have had wide and varied experiences using software for simulation, data analysis, drafting, and research communication.
Mentorship and sponsorship of others		✓			I have some limited experience tutoring and facilitating labs. In academic tradition, I should take up further opportunities to teach, to reinforce my science communication skills and understanding of subject matter fundamentals.
Industry engagement and marketing technology to private sector		✓			Through previous employment and extracurricular activities at university, I have had exposure to consumer products and manufacturing processes still under development.

Skill	Personal Rating				Evidence
	None	Basic	Competent	Proficient	
Academic writing and publication				✓	I published a journal article prior to commencing my PhD, with guidance from Dr's Schediwy and Gozzard. This was a immensely useful and practical learning experience in academic writing. Since then I have successfully applied for a cash prize from the Andy Thomas Space Foundation based on an abridged version of this written proposal.
Presentation skills including graphic content creation and public speaking			✓		In the course of writing a journal article, delivering presentations to Square Kilometre Array Organisation colleagues, and preparing my proposal seminar, I have had recent experiences preparing assets for graphical communication of my research. This is aided by the tried-and-tested inhouse graphical communication style developed by Dr Schediwy.

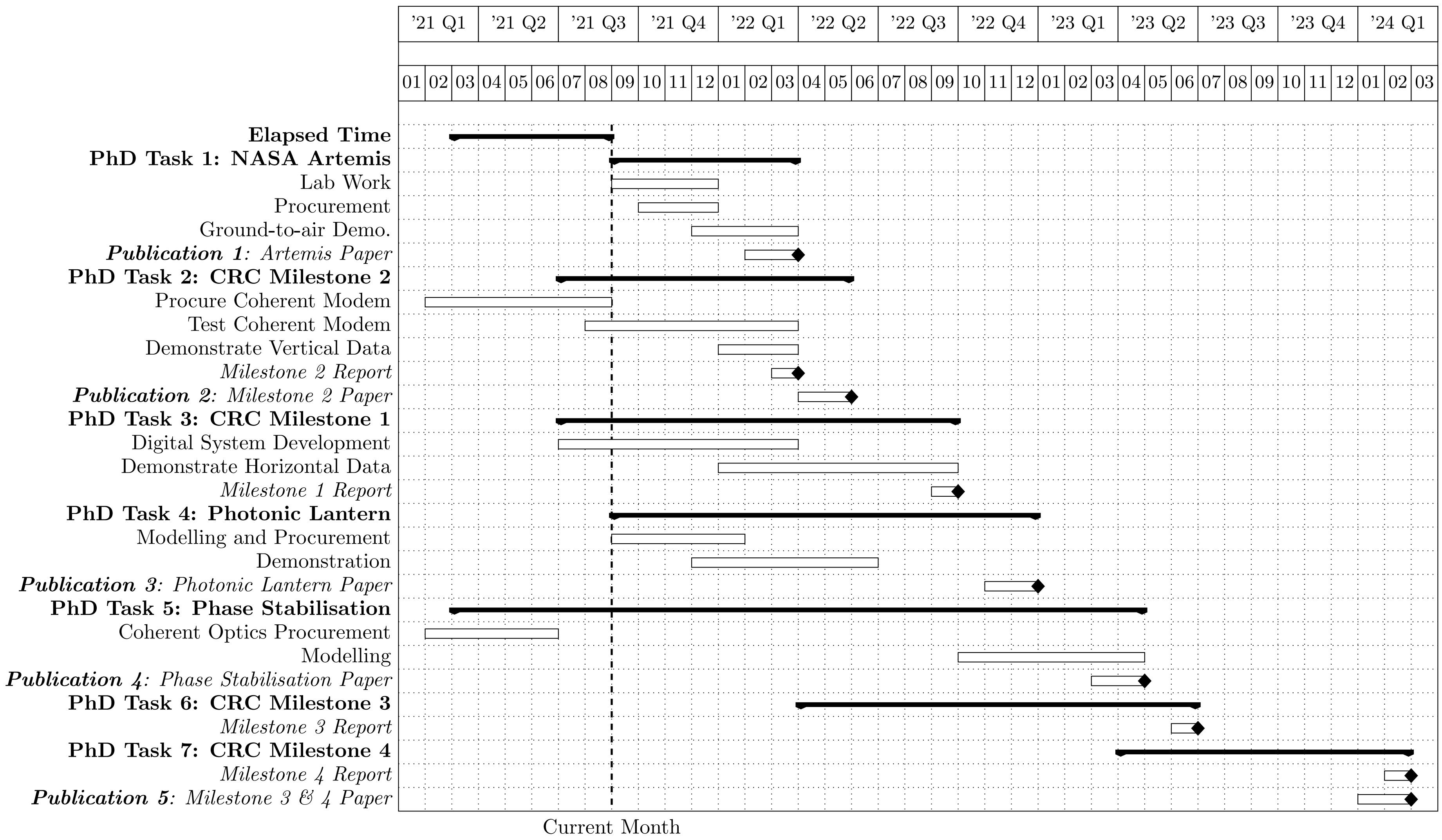
D.2 Confirmation of Candidature

Designated Task	Proposed Completion Date
DELNA	28 Feb. 2021 (temporarily unavailable online)
ACRI9000	28 Feb. 2021
Oral proposal presentation	17 Aug. 2021 (complete)
Research proposal approval	Aug-Sep. 2021
Substantial piece of writing: Draft of NASA Artemis communication paper	28 Feb. 2022
6 credit points of coursework: enrolled in ELEC4406	Nov. 2021
Laser safety in research course	23 Mar. 2021 (complete)
Workshop hand tool training	17 Jun. 2021 (complete)
Electronics lab and hot work (soldering) induction	2 Sep. 2019 (complete)

D.3 Research Training Plan



E Candidature Summary Plan



F Budget

Description	Year Cost Incurred			Source
	Year 1	Year 2	Year 3	
Administrative costs				
Student computer	$1200			UWA
Thesis printing and binding			$200	ICRAR
Research costs				
Lab equipment	$1000	$1000	$1000	Supervisor PG
Travel costs				
International Astronautical Congress			$1850	GRS
IAC additional costs			$1000	Supervisor PG
South Australia visit		$1000	$1000	ICRAR
Year sub-totals	$2200	$2000	$5050	
			UWA Contribution	$1200
			ICRAR Contribution	$2200
			Supervisor PG Contribution	$4000
			GRS Contribution	$1850
			Total	$9250

G Supervision

Coordinating supervisor: Prof. Sascha Schediwy (40%)

Dr Schediwy is an expert in highly-stable frequency transfer over optical fibre and free space, and leads the Astrophotonics group at UWA. He has been recognised as a leading space scientist in Australia and in 2021 won the Academic of the Year and Individual Excellence Award at Space Connect's Australian Space Awards event. As coordinating supervisor, Dr. Schediwy facilitates weekly research group meetings.

G.1 Co-supervisor: Dr. David Gozzard (40%)

Dr Gozzard is an expert in photonics for frequency transfer and optical phased arrays, and current Forrest Fellow. Dr Gozzard occasionally facilitates the weekly research group meetings.

G.2 Co-supervisor: Prof. Brett Nener (10%)

Dr Nener is a professor in the school of Electrical, Electronic and Computer Engineering at UWA. He is a subject matter expert in simulating atmospheric optical transmission. Dr Nener attends the monthly SmartSat CRC progress meetings.

G.3 External supervisor: Prof. Gottfried Lechner (10%) (University of South Australia)

Dr Lechner is a Research Professor in the Institute for Telecommunications Research at the University of South Australia, and Program Director for Advanced Communications, Connectivity and IOT in the SmartSat CRC. He is a subject matter expert in communications engineering. Dr Lechner attends the monthly SmartSat CRC progress meetings.

G.4 Industry supervisor: Michael Clark (Thales Australia)

Mr Clark is the Director of Technical Strategy at Thales Australia, and is the representative for Thales Australia in UWA's SmartSat CRC research project. Through his work at Thales, Mr Clark has extensive experience guiding the outputs from specialist research and development projects into marketable products. Additionally, as a representative of Thales Australia's interest, he is uniquely-placed to identify and point out which developments are aligned with the organisation's roadmap for FSO communications. Mr Clark attends the monthly SmartSat CRC progress meetings.

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