PhD Proposal: Mobile Optical Ground Stations for Free-Space Laser Links

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A Project Summary

In the modern era, the demand for faster, more efficient communications is inescapable. Wireless communications systems such as those found on aircraft, ships, terrestrial vehicles, and spacecraft, heavily rely on radio frequency (RF) technology. This technology, limited by its low frequency, directionality and strict bandwidth regulations, is now struggling to keep up with modern requirements. This is causing substantial limitations across a host of commercial, scientific and military applications.

The introduction of fibre optics revolutionised the wired communications industry. By harnessing optical frequencies it provided an unprecedented increase in wired data rates. By using lasers, Free-space optical (FSO) communication leverages the same optical frequency advantage to provide fibre-like data rates over free space. In addition to its increased data rate, FSO communications systems have particular benefits for mobile applications such as lowered size, weight, and power (SWaP) requirements and significantly increased transmission security.

Despite this, the effects atmospheric turbulence, as well as strict pointing requirements, have faltered the widespread implementation of FSO technology. The Astrophotonics research group at the International Centre for Radio Astronomy Research (ICRAR) has developed world leading atmospheric-stabilisation techniques, as well as novel acquisition and tracking algorithms to combat these issues and has successfully demonstrated 100 Gb/s communications to both an airborne drone and a high-altitude aircraft, as well as over terrestrial links of up to 10.3 km.

Building on this work, the aim of this doctoral project is to develop the necessary techniques and subsystems to create a fully functioning, rapidly deployable mobile optical ground station (OGS): TeraNet-3 (TN-3). This mobile OGS will house laser communications equipment designed by the Astrophotonics group, advancing from the groundwork laid by group's two existing optical systems: the Western Australian Optical Ground station (WAOGS) and the the Deployable Optical Terminal (DOT). The system will be capable of establishing robust optical links for communications to land-, air-, sea- and space-based targets, providing fibre-like data rates to a host of scenarios previously limited to RF.

B Research Project

B.1 Background

Communications networks are the foundation of modern society and lie at the core of technologies used billions of people every day [1, 2]. Communications networks have a long history that predates the Industrial age. Although they were initially restricted to technologies like smoke signals, flashing mirrors, and semaphore flags, these networks still managed to transmit complex information over considerable distances [2]. These wireless networks were followed more sophisticated wired technologies, such as the telegraph networks, invented in 1838. These networks enabled unparalleled global connectivity, enabling nearly instant communications between continents [2, 3]. However wireless technology did not undergo significant modernisation until the advent of radio frequency (RF) communications in 1895, allowing for the development communications systems across land-, air-, sea-, and space-based vehicles [2]. Further development in the early 1970s saw the first packet RF network, allowing the wireless transmission of more complex data to computer systems [4]. Building on this advancement, modern wireless communications are almost entirely conducted using RF. They are found in a variety of applications, ranging from the broadcast of music and television, to Bluetooth, satellite communications, and modern 5G cellular networks [5, 6, 7, 8]. In the modern era, as the sheer amount of data generated increases, the demand for fast efficient communications is inescapable. Wireless communications systems such as those found on aircraft, ships, terrestrial vehicles, and spacecraft, are still hugely dependent on RF technology and are struggling to keep up with this ever-increasing data demand [9, 10, 11, 12].

The achievable data rate via wireless propagation scales with the frequency of the carrier signal. RF occupies the lowest section of the electromagnetic spectrum, meaning its use for high-speed communications is sub-optimal [13, 14]. In practical scenarios, data rates are also influenced by transmit power and receiver gain, meaning the only way to increase the data rate of radio transmissions is to increase transmission power or increase either the transmitter or receiver size. For mobile applications, increasing these parameters is especially problematic, as the SWaP of an aircraft, spacecraft, or maritime vessel is an extremely precious commodity. An increase in power usage, size, or weight, significantly impacts the capabilities of a given system, or substantially adds to its cost [15, 16]. In addition, due to its diverse range of modern applications and low directionality, RF usage now suffers from strict regulations to prevent interference, further limiting its capacity [17]. Due to these limitations, various systems face an on-board bottleneck. This is where data is acquired faster than it can be transmitted, which greatly limits the capabilities of a system due to finite on-board storage space [12]. As was the case with wired communications, moving to optical frequencies has emerged as a solution to these problems.

By using lasers for wireless communication, FSO communications leverage the significantly higher frequencies used by modern fibre optic networks. This technology not only provides a substantial increase in data rates but through the high directionality of laser beams, offers benefits such as reduced SWaP requirements and significantly increased security, particularly when paired with novel quantum communications protocols. This makes it ideal for a host of mobile applications in land, air, sea and space. Existing FSO technology has already demonstrated links of several terabytes per second [18, 19]. However, FSO communication are heavily affected by atmospheric turbulence, with robust communications systems requiring active atmospheric-stabilisation. In addition, the high directionality of laser beams places much stricter requirements on acquisition and tracking systems when compared to RF ground stations.

Given these challenges, the Astrophotonics group at ICRAR has developed world leading atmospheric-stabilisation technology, which has been tested in conjunction with novel acquisition and tracking algorithms I have developed personally. As a result, the group has successfully demonstrated 100 Gb/s communications to both an airborne drone and a high-altitude aircraft, as well as over terrestrial links of up to 10.3 km [20, 21, 22].

Building on this work, the group is now developing a three-node commercial optical communications ground station network (TeraNet) funded through an Australian Space Agency (ASA) Moon-to-Mars Demonstrator Mission (MTMDM) Project, conducted in collaboration between The University of Western Australia, Goonhilly Australia, Thales Australia and Geoscience Australia. TeraNet-1 (TN-1) and TeraNet-2 (TN-2) will be centred around observatory-class telescopes stationed in Perth and Mingenew. Their larger collecting areas make them capable of deep-space communications. The emphasis of the smaller-aperture, mobile OGS (TN-3) at the core of my doctoral project, is to leverage the low SWaP requirements of optical technology to enable optical links to land-, air- and sea-based targets as well as low Earth orbit (LEO) satellites.

B.2 Significance

The need for high data rate connectivity to vehicles is becoming increasingly important. On aircraft, as the sophistication of remote sensing, imaging, and other sensor suites increase, so does the amount of data being generated. This is placing an unrealistic demand on traditional RF communications systems. Applications in Australia such as maritime surveillance and airborne surveying suffer from bottlenecks with on-board storage, often necessitating the recall of the vehicle and the physical removal of storage devices. The ability to have on-board data transmitted in a rapid and convenient manner allows for the continued deployment of these systems, reducing downtime and allowing for the full capability of the systems sensors to be utilised. Maritime vessels often incur similar limitations. Larger ships such as those operated by the Royal Australian Navy generate extremely large amounts of data through the myriad of sensors and devices on-board. Currently, the vast majority of this data is trapped on-board and cannot be communicated effectively either to shore or to other ships. Mobile OGS technology would provide an unparalleled level of inter-connectivity between vessels.

Temporary commercial, scientific, military, and disaster management and recovery installations will all benefit from the avoidance of permanent and expensive optical ground station infrastructure, whilst still reaping the benefits of secure efficient communications of up to terabytes per second.

Satellites in LEO can only see a radius of approximately 1000 km. As a result, the communications support of space missions often incurs gaps that necessitate increased global coverage. The ability to deploy a mobile OGS in a rapid and cost-effective manner to support these missions will be crucial in developing Australia's emerging capability in the space domain.

The development of TN-3 will not only pioneer the concept in Australia, but provide a level of mobility not yet seen internationally in OGS, paving the way for future development and further investment in the aforementioned key areas.

B.3 Methodology

The development of TN-3 will draw on expertise I have gained in the development of the tracking and acquisition systems for both WAOGS and DOT during my MPhys (Astronomy & Astrophysics). The system will use a Planewave Instruments PWI L-500 telescope mount and have two configurations. The first will use a 40 cm reflector-style telescope (Shown in Figure 1) and will be capable of LEO links, whilst the second uses a smaller custom designed terminal for terrestrial links. The telescope mount will be affixed to the tray of a dual-cab utility vehicle for mobility. Target tracking and identification will utilise refined iterations of the algorithms I have previously developed for use with optical terminals. These have already demonstrated their ability to track and maintain sufficient accuracy to facilitate optical links. Knowledge gained developing the positioning modules designed for previously conducted drone tests (see [20]) will also be instrumental to the development of self-localisation algorithms which are envisaged to utilise a high-precision inertial measurement unit to correct for alignment offsets in real-time.

Figure 1: The Planewave Instruments PWI L-500 telescope mount and 40 cm reflector assembly in the foyer of ICRAR prior to deployment on TN-3.

The ICRAR Astrophotonics group have ongoing and new collaborations with the French National Centre for Space Studies (CNES), German Aerospace Centre (DLR), Thales Alenia Space, Defence Science and Technology Group, Australian Remote Operations for Space and Earth Consortium (AROSE) and Goonhilly Earth Station. This will provide access to current and future LEO satellites with suitable optical payloads in order to test the systems capability in this aspect. These satellites icnlude OSIRIS, Optel-µ, T-BIRD and ILLUMA-T. UWA and Astrophotonics are also members of the UK International Network for Space Quantum Technologies. This will facilitate partnerships supporting quantum communications, and position navigation and timing tests with missions such as the Canadian QEYSSat quantum communications satellite.

B.4 Aims

B.4.1 Planned Thesis Content

1. Framing Chapter - Introduction: This chapter will contain a brief history of free space optical communications with a specific focus on previous works focused on mobility, as well as the motivations for the work carried out and a brief outline of the rest of the document.

2. Framing Chapter - Technical Background: This will contain a more detailed overview of the underlying physics and concepts related to the following science chapters such as an overview of the atmospheric physics which necessitates certain subsystems on TN-3, PID controller dynamics, and optical communications protocols and their differences.

3. Science Chapter - Paper 1: Coherent Optical Communications to Aircraft: This paper will focus on the results of the recently completed ground-to-aircraft communications test described in Section B.5. It is anticipated the focus of the paper will be on the efficacy of the overall system and its capability to go from receiving a signal from an aircraft's ADS-B

transponder (standard aviation on-board tracking system) to closed loop tracking and robust single-mode fibre coupling effortlessly to facilitate robust communications links. It will also include a detailed analysis of the quality of the tracking systems and optical link parameters.

4. Science Chapter - Paper 2: Design Summary of TeraNet-3: This paper will introduce the TeraNet-3 system. It will provide a detailed overview of each of its subsystems, their capability and how this translates into an effective mobile communications platform. It is envisioned that tests, either to aircraft or the group's drone, will have been completed and be presented in this paper, with a similar level of analysis to the preceding paper. The aim is to demonstrate that the versatile nature of the platform has not acted to severely diminish its capability, when compared to the group's previous static system. This comparison as well as a detailed analysis of its acquisition time and robustness to GPS-denied environments and uneven surfaces will be the core emphasis of this paper and therefore chapter.

5. Science Chapter - Paper 3: LEO Downlink to TeraNet-3: Communications to LEO satellites will require a much higher level of precision with respect to the systems acquisition and tracking. It will also require a suitable target satellite to communicate to, requiring an agreement between the Astrophotonics group and one of the collaborators mentioned in Section B.3. The success of such a link would represent the first time that a system with TeraNet-3's level of mobility has performed a ground-to-space optical communications link (at the time of writing). As such, a detailed analysis of the performance of TeraNet-3 subsystems will form a large part of the paper, while a comparison of various qualities of the communications link to theoretical models and previously published static-to-space links will also be included. If by the time of this experiment TeraNet-3 is not the first of its kind, the works will still be suitable as a stand-alone publication detailing the experiment given the relative novelty of the capability globally.

6. Science Chapter - Paper 4: Point-to-point Communications to Aircraft: This paper will heavily focus on the mobility of not only TeraNet-3, but also the optical communications terminal to be designed and hosted on an aircraft. The real-time capability to compensate in real-time for the changes in orientation and vibrations of an aircraft whilst maintaining a bi-directional communications link is key to demonstrating the use of this technology for terrestrial use cases. The paper described in Chapter 1 will detail a reflected link with no significant communications equipment on-board the aircraft, however this experiment will demonstrate efficient high-speed real-data uplink and downlink from an aircraft to the ground. The focus of the paper will be on highlighting the novelty of this work as well as specific performance and experimental setup information.

7. Framing Chapter - Conclusion: This chapter will contain a brief summary of the works detailed in the thesis as well as their significance, before potential future work is described.

B.4.2 Summary

Chapter	Type	Description
1	Framing Chapter	Introduction
2	Framing Chapter	Technical Background
3	Science Chapter	Paper 1: Coherent optical Communications to Aircraft
4	Science Chapter	Paper 2: Design Summary of TeraNet-3
5	Science Chapter	Paper 3: LEO Downlink to TeraNet-3
6	Science Chapter	Paper 4: Point-to-point Communications to Aircraft
7	Framing Chapter	Conclusion

B.5 Summary of Work Completed

Before commencing with the design and procurement of TN-3, I have continued my participation in the ongoing SmartSat-CRC project (P1-18) being undertaken by the Astrophotonics group.

Achieving a vertical coherent data link to a low-altitude drone (P1-18: Task 1) as part of this project was the focus of much of my Masters thesis. The first months of this project I have spent refining and testing the target acquisition, machine-vision target identification and real-time tracking algorithms of the existing DOT terminal. An example of the Graphical User Interface (GUI) display during a tracking test is shown in Figure 2.

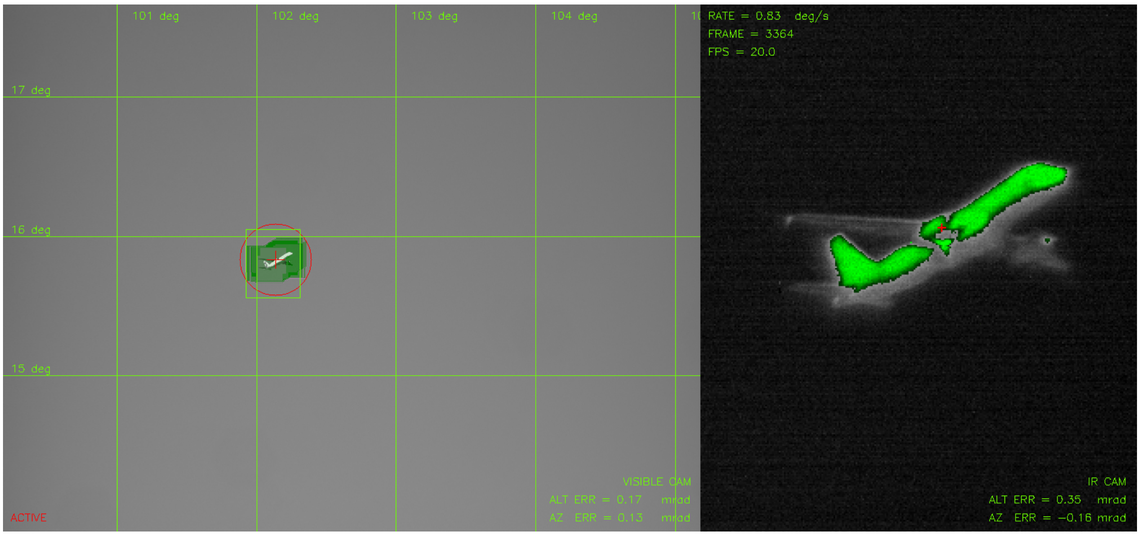


Figure 2: An example of the GUI during a tracking test. Left: The target identification algorithm operating on a visible wavelength camera. The identified components of the target are highlighted in Dark Green, with the red cross and circle indicating the centre of the target. The field of view of the Infrared camera (seen on right) is displayed as the light green rectangle. Right: Infrared camera where a simple thresholding algorithm is acting to isolate the aircraft in the image from the surrounding sky. Visible in both frames are tracking errors in altitude and azimuth axes (effectively Y and X directions in this image).

This work has culminated in a successful demonstration of a vertical coherent data link to high-altitude aircraft (P1-18: Task 3). The remaining task in this project relates to Doppler measurements taken using the optical link to a high-altitude aircraft (P1-18: Task 4). It is not anticipated that any major modification of adaptation of existing algorithms will have to be performed in order for the group at-large to complete this task. My presence during the testing process will however be required to operate the terminal and be available should any modifications need to be made. This low FTE contribution is reflected with a significant task-overlap in the Gantt chart displayed in Section E.

Given that the DOT is centred a PlaneWave L-350 which utilises the same API as the L-500 that will provide pointing control to TN-3, these algorithms can be used interchangeably between systems, making their refinement not only valuable to the short-term SmartSat tasks, but to the broader project and future milestones. The results of the successful aircraft-link demonstration (P1-18: Task 3) will form the basis of the first publication of this project and preliminary data analysis has commenced.

C Research project Details

C.1 Intellectual property and confidentiality

Part of the proposed project fall within The University of Western Australia (UWA)'s work with the SmartSat Cooperative Research Centre (SmartSat CRC). Therefore intellectual property obligations between the 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 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 and aircraft flights over 120 m altitude, the Civil Aviation and Standards Authority provides guidelines and exemptions to be observed. 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, it will also include deployments off-campus to test TN-3 as well as a demonstration in Townsville and Canberra to showcase the current capability of the existing terminal DOT with an emphasis on ground-to-aircraft laser links. The facilities on campus have existing safety controls in place, which have been set up within the larger context of the Astrophotonics group's activities. As for external fieldwork, all activities will have a Fieldwork Risk Assessment form completed, which will be compiled with input from both Dr Schediwy (coordinating supervisor) and Dr Gozzard (Health and Safety representative for Astrophotonics).

C.4 Research Outputs

The results from this project are intended to be communicated in a series of four journal papers. The thesis will be formatted from the collected journal papers, with expected submission dates and corresponding subjects outlined in the table below.

Communication Type	**Submission Date**	**Subject**
Journal Paper	Nov. 2023	Coherent Comms. to Aircraft
Journal Paper	Aug. 2024	Design Summary of TeraNet-3
Journal Paper	Feb. 2025	LEO Downlink to TeraNet-3
Journal Paper	Aug. 2025	Point-to-point Comms.: TeraNet-3 to Aircraft

C.5 Data Management

Data collected in the course of this project will be stoed on the research groups shared online drive. Personal documents will be stored on my student drive and my university computer. Additional files will be present on the control computers of both DOT and TeraNet-3. .

D Training and Development

D.1 Skills Audit

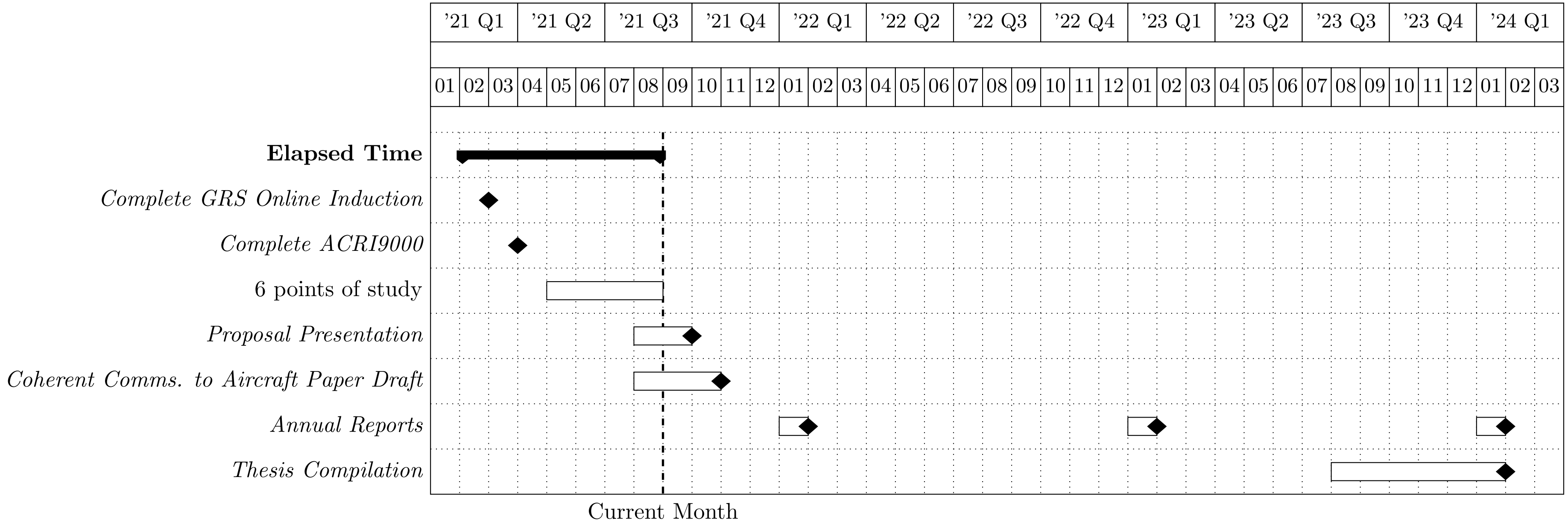
Skill	Personal Rating				Evidence
	None	Basic	Competent	Proficient	
Evaluate and synthesise existing disciplinary knowledge		✓			This is a critical skill that I have begun to hone through my research experience as a master's student. I will further refine this during my PhD project through my own efforts and through the mentorship of my supervisors and colleagues.
Collect, analyse and present data				✓	I have extensive experience in data collection and analysis through my master's project and the compilation of my thesis.
Programming for telescope control, and target acquisition and identification				✓	This skill was fundamental to my previous research with Astrophotonics during my master's project and will again be crucial to the success of my PhD project. Although I believe I am proficient in this particular skill I believe I will be able to improve even further through the extended experience that this project will provide.
Mentorship and sponsorship of others		✓			I have some experience running undergraduate practice-classes and facilitating labs. Further opportunities to teach will strengthen both my ability to communicate scientific concepts and foundational knowledge in the subject matter.

Skill	**Personal Rating**				**Evidence**
	None	Basic	Competent	Proficient	
Presenting research to attain funding for additional projects from both academic and private sectors		✓			The technology being developed is supported through grants funded by various entities. The ability to identify areas of further research and present them to potential investors in such a way that culminates in additional funding and opportunities for valuable research is an important skill that I will refine throughout my project.
Academic writing and publication			✓		I have attained experience in academic writing through my postgraduate education, primarily through the compilation of my master's thesis. I am also currently enrolled in an academic writing coursework unit to further refine my skills. By writing journal publications throughout this project, This skill will be honed greatly.
Presentation skills including public speaking and slide deck / visual media creation			✓		I have experience in preparing and delivering presentations gained through both undergraduate and postgraduate levels of education. I am particularly proficient in the slide and visual media generation aspect but wish to further improve my public speaking skills through this project.

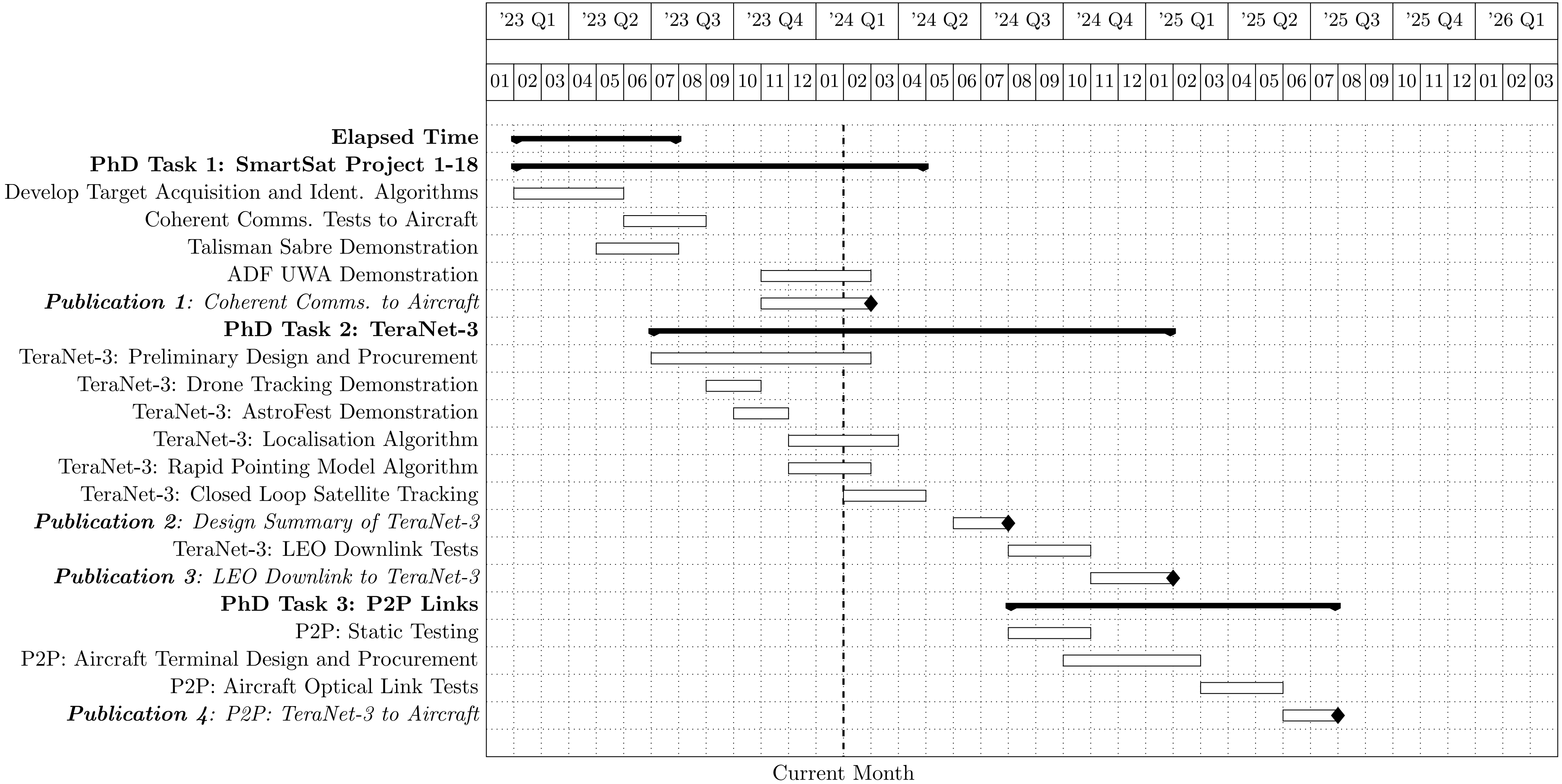
D.2 Confirmation of Candidature

Designated Task	Proposed Completion Date
GRS Online Induction	20 Feb. 2023 (complete)
ACRI9000	27 Apr. 2023 (complete)
GRS Welcome	7 July. 2023 (complete)
Research proposal approval	Aug 2023
6 credit points of coursework: enrolled in PHYS5512	Aug. 2023
Oral proposal presentation	Aug-Sept. 2023
Substantial piece of writing: Draft of coherent comms. to aircraft paper	Nov. 2023

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	$1,200			UWA
Thesis printing and binding			$200	ICRAR
Research costs				
TeraNet-3 Development	$125,000[1]			ASA
Travel costs				
Talisman Sabre Demonstration	$3,000			DSTG
9FSM Conference	$1,500			Personal PG
TDB Conference		$1,500		Personal PG
TBD Conference			$1,500	Personal PG
Year sub-totals	$130,700[2]	$1,500	$1,700	
			UWA Contribution	$1200
			ICRAR Contribution	$200
			ASA Contribution	$125,000[1]
			DSTG Contribution	$3,000
			Personal PG	$4500
			Total	$133,900[3]

[1] This amount and its effect on subsequent totals ([2,3]) reflects the total ASA MTMDM budget allocation for the development of TeraNet-3. Its entirety is not a necessarily reflection of the money directly at the disposal of this specific PhD project. This amount may be dispersed over the duration of the project.

G Supervision

G.1 Coordinating supervisor: A/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.2 Co-supervisor: Dr. Shane Walsh (30%)

Dr Walsh specialises in Adaptive optics and has extensive experience at Las Campanas, Gemini and Large Binocular Telescope Observatories. Dr Walsh occasionally facilitates the weekly research group meetings.

G.3 Co-supervisor: Dr. David Gozzard (20%)

Dr Gozzard specialises in photonics for frequency transfer and optical phased arrays, and a former Forrest Fellow. Dr Gozzard occasionally facilitates the weekly research group meetings.

G.4 Co-supervisor: Dr. Ben Dix-Matthews (10%)

Dr Dix-Matthews specialises in real-time turbulence compensation technology for ultra-stable optical signal transmissions through the atmosphere for metrology, geodesy, and communications purposes.

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