2026-2035 Decadal Plan White Paper

Working Group 2.4: Instrumentation[1]

Executive Summary

Background: Australia has an established history of designing and building innovative astronomical instrumentation, characterised by deep collaboration of astronomers and engineers, and spanning across astronomy domains from radio to optical to gravitational waves. By enabling new capabilities, Australian instrumentation forms the backbone of many astronomy discoveries. However, instrumentation programs also provide key strategic benefit to the astronomical community far in excess of their discovery potential alone: they provide access to state-of-the-art telescopes; keep existing facilities globally competitive; are a valuable bargaining chip when joining large international collaborations (e.g. ESO, SKA); provide diversified astronomy-related training and career paths; and seed spin-off companies and industry engagement.

Workforce: 15% (TBC) of individual community survey respondents work on instrumentation development at some level, though institutional responses report a larger instrumentation workforce, reflecting the high number of non-academic professional engineers that may not identify with the astronomy community. The instrumentation workforce is disproportionately male, with 114 (67%) of survey respondents identifying as men – an imbalance accentuated among continuing positions and senior levels.

Current Activity: Instrumentation activity is concentrated within CSIRO (predominantly radio instrumentation) and a small number of University groups, each of which have dedicated concentrations of expertise across various areas of instrument science, optics, mechanics, electronics, controls, detectors, software, system engineering, product assurance, project management, and capacity to design and build complex instrument systems or subsystems. These are specialised teams and facilities, often hiring from industry rather than academia. With the notable exception of the role of instrument scientists, instrumentation teams are typically focussed on project work rather than undergraduate teaching and publishing research. Non-academic instrumentation career paths within Universities follow professional, rather than academic, work structures, and comprise short-term or funding-contingent contracts.

Australian instrumentation groups are engaged in a number of major (10-year, 10's of M$) projects for the world's largest telescopes, including SKA, next-generation ELTs and Gravitational Wave Detectors. The sector has invested over $100M across astronomy instrumentation portfolios over the past 5 years via Universities alone (mostly salary costs), which includes seeding activities in adjacent areas such as space domain awareness, optical communications, bio/agriculture, remote sensing, space environment testing, and other applications of instrumentation technology and expertise. Development of non-astronomy activities is a growing feature of Australian instrumentation groups, driven by a need to generate diversified income streams to support core astronomy instrument work – in particular supporting R&D activities for new technology development, and to sustain expert teams over variable University budget cycles, insecure contracts, and long project durations.

Funding: Instrumentation development, regardless of wavelength or domain, is an investment in the long term. The path from a new idea to deployment of an instrument can take many years. Instrumentation teams require highly specialised skills, with expertise built up through internal training over decades. Short-term budget shocks can decimate expert teams that can take many years to recover, and funding uncertainty prevents teams from bidding for large, long-term opportunities with international facilities. Therefore, a key recommendation of this white paper is for the establishment of long-term, stable funding, to ensure that Australian instrumentation programs continue to thrive, lead scientific discoveries, and provide benefits to the community.

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Recommendations

1. ***Continue to ensure Australian instrumentation excellence is enabling world-class science in astronomy.***

   Rationale:
   - Australia has an internationally valued track record and capacity for innovation in astronomical instrumentation, with a skilled workforce decades in the making.
   - Through the co-development of science and instrument research, this capability enables Australian scientific leadership in the technology-driven research field of astrophysics and space science.
   - Building instruments for observatories can enable dedicated access to those facilities, while at the same time developing national capacity in associated technical areas, such as optics, electronics, software and data.

2. ***Secure stable, dedicated base funding for national-scale instrumentation programs (including those of Astralis and CSIRO) for the next decade, with a broad mandate to both deliver and develop new astronomy instrumentation capabilities with international impact.***

   Rationale:
   - Astronomical instrumentation is a specialised area. Growing and maintaining instrumentation groups requires long-term development of the relevant expertise, drawing from a small pool.
   - Funding for individual instrumentation projects tends to be stochastic, and varied in scale, inhibiting strategic investment, planning, and recruitment of young talent.
   - Project funding does not fund development of emerging technologies for future instrumentation.

3. ***Align national-scale instrumentation program funding with the community's long-term major facility investments, potentially via in-kind arrangements or partnership agreements.***

   Rationale:
   - Alignment of instrumentation activities with major facilities builds the engagement of Australian astronomers with Australian instrumentation, maximising the science return of both investments.
   - In-kind instrumentation contributions can offset partnership costs to international facilities, reducing the off-shore spend, and increasing return on investment in national instrumentation programs.
   - Major facility partnerships typically run over many years, ensuring long-term engagement (scientifically, and financially) well-suited to typical instrumentation projects.

4. ***Enable access to stable, mid-level ($5-10M p.a.) funding over 5-10 year periods that permits full engagement and leadership of major instrumentation projects for world-class astronomy facilities.***

   Rationale:
   - Taking a leading or major role in new instruments for next-generation astronomical facilities (e.g. ELT, GMT, or SKA) requires a scale and duration of funding currently not catered for by any national competitive grant scheme.
   - Australia has the internationally-competitive workforce and facilities to lead and deliver such projects, but lacks the long-term funding mechanisms to secure them.

5. ***Establish sustainable and rewarding career paths within the sector for instrumentation professionals from academic and non-academic/industry backgrounds.***

   Rationale:
   - The vast majority of the astronomical instrumentation workforce are non-academic technical professionals and engineers with little or no background in astronomy.
   - Outside of CSIRO, astronomical instrumentation activity largely happens within University-based groups, supported through limited-term project-based funding.
   - Universities generally have limited mechanisms for supporting long-term career development and substantive employment for non-academic staff.
   - Limited career stability and progression makes recruitment and retention of highly-trained technical professionals a major challenge.
   - Academic careers emphasise a ‘publish or perish’ pathway that is not well suited to high-risk, high-reward research into new instrumentation, inhibiting the growth of technical research academics within University groups.

1. Introduction

1.1 Overview

This White Paper provides input to the Decadal Plan from the first Working Group dedicated to astronomical instrumentation. This reflects a growing instrumentation capacity in the Australian astronomy community, and an increased strategic role and need for instrumentation as part of the national astronomy research infrastructure landscape. The term ‘instrumentation’ includes a wide range of activities and disciplines, from optical, mechanical, electronic and software engineering, to the fundamental physics of material science, lasers, nonlinear optics and photonics, to systems engineering and project management, real-time control systems, and more. Capturing a complete view of this broad range of activities is beyond the scope of this White Paper. Instead we aim to capture a cross-section of the major projects and activities happening within the astronomy instrumentation community, how this activity is funded and supported, and reflect on the potential opportunities and limitations faced by those working in this area.

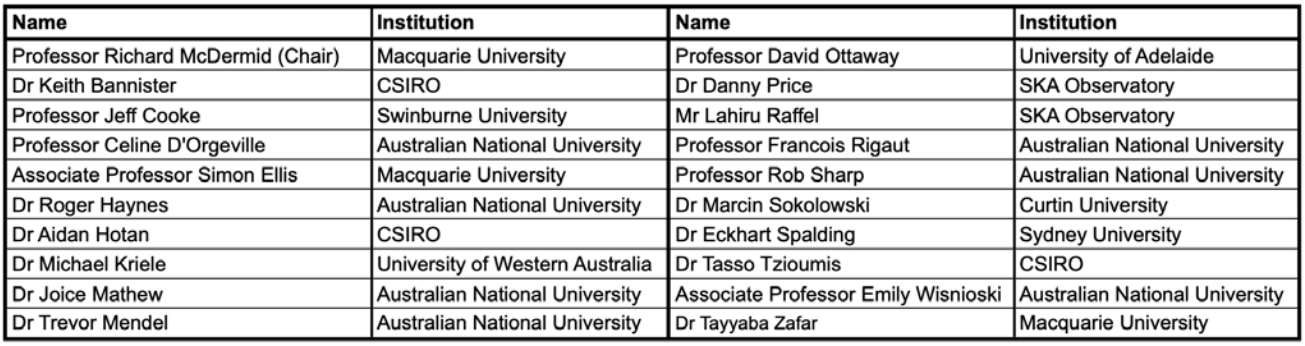
1.2 What is not covered in detail in this White Paper

Instrumentation for space-based astronomy. Many Australian groups working with astronomical instrumentation have some level of activity in the area of instrument development for space applications. This is an emerging area driven by reducing costs of launch, standardised modular satellite platforms, and increasing industry activity in the space domain. However, we direct the reader to the White Paper of *Working Group 2.1: International and Space Facilities*, who address the role of space astronomical facilities and Australia’s instrumentation capacity in some detail.

Industry engagement. Astronomy instrumentation development often includes interaction with industry, and can result in technologies suitable for commercialisation. We discuss a few examples in this paper, but also direct the reader to *Working Group 3.3 Industry and Translation* for a fuller account.

1.3 Working Group membership and methodology

The Working Group was established in late 2023 through a community-wide expression of interest call for volunteers from the National Committee for Astronomy (NCA), primarily through the Astronomical Society of Australia (ASA) members email list. Group chairs were appointed by the NCA, and members established through the initial expression of interest. Additional members were later included through direct enquiry to address balance of interests within the group, and via subsequent volunteers. The final Working Group membership is provided in the table below.



Name	Institution	Name	Institution
Professor Richard McDermid (Chair)	Macquarie University	Professor David Ottaway	University of Adelaide
Dr Keith Bannister	CSIRO	Dr Danny Price	SKA Observatory
Professor Jeff Cooke	Swinburne University	Mr Lahiru Raffel	SKA Observatory
Professor Celine D'Orgeville	Australian National University	Professor Francois Rigaut	Australian National University
Associate Professor Simon Ellis	Macquarie University	Professor Rob Sharp	Australian National University
Dr Roger Haynes	Australian National University	Dr Marcin Sokolowski	Curtin University
Dr Aidan Hotan	CSIRO	Dr Eckhart Spalding	Sydney University
Dr Michael Kriele	University of Western Australia	Dr Tasso Tzioumis	CSIRO
Dr Joice Mathew	Australian National University	Associate Professor Emily Wisnioski	Australian National University
Dr Trevor Mendel	Australian National University	Dr Tayyaba Zafar	Macquarie University

Table 1: Membership of Working Group 2.4

The Working Group met via videoconference initially fortnightly in early 2024, moving to weekly meetings during June-August 2024. Meetings were well attended, with notes captured in a commonly-accessible Google Doc. A Google Drive folder was also shared, where additional data and materials could be gathered.

The Working Group gave direct input into the demographics survey administered through Working Group 3.1 Demographics, Society, and Workforce, including questions specific to individuals and institutions working in the area of astronomical instrumentation. These data are used in this White Paper, but the reader is also referred to the White Paper of Working Group 3.1 for additional context.

The Working Group was engaged with the in-person Decadal Plan Town Hall meetings held over a two-week period in July, presenting an initial set of findings, and receiving in-person and follow-up input that has been incorporated into this document.

1.4 Why have an Australian instrumentation program?

The connection between high-impact astronomical discoveries and large, expensive observatories appears self-evident. However, the most important part of the journey for any astronomical messenger signal is what happens in the final few moments of their cosmic journey, where it interacts with some kind of instrument. The world’s leading observatories are never short of new instruments vying to use the signals they collect, and the market to develop and deliver such instruments is highly competitive. Why must Australia participate in this complex market?

There are two primary science drivers for the national astronomy community:

- It ensures science the Australian community is most interested in is prioritised on the world stage;
- It allows Australia science teams to take the lead in delivering these programs.

Without a world class instrument program, Australian astronomy risks being a passive consumer of capabilities available to the world community. While this will work well for individual PIs as part of international collaborations, global leadership will not be a practical goal of the wider community.

In addition, there are strategic drivers to having an active and vibrant instrumentation program in Australia:

- Major instrument projects require high levels of international collaboration and cooperation, keeping Australia connected to the world’s leading researchers and technologists;
- The technology developed for new instruments can have applications beyond astronomy;
- Astronomy is an inspiring and engaging STEM discipline, giving a novel and diverse channel to attract young people into technical training and education pathways, and supporting national goals around increasing research and development capacity.

In this white paper we present some of the historical and contemporary strategies used to deliver instrumentation excellence for Australia, consider the contemporary playing field and propose a number of strategies that we consider necessary to secure Australia's reputation and scientific productivity in this critical field into the next decade and beyond.

2. Instrumentation in Australian Astronomy

The direct relationship between astronomical discovery and new instrumentation is well established. Australia has a long history of finding new technological solutions to advance astrophysical knowledge, spanning multiple wavelength, frequency, and indeed messenger, domains. The scale of modern astronomy facilities requires large, usually internationally distributed, collaborations of expert teams working for many years to develop and deliver novel instrumentation. That Australia can engage with these endeavours is the product of many years of investment in, and development of, teams of skilled experts across multiple domains, working in close proximity to leading researchers over a sustained period of time.

Here we provide a somewhat selective historical narrative on how instrumentation activity in certain domains has evolved over the course of multiple individual projects, which collectively have built a globally competitive capability in those areas. This provides context for some key points:

- Investment in basic research is crucial to developing truly innovative instrumentation, capable of ground-breaking discovery.
- It is not obvious where break-throughs will come from when research begins, so rather than picking winners, supporting a broad diversity of ideas is the best strategy;
- Sustained investment in growing and retaining expertise is crucial to building scale and focus in important areas with longer-term potential;
- We are not at the end-point of historic trajectories - many new opportunities are within reach, but require ongoing or expanded investment.

2.1 Optical and Near-Infrared Spectroscopy

The Australian community was a pioneer in the use of optical fibres for multi-object spectroscopy (MOS), using the high-multiplex advantage (factors of x50 initially up to x400 with the 2 degree field facility on the Anglo-Australian Telescope - AAT) to counter the shortcomings of the Siding Spring site in from the mid-1980s onwards. This delivered not only important science programs in cosmology, but fostered the development of a strong survey spectroscopy community that developed a diverse series of influential science programs (most recently the GAMA and GALAH surveys) that involved large portions of the Australian community across multiple institutions. Indeed, collaboration through observational surveys has become a hallmark of the Australian community beyond the use of national facilities, training young researchers in the value and methods of well-run consortia, and building a cohesive national research community.

In parallel, the Australian community was an early adopter of the now mainstream technique of Integral Field Spectroscopy (IFS). Many first-generation instrumentation experiments were deployed on the AAT leading to a small but talented community ready to scientifically exploit the second generation of facilities (such as the Australian-made Gemini/NIFS instrument) as they came on-line. Harnessing the aforementioned extensive institutional experience with fibre optics, the SAMI, and now HECTOR, instruments pioneered large scale multi-object IFS survey programs which have been highly productive as multi-institute national initiatives, and replicated by other prominent collaborations (most notably the Sloan Digital Sky Survey).

These IFS and fibre MOS projects formed central pillars of flagship Australian Research Council (ARC) Centres of Excellence - the largest scheme in Australia for funding basic research at the level of $5M p.a. over seven years, supporting around 20-30 postdoctoral researcher salaries per year. Resourcing these innovative instrument-enabled surveys with dedicated early-career researchers (ECRs) through Centres was key to their scientific impact and success. The collaboration skills and training also equipped numerous ECRs to lead major parallel initiatives such as the ESO/MUSE MAGPI and GECKOS Large Programs. The synergy of science researchers with instrumentation development has also ensured strong scientific support for third-generation IFS instruments such as GMT/GMTIFS, VLT/MAVIS, and most recently ELT/HARMONI (as well as supporting strong Australian leadership in MOS programs such as the ESO/WAVES program). As is seen in Australian astronomy instrumentation at all wavelengths, these science-driven developments are enabled by well-supported early investment in emerging technologies and approaches as they mature, ensuring the scientific community to deliver on the world stage.

2.2 Gravitational Wave Astronomy

Australian instrumentation scientists have made significant contributions to the world's interferometric gravitational wave detectors. This has been predominantly through contributions to the LIGO detectors that are sited in the US and observed the first directly detected gravitational wave signatures as opposed to the indirect signature from the observations pulsar orbit decay made by Hulse and Taylor. It is worth remembering that both observations led to Nobel Prizes being awarded. The Australian GW instrumentation community has also made occasional contributions to the Virgo detector which is located in Italy and is now a predominantly European wide collaboration.

Australian technology contributions include the parts of the squeezing system that injects non-classical states of light into the detector which has improved the sensitivity of the detector by almost a factor of 2 in its most sensitive frequency band around 100 Hz. This is arguably the first demonstration of quantum advantage delivering an improvement in the sensitivity of a detector that cannot be achieved any other way. Australian technology has also been implemented to sense and control the optical fields inside the interferometers to ensure that benefits of squeezing are exploited to their maximum extent.

This work has been crucial but it is not completed. The next generation of gravitational detectors call for a further increase in the benefits realised from squeezing from the nearly 6dB improvement used at the moment to at least 10 dB in future detectors. The future detectors also call for a quadrupling of the circulating power from the current 400kW to 1.5 MW. This will push the limits of what can be achieved from interferometers that use silica based optics. Exquisite control of optomechanics effects and interferometer wavefront control will be needed to achieve the tripling of range that this will enable. Australian scientists are well placed to make significant contributions to these technology upgrades.

Spaced based gravitational wave detectors will likely be realised sometime in the next decade with the European Space Agency and NASA supported Laser Interferometric Space Antenna (LISA) expected to launch around 2035 . Precursor missions such as the NASA Grace Mission have already illustrated the benefits of deploying interferometric detectors in space and have made real contributions to understanding the depletion of critical water resources on Earth. Scientists at ANU have made significant contributions to the instrumentation development for these missions. This hardware research and development has also contributed significantly to the technology developments that have resulted in ANU's successful spinout company Liquid Instruments.

2.3 Radio wavelengths

The Australia Telescope National Facility (ATNF) group within CSIRO maintains a strong instrumentation group to support its primary facilities: Murriyang (the 64m dish at Parkes), The Australia Telescope Compact Array (ATCA), and the Australian Square Kilometre Array Pathfinder (ASKAP). This group is globally unique, in that spans the full suite of radio instrumentation, including:

- Ultra-wideband single pixel, multibeam and phased array receiver design and fabrication, for both cryogenic and room-temperature applications.
- Cryogenic Low Noise Amplifier design

- Long distance RF signal transport over fibre,
- Extremely large scale digital signal processing (100s of terabits / terapixels per second)
- Software and algorithms for imaging on High Performance Computers (HPC)
- Operations software, archives and data management

From a capability standpoint, ATNF/CSIRO have invested in a sustained program of development over many years, focused on key instrument technologies, including:

- **Radio telescope Feeds:** Radio telescopes have traditionally used single-pixel feeds observing by tracking a specific position in the sky (area equal to the primary beam of the antenna). Surveying the whole sky for millions of objects has been a very time consuming activity, often taking many months or years. CSIRO pioneered multi-beam technology (e.g. 13 fixed beams at Parkes) more than 20 years ago, improving survey speed.
- **Phased Array Feeds:** Recent developments of multi-element arrays of feeds (~100 dipoles) has completely revolutionised the surveying capabilities of radio telescopes. The array elements can be electronically combines ("phased") to form multiple simultaneous beams ("beam-forming") which can be pointed flexibly within the telescope primary beam.For example the PAFs on the ASKAP antennas produce 36 beams and the cryoPAF at Parkes 70 beams (x 2 polarisations). As the survey speed is proportional to n**2 (where n is the number of beams) the PAFs improve survey speed by orders of magnitude! Hence, surveys that took years to complete can be done in weeks!
- **Digital requirements:** Each PAF produces ~200 raw data streams of 3-5 Gbps each which need to be processed through beamforming in real-time. This processing rate has been achieved thanks to rapid developments in digital hardware and firmware with ATNF working closely with industrial partners. This volume of processing in real-time was not possible more than ~10 years ago. This digital revolution has enabled the full development of PAFs, and CSIRO is leading this development world-wide.
- **Computing:** To produce the final radio astronomy products (images, spectra, timing, transient detection…) in real time requires huge computer resources. ASKAP pushes the limits of the super-computing capacity at Pawsey. Parkes can observe commensally in many-modes and needs a large GPU cluster (>20 nodes) to process that data. And even after that, big data centres are required to store the final results.
- **Aperture arrays:** Phase arrays may also be installed outside a radio telescope and then can survey the whole sky at once! Many 100s of elements are needed and again the digital and computer requirements are often the determining factor.

Many technologies have been successfully open-sourced, exported to overseas observatories such as the Square Kilometre Array (SKA), and spun off to industry (e.g. see section 2.5). The ATNF is keeping its facilities globally competitive, with the upgrade projects recently completed or underway:

- Parkes-Murriyang:
  - Ultra-Wideband-Low currently operating.
  - Ultra-wideband-High under development.
  - cryoPAF in commissioning.
- ASKAP instrumentation upgrades
  - CRACO coherent FRB detector - in commissioning
  - PAF sensitivity upgrade - first prototype funded
- ATCA instrumentation:
  - Bigcat correlator and bandwidth upgrade - in development.

2.4 Research and Development Activity

Research and Development (R&D) Activity in Instrumentation falls into three categories:

1. R&D required for the delivery of instrumentation projects. This type of R&D is generally at a higher technology readiness level (TRL) and relatively low risk. Funding for this R&D is part of the instrumentation programme.

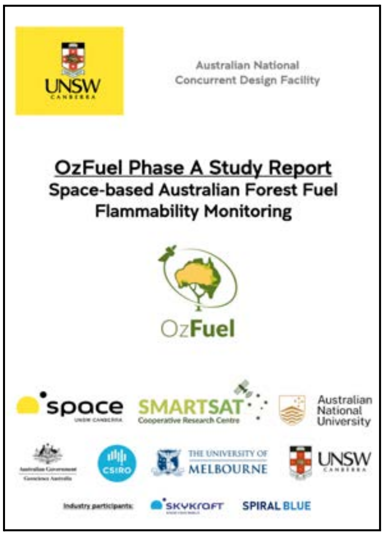
2. R&D to explore and prepare new technologies for instrumentation, which is generally at lower TRL and has higher risk. Australia has a long history investing in novel and emerging technologies, and indeed this often lays the foundations for later successful contracts to build instruments for major international observatories. This type of R&D is funded through competitive grant schemes as for other areas of astronomical research, and is thus currently insecure and somewhat haphazard. We note that the Go8 universities have identified increased funding of R&D (aiming for 3% of GDP cf. 1.7% currently) as a priority for investment[2]. Examples of R&D in this category include work in astrophotonics, adaptive optics (AO), detectors etc.

3. R&D to translate the technologies developed for astronomical instrumentation to applications in other fields. This usually involves commercial interests and industry partners. Examples include AO in optical communication, remote sensing and Earth observations etc.

2.5 Industry Engagement and Commercialisation

Astronomy faces a challenge common to any industrial R&D program, how does one develop and maintain a highly skilled workforce, able to respond in an agile way to emerging new opportunities, in periods where investment is lean or highly focused. Diversification outside of astronomy can provide opportunities to create a sustainable technical program that can navigate the boom-bust cycle, whilst also providing the opportunity to reinvest technology developed for astronomy into society. The challenge is to identify genuinely interesting applications (be they scientific, social, economic or environmental) that remain astronomy adjacent and support the broader instrumentation goals without distracting key personnel.

While there is a dedicated Working Group focused on industry engagement and commercialisation activities (*Working Group 3.3 Industry and Translation*), we include here an example case study of instrumentation cross-over, as well as some other examples that may be useful. Our Working Group can provide additional information if needed.



Australian National
Concurrent Design Facility

OzFuel Phase A Study Report
Space-based Australian Forest Fuel
Flammability Monitoring

OzFuel

Industry participants:

OzFuel: Earth observation remote sensing technology transfer

The Australia Remote Sensing community is world leading on the international stage, but largely only as data users (supported by significant ground-based field calibration/validation expertise). This leads to data sets often not optimised for Australian national needs. The visible light remote sensing market is already well catered for by a range of governmental and commercial platforms, however due to perceived technical difficulties there is a gap in the market for “ShortWave Infrared” (SWIR - 1-2.5 microns) observations and hence an opportunity to meaningfully contribute, with small form factor satellite based systems, to nationally significant programs in Bushfire risk management, mineralogical surveys and agricultural monitoring.

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[2] https://go8.edu.au/australias-rampd-intensity-a-decadal-roadmap-to-3-of-gdp

To this end, the ANU detector electronics team has leveraged expertise in high-performance focal plane array sensors (those used not only for ground based astronomy, but also found on space missions such as the *JWST* and *Roman* camera systems) alongside optical design expertise, to pursue missions of national significance in remote sensing. The OzFuel program[3] is a wider initiative to provide national monitoring of bushfire fuel loads and flammability. This augments systems already in place but which are based on freely available data from international programs that typically provide compromised data with less than ideal ground sampling, temporal coverage, time of day observation or pass bands poorly matched to the Australia ecosystem. The OzFuel project is still in development, with the optical system prototype to be qualified under simulated orbital conditions in 2025. The testing process will use the “Rosella” detector control system (underdevelopment thought the partnership with the iLAiNCH Trailblazer program with led Industry partner Leonardo UK) coupled to the high-performance SAPHIRA *e*APD detector system adopted locally for use with GMT/GMTIFS and ESO/MAVIS astronomy programs.

Other examples of industry partnerships and commercialisation

Prototype of an optical head assembly, designed by Macquarie University/AAO in partnership with Advanced Navigation, 3D printed at ANFF OptoFab Node at Macquarie University and fine-tuned by Josh Hacko's team at NH Micro.

- **NH Micro** (https://www.nhmicro.com) - Precision manufacturing SME created from collaboration with ASTRALIS. Worked on Hector IFS and recent space tech development

- **Vai Photonics** - Vai Photonics is an ANU spinout company co-founded by Dr Lyle Roberts and Dr James Spollard. Lyle and James pioneered a range of sensing technologies while working for the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) on gravitational wave detection technology. The intellectual property developed by Lyle and James formed the basis of a research translation activity which resulted in the development of sensing capabilities that could be used for GNSS-denied navigation. Vai Photonics was founded to commercialise this research, and was subsequently acquired by Advanced Navigation in 2022 due to the symbiotic relationship between the two companies.

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[3] Full Phase-A Study Report: https://www.unsw.edu.au/content/dam/pdfs/unsw-adobe-websites/canberra/research/2023-04-990391422-OzFuel-Report-Publication_FA_0.pdf

- **Fourier Space:** Fourier Space Pty Ltd is a spin-out of Swinburne University of Technology formed in 2021. Its headquarters are in Hawthorn, Melbourne, and currently employs 6 people and has a projected revenue of in excess of 1M for the 24/25 financial year. It has a major construction contract with the Square Kilometre Array, but has also worked with CSIRO spin-out QuasarSat on space communication solutions for phased array feeds, the CSIRO and the US National Radio Observatory, for which it developed new receivers for the Very Long Baseline Array (VLBA). Its core technology was originally developed to reliably observe radio pulsars and Fast Radio Bursts (FRBs), but has found industrial applications in satellite communications. It is supporting industry-linked PhD places and will be taking on its first postgraduate intern this summer.

- **RedBack Systems** (https://www.redback.systems) - Redback Systems is an Australian spin-out company from Macquarie University with support from the CSIRO ON startup accelerator program. RedBack Systems bring advanced spectroscopic techniques developed for high-precision spectroscopy in astronomy into the broader scientific and industrial domains. Their compact and high-resolution spectrometers allow the capture of a wide spectral range in a single snapshot without the need for moving dispersive elements or alternating between multiple spectrometer systems.

- **Quasar Satellite Technologies (https://quasarsat.com/)**: The Phased Array systems on the Parkes radio telescope have naturally led to the development of commercial aperture array systems for satellite tracking and Space tracking. CSIRO teamed up with industry and funds from government and venture capital companies to establish a start-up to develop and commercialise these technologies. The combined CSIRO/Quasar team demonstrated a world first, simultaneous tracking of 10 satellites with the phased array under fully automated control. As a result, Quasar will be the sole non-US participant in the U.S. Space Systems Command's Space Domain Awareness (SDA) Tools Applications and Processing (TAP) Lab Apollo Accelerator Cohort 4, commencing in August 2024

2.6 Funding

In this section, we provide a top-level overview of funding mechanisms commonly employed for instrumentation projects. This complements the information presented by *Working Group 3.4 Research Funding*, which focuses on funding for pure research, largely through national competitive grant schemes. By contrast, funding schemes for instrumentation projects are varied and depend on the particular contract with the researcher, observatory, or client. We discuss these main funding channels below.

NCRIS and Astralis

Part of funding the 10-year Strategic Partnership with ESO required transitioning the then-called Australian Astronomical Observatory “AAO” from a Governmental department to the University sector. A consortium of Universities agreed to fund the Anglo-Australian Telescope (AAT) at Siding Spring Observatory; and the technical group based in Sydney was taken over by Macquarie University, following a competitive bid process, to become Australian Astronomical Optics (AAO - thereby preserving the well known acronym and brand). At the same time, a “National Instrumentation Capability” budget item was formed in the astronomy NCRIS funding program administered by Astronomy Australia Limited (AAL), funded at the level of $5M per annum. This funding is directed to the *Astralis Instrumentation Consortium* (known simply as “*Astralis*”) - a consortium of three Universities hosting established instrumentation groups: the AAO at Macquarie University; the Advanced Instrumentation and Technology Centre (AITC) at ANU; and the Sydney Astrophotonic Instrumentation Laboratory (SAIL) at Sydney University.

Astralis was created to coordinate the national presence of Australian instrumentation on the global stage, creating a single collaborative platform through which the scale and diversity of expertise required to lead or partner in major instrument projects could be established. Astralis currently supports a range of instrumentation-related activities, from the decade-scale multinational MAVIS facility instrument for the VLT, to seeding industry engagement activities and translational technology development. Most importantly, Astralis has provided a modest but stable base of funding for the consortium members, allowing them to successfully collaborate and compete for large projects, retain key staff through variable project and institutional budget cycles, and invest strategically in developing new partnerships and capabilities. The importance of this stability cannot be understated - it is the only way to engage with major projects, and to remain competitive with other countries where long-term funding is well established.

Astralis NCRIS funding does not directly fund basic research - it can only fund projects. Support for Astralis is also tied to the NCRIS funding cycle, which is revised and renewed by the government every five years - half the length of the typical major instrument project. Moreover, the “National Instrumentation Capability” funding stream was created in response to the ESO Strategic Partnership. The availability of this funding beyond the duration of the partnership is uncertain.

Fixed price

FIxed-price contracts cover the cost for the end product, including all hardware and labour, where the price is agreed upfront. This carries a very real risk of financial loss unless a significant contingency is included in the price. We note that fixed price contracts are common, and further that for some significant contracts, including ESO instrumentation, only hardware is funded; labour costs, as well as any gaps in hardware funding, must be paid for separately, and is recompensed with guaranteed nights on the telescope. One successful approach to fill this funding gap has been to use NCRIS money, administered through AAL via Astralis (see above), to fund projects that are considered to be of strategic importance for the Australian astronomical community. In return for this investment of national funds, the astronomical community receives access to the GTO nights obtained as part of the instrument build.

Labour and materials

These are contracts in which the client pays for all labour and materials used in a job, plus a predetermined percent markup. These represent the lowest risk in terms of financial loss, as terms are generally more flexible than fixed-price contracts. They also have the advantage that no additional funds must be raised in order to deliver the project. The downside is that in-kind contributions are not recognised, and facility access through guaranteed time observations (GTO) is generally not included. This can strongly limit community participation and engagement, meaning that Australia develops, designs and builds the technology, but Australian astronomers have no direct access to, or benefit from, the instrument.

National competitive grants

National competitive grants generally refer to schemes run by the Australian Research Council (ARC), such as Linkage Infrastructure, Equipment and Facilities (LIEF). LIEF grants have been used to great effect by instrument teams to fund domestic projects with strong national benefit. However, they require broad community participation and support beyond the immediate instrument teams, accomplished through compelling science drivers. The funding scale is also somewhat limited, with the median award since 2010 being $500k. Combined with the low success rate (typically around one in three applications are successful), this greatly limits the usefulness of LIEF when planning or bidding for a major instrument project.

Research and development (R&D) not directly associated with instrumentation projects is funded through other competitive research grants, such as ARC Discovery Program grants such as Discovery Projects and individual Fellowships (DECRA, Future Fellowships). It is important to recognise that without such grants novel and innovative R&D will be very difficult to maintain, especially in optical/infrared instrumentation for which we no longer have a national observatory to support such research (Astralis is generally dedicated to project activities and other national priorities like industry engagement. It does not fund basic research). Yet without R&D at this level, Australia risks losing its competitive reputation as a leader in innovative instrumentation. It is also extremely difficult to fund meaningful R&D activities through e.g. charging project overheads or via commercialisation activities. Adding ‘markup’ to projects results in uncompetitive pricing for contract bids, especially where competitors enjoy national subsidies; and even technologies with promising commercial potential take years of development investment to realise significant profit.

Comparison with other countries

Here we provide the Working Group’s (anecdotal and incomplete) reflections on how instrumentation is supported and funded in countries with comparable instrument programs to Australia, and with whom we partner and compete for projects.

In the UK there is an ESO instrumentation “rolling grant” program - a series of predefined grants provided to institutions on an ongoing basis. Grants have to be justified every 3-5 years of course, but justification results in variation around a baseline, not like an ‘all or nothing’ grant scheme. This provides opportunities for groups to grow by engaging in new programs of significance, and a tapered reduction for groups in decline. This avoids the ‘boom-bust’ cycle that Australia has historically had with NCRIS for large scale national funding. It leads to competition, but this is within the astronomy community, and is probably healthy for science/quality.

Many US observatories have “instrument programs” built into the budget to some degree. They often need to find external support as well, but there is a baseline. The private observatories have access to significant philanthropic donations which we can’t easily advocate for.

In continental Europe, large scale, international (European) technology development programs for astronomical instrumentation have been/are typically funded through the European Union’s Horizon 2020 and newer large scale funding programs, bringing together experts from academia and industry from all European countries, and often led or coordinated by ESO. These are large scale, well coordinated, generously funded programs which deliver significant technology step-changes to enable new scientific discoveries through technology innovation.

For the European radio astronomy community, RADIOBLOCKS[4] is a new European Consortium to develop Next Generation Technologies for Radio Astronomy Infrastructures. The RADIOBLOCKS project, coordinated by JIVE ERIC and including major European research infrastructures for radio astronomy, together with partners from industry and academia, has been granted 10 M€ by the European Commission to develop “common building blocks” for technological solutions beyond state-of-the-art, that will enable a broad range of new science and enhance European scientific competitiveness. The RADIOBLOCKS started on 1 March 2023 and has a 4-year development plan. The RADIOBLOCKS project will take a holistic view of how radio telescopes arrays capture, process, synthesise and analyse cosmic signals and will develop components, technologies and software, applicable to a wide range of instruments, to enable the next major discoveries in radio astronomy

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[4] https://jive.eu/radioblocks-eu-next-generation-technologies-radioastronomy

3 Instrumentation workforce

3.1 Demographics and Career Paths

A total of 173 individual Decadal survey respondents indicated that they work on instrumentation, totalling more than 95 FTEs. These numbers include both post-graduate students and people on fixed-term and continuing contracts, scattered across about a dozen universities and CSIRO.

Over the past decade there has been growing awareness and institutional priority placed on workforce diversity to help reflect the demographics of the country at large,[5] but the instrumentation workforce is still disproportionately male, with survey respondents indicating 114 men (67%), 51 women (30%), and 7 nonbinary or preferred not to say (4%; others did not indicate a response). These ratios are similar to those of the international AO community in 2024, based on individual surveys, where ratios of M/F/other were 63%/33%/4%, some change from 73%/27%/0% in 2014.[6]

These ratios among Australian instrumentalists remained similar when limited to people with masters or PhD degrees (M/F/other 67%/30%/3%). This imbalance is smaller among fixed-term positions (60%/36%/4%), and greater among continuing ones (73%/26%/1%). The imbalance is also higher at higher career levels (see Figure 1).

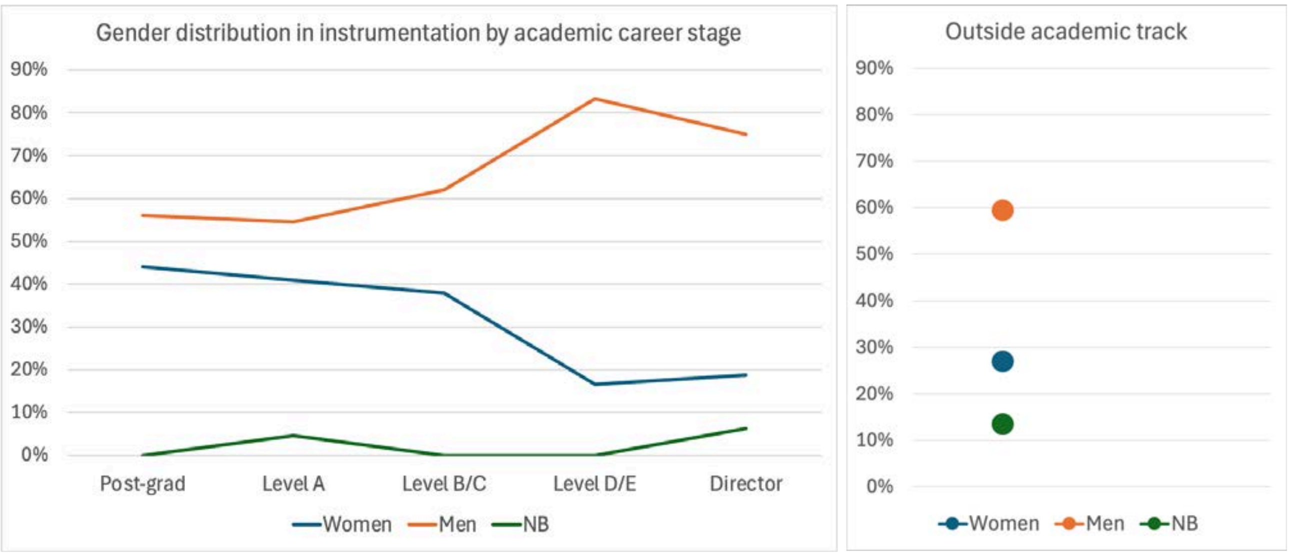

Figure 1: Gender distribution by career stage. 'NB' combines data from respondents identifying as non-binary and those who did not specify a gender.

The following community members expressed willingness to provide example information for their career pathway if useful for the Decadal Plan writing team:

- Trevor Mendel (ANU): Instrument science, coming from astronomy research
- Noelia Martinez (ANU): Instrument science, coming from engineering; DECRA Fellow
- Mark White (ANU): Software for astronomy, coming from astronomy
- David Brodrick (ANU): MAVIS project engineer, coming from software engineering for radio astronomy/high energy particle physics
- Jamie Gilbert (Rocket Labs, NZ): Formally ANU detector program lead

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[5] E.g., https://aao.org.au/diversity/

[6] d'Orgeville+ 2024 *SPIE Proceedings*, "Gender equity and diversity in astronomy and adaptive optics: what has changed since 2014 and what more can be done"

- Marcus Birch (laser comms company TBC): Recent ANU/AITC PhD graduate in adaptive optics and laser communications
- James Webb (Entrepreneur, CEO Platypus Instruments): Previous instrument scientist academic at ANU RSAA and research engineer at EOS Space Systems

In addition, any member of the Working Group may also be contacted to provide their perspectives on workforce and career path issues, or provide additional options.

3.2 Training in instrumentation in the academic environment

Training in astronomical instrumentation in academia can be seen as a launchpad to a number of possible careers, as it equips trainees with varied and highly employable skills, and bestows trainees with a level of rigour that is valuable in both academia and in industry, even if academically-trained personnel represent a minority in industry. Given the wide parameter space of possible careers, this produces positive knock-on effects for Australian society at large, and can cater to a variety of personal preferences regarding the subject matter of the job, salary level, contract lengths, location of work, and work/life balance.

The free and open research environment of a university is where many valuable ideas relevant to astronomical instrumentation germinate and develop, long before there is any industry incentive (or interest) in adopting them. Compared to many industry counterparts, trainees in this ecosystem imbibe rigorous training in maths and statistics, skills in programming and the processing of data, become adept at conveying technical ideas in holistic and clear ways, and by extension, to advocate for and "sell" their ideas. Trainees also gain long-term strategic thinking, with an in-depth familiarity with the underlying scientific motivations of the work.

Academia is also very amenable to international travel and collaboration, as well as the open sharing of techniques and results, whereas in industry much is proprietary or even classified. However, instrumentation projects can stretch over several years, with much of the work being done by students or postdocs-- and on timescales that are much longer than the lifespan of a PhD or postdoc position. Working on instrumentation can be an excellent learning experience, but it can be more inefficient to the project than if the work were carried out by engineers.

Once on the job market after graduation, instrumentalists are generally more employable in astronomy than many of their peers who do not have hardware experience. However, the technical and support roles in academia commonly subsist on short-term contracts, and the tightness of the job market means one has to be willing to move home, sometimes frequently. Industry or observatory work can offer comparatively longer contracts, and there is much greater choice of where to live. People tend to take on much more focused roles in industry, and tend to report a better work-life balance and less distraction from the need to apply for funding or the next job.

3.3 The worlds of academia and industry

[7]Industry jobs benefit from greater financial resources to do the work, the projects can move fast in pursuit of clear and circumscribed goals, and people with industry experience are often good at things like risk mitigation, or knowing where to find physical resources like tools— skills which are underemphasized in academia. While the reduced budgets of academia make projects take longer, it also means that astronomers, or people in industry who have trained as them, are resourceful and (out of necessity) become skilled at working on shoestring budgets. Given their exposure to a wide

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[7] *We acknowledge Marcus Birch, Anthony Cheetham, Luke Gers, and James Gilbert for sharing their experiences for this section.*

base of ideas and techniques, they are accustomed to thinking outside the box and avoid becoming siloed in terms of their methods and expertise.

People who have trained in instrumentation and have moved to industry or observatories report a more developed culture of project management in their new jobs, engineering controls, and documentation versioning, which can reduce the risk of additional overheads over the long term. This highlights an area of potential improvement on the academic side— namely, that of professionalising engineering practices. The main challenge is that this requires commensurate funding (often subsidised by the funding profiles of our international competitors), and the required expertise cannot be recruited quickly, as the pool of suitable candidates is small (unlike for many astronomical science programs). Specific expertise is needed from across diverse fields, each with solid technical engineering foundations, and operating to best practice. Moreover, this needs to be in place *before* competing to win large scientific instrumentation contracts, requiring a pre-existing level of stable base funding to build from.

Despite reduced budgets, academia retains a great need for instrumentalists who understand both the instrumentation and the science. Observatory work is critical for keeping astronomy’s large facilities well-oiled, productive machines, and some positions offer a 50-50 split between scientific research and instrumentation work. Observatory work also offers a profession which is in some ways “in between” academia and industry, where many of the work methods mirror those of industry, but the objectives are strictly scientific. In addition, a pre-existing professional network from academia remains more important than if one were to transition to, for example, defence work. There are still plenty of collaborative learning opportunities in the workplace in industry, and in fact in a smaller company it may be the case that the work environment is less hierarchical, so that it’s easier to connect with management. (Some people who have moved to industry also maintain visiting positions at universities– another "in between" option.)

Students and EMCRs in instrumentation who are open to the idea of taking their training outside academia should look out for industry internship opportunities to get a sense of what the culture is like, consider attending an industry conference, and to make use of other options (like taking a project management course, for example) that can open up more possibilities in the future. If trainees are on the job market and have found a company culture that is right for them, they should feel encouraged to make that transition. The transition to industry is not entirely frictionless, as there are new and different learning curves, from learning new machine learning techniques to adapting to different management styles, but the training in instrumentation can leave them well-placed for pursuing a wide variety of options.

4 Future Trends and Opportunities

4.1 Facilities

Here we outline a number of key facilities where Australian researchers have (or could have) access, and where there is potential for instrumentation contributions. This complements the science-driven perspectives documented in the Working Group 2.1 White Paper, and is provided to inform the nature of the partnerships and opportunities from an instrumentation program perspective.

4.1.1 European Southern Observatory (ESO)

By its nature as the largest network of large-format research telescopes in the world, ESO represents a significant and ongoing opportunity for large-scale investment (and returns on that investment) in technology and engineering for instrumentation. Even with attrition from some of the smaller elements of the ESO suite in the future (e.g. closure of the smaller telescopes; smaller instrument suites maintained on the VLT to streamline operations, etc.) the large number of available telescope foci ensure that a wide range of scientific instruments will be required to serve the extensive ESO community. This ensures critical mass of expertise can be maintained across the community, and supports local institutional specialisation as multiple opportunities will be available with international collaboration, ensuring carefully considered specialisation can be widely deployed and is not a deadend.

The Extremely Large Telescope (ELT) will be the largest, and almost certainly the first operational, next-generation 20-40m class optical/IR telescope on the planet. The first generation instrument program is mature, with four instruments well advanced in their design: MICADO (NIR imager/spectrograph), HARMONI (optical/IR IFS), METIS (thermal IR imager and spectrograph), and MORFEO (multi-conjugate adaptive optics system). These represent the most ambitious and scientifically exciting instrument projects of their kind, involving many hundreds of FTEs over their duration. Australian instrumentation groups already have opportunities to contribute to these projects in small ways; however the scale of opportunity and the return on investment are currently limited. As non-ESO members, in-kind contributions have essentially half the value in terms of telescope time. However, as full members, Australian groups would be exceptionally well-placed to make major contributions to the ELT instrument program in the medium-to-long-term.

ESO membership does, however, bring challenges. The geographically diverse nature of (largely Euro-centric) collaborations requires excellent communication and project management. This brings local overheads and likely some duplication of effort. Timescales for large instrument programs have escalated over the last decade, with a move away from small PI-driven projects to complex facility-grade instruments, that leverage multiple technological developments, and require a decade or more of scientific and technical engagement.

Perhaps the major hurdle to realising the full scientific benefit of ESO membership is the instrumentation funding policies in place. Historically, ESO has contributed only hardware funding and ESO technical staff in-kind costs to projects (with even hardware costs now often only partially covered). With 60-80% of an instrument program typically comprising staff costs (technical and scientific), funding for the labour full-time equivalent (FTE) for project execution at member state institutes must be found within national funding programs. The broad community will benefit simply from regular competitive access to ESOs impressive and wide-ranging suite of observational capabilities. However, experience shows that engagement in truly groundbreaking observational programs requires full membership of the consortium building each new instrument, and this requires scientific and technical FTE contributions.

Historically, instrument consortium funding has come from a mixture of philanthropic donations, national ongoing/rolling grant programs, and short-term scientific grant opportunities. Philanthropy in Australia has typically been restricted to modest donations supporting endowment of staff positions etc. and not at the scale required for meaningful contributions to instruments. National ongoing funding currently comes via NCRIS, but is both modest ($5M p.a. spread across a portfolio of projects, including covering 45% of the labour costs of ESO/MAVIS) and insecure (needing renewed every 4-5 years), and is strategically managed by AAL, not directly by instrumentation groups and scientists, limiting agility and community-driven engagement. The Australian National competitive grants program (i.e. those administered by the ARC) has historically been used to extend of fill ‘gaps’ in instrument project funding; however, success rates are low, the time from grant development to outcomes is long, and the scale of funding available is inadequate to justify significant project roles.

4.1.2 Giant Magellan Telescope (GMT)

The GMT organisation has historically funded instrumentation programs from Observatory consolidated funds. These funds are of course raised from the member institutes/states. Australia (a 5-10% partner in this $2B facility) has been successful in securing return of a significant fraction of its committed funds as funded work packages for GMT instrument projects, and for the GMT baseline engineering. Given funding challenges in recent years, GMT has been required to accept a greater amount of in-kind contribution from member institutes in order to secure project progress on all fronts. Australia has benefited from this, from modest investment in MANIFEST and GMTIFS. However, this was largely during the COVID period while focus was on maintaining viability of institutes. At the current time, this investment has dried up, resulting in significant slow down in programs and a missed opportunity to secure a large role in GMT while retaining Australian investment in itself.

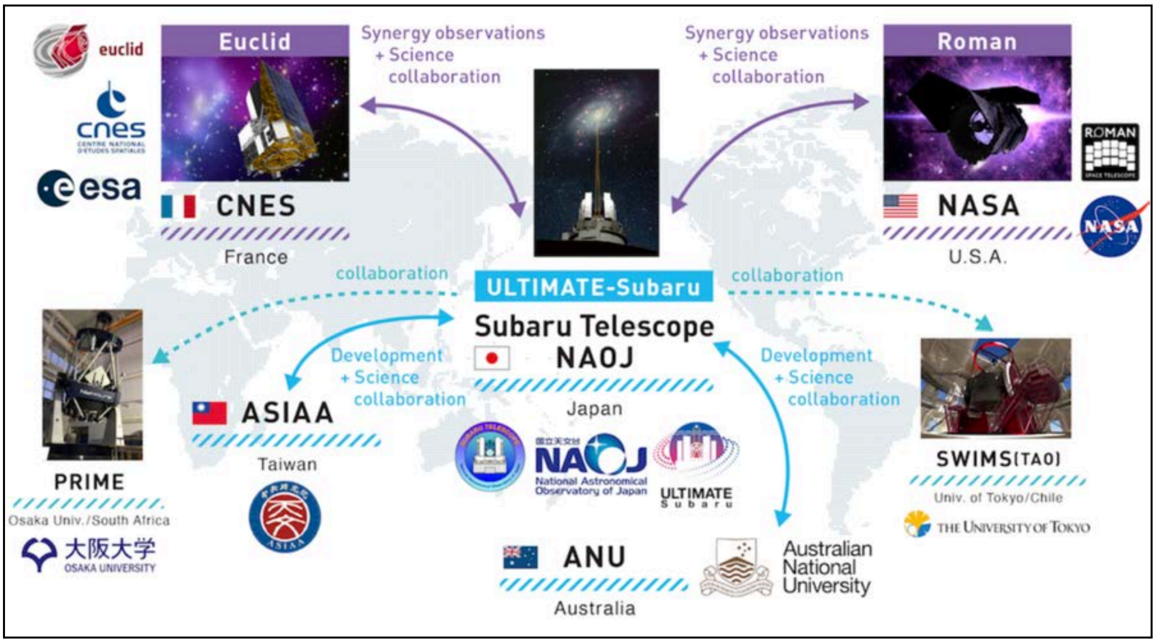
Currently, there are three Australian-led components to the GMT instrument program, GMTIFS, MANIFEST and LTAO, with an estimated budget (for completion over the next decade) of order AUD130M. This is approximately 50% of the AUD~260M investment that will be required to return Australia to a 10% partner in the GMT (a partnershare that ensure the Australian community is an equal partner with other leading members of the GMT community).

GMT have been very supportive in partnership with ARC-LINKAGE program applications, acting as industry co-funding partner. This has secured funding to develop high-speed IR wavefront sensors (for GMTIFS and GMTNIRS etc.) through the national competitive grant scheme but outside of the instrument projects directly. Additionally, they have engaged extensively with technical and engineering staff expertise at Astralis nodes for specific focused assistance in the wider GMT effort via Task Orders (small, well-defined work packages that can be flexibly scheduled and funded). This allowed technical staff at these institutes have remained engaged with the wider GMT program during periods where individual instrument projects where less active. This is an example of export of technical and engineering research services into an industry with which the instrumentation community has direct experience, which can be challenging with commercial industry.

4.1.3 Other 8-10m-class facilities

Australian astronomers have recent and existing relationship with many of the world’s premier 8-10m class telescopes. Here we provide a short overview of those connections, in relation to potential instrumentation projects and broader program developments

Subaru: Subaru Observatory operates an 8m optical/IR telescope located at the summit of Mauna Kea, Hawaii. In recent years, Subaru have focused on wide-field capabilities, both in imaging and multi-object spectroscopy, filling a niche that is not covered by other telescopes of this aperture size. This wide-field capability overlaps with Australian science interests, and there have been various strategic/collaborative activities between Australian and Japanese astronomers via Subaru and AAT access arrangements in the past.



ULTIMATE-Subaru is a program of instrument upgrades and development for the Subaru Telescope, centred around a new adaptive optics (AO) capability that will feed new imaging and multi-object spectroscopy instruments. This development program is supported by a research network, SUPER-IRNET, which is part of the Japan Society for the Promotion of Science (JSPS) Core-to-Core Program "International research network toward the era of deep and wide near-infrared survey of the universe with space and ground-based telescopes". The ULTIMATE-Subaru program is currently in a fund-raising phase for the AO upgrade and initial science imaging camera, and has collaborative ties with Australia through ANU's involvement in SUPER-IRNET, and directly with Macquarie University.

Keck: W. M. Keck Observatory (Keck) operates two 10m-class optical/IR telescopes at the summit of Mauna Kea, Hawaii. Currently, the only Australian access to Keck is restricted to researchers at Swinburne University, who pay for institutional access to 20 dedicated nights per year, and via collaboration. Swinburne also has representation in the observatory governance, being recognised as institutional partners. In terms of instrumentation, Swinburne, ANU-AITC and AAO-Macquarie are championing a new project - the UV/optical Keck Wide Field Imager (KWFI) - which has a strong science case, and will provide guaranteed time access to be awarded as part of the grant funding and for in-kind contributions made via the instrument project.

4.1.4 Widefield Spectroscopic Telescope (WST)

WST is a 12-metre wide-field spectroscopic survey telescope project under consideration as a potential next European Southern Observatory (ESO) project after completion of the 39-metre ELT. WST currently includes simultaneous operation of a large field-of-view (3 sq. degree), high-multiplex (20,000) multi-object spectrograph (MOS), with both a low and high-resolution modes, and a giant 3x3 arcmin^2 integral field spectrograph (IFS). In scientific capability, these specifications place WST far ahead of existing and planned facilities. In only 5 years of operation, the MOS would target 250 million galaxies and 25 million stars at low spectral resolution, plus 2 million stars at high resolution.

The WST project is at an early phase, with a full 3-year concept design study recently approved by the Horizon Europe funding scheme. The timescale for WST becoming fully operational is beyond the current decadal plan; however, there is a significant instrumentation component to the project, being a purpose-built spectroscopic telescope. There is strong potential for Australian instrumentation involvement, in addition to industry contracts for construction, that could form part of ESO membership negotiations.

4.1.5 Radio facilities and upgrades

The following text is extracted from the ATNF Draft decadal plan - please consult that document for additional information.

Improving the resolution of SKA-Low

SKA-Low is designed for baselines up to 74 km. With our observatory sites on the eastern side of Australia we could extend these baselines to over 3000 km. This would enable the resolution of SKA-Low to match that of the James Webb Space Telescope (JWST). Our Low-frequency Australian Megametre-Baseline Demonstrator Array (LAMBDA) is being developed for this purpose. A fully operational LAMBDA would provide a major addition to the SKA-Low capabilities, allowing many of the SKA VLBI science cases to be achieved, including the study of distant galaxies from the early Universe at sub-Galactic scales as well as the detection and imaging of the non-thermal radio emission from extrasolar planets, which requires sub-arcsecond resolution. As a pathway towards this longer-term goal, we are currently developing an early prototype and increasing our staff expertise in low-frequency VLBI.

Complementing SKA-Low with precision radiometers

Our development of precision radiometers, such as the Global Imprints from Nascent Atoms to Now (GINAN) system, advances our strength in developing high performance antennas and receivers operating in and around the SKA-Low observing frequencies. Such radiometers will provide the absolute calibration of the radio sky required for setting the flux density scale needed for SKA-Low measurements. Additionally, such systems enable niche, high-risk, high-gain science measurements of the global cosmological 21-cm signal that are complementary to the Epoch of Reionisation science to be carried out with SKA-Low.

Complementing the SKA telescopes with our current facilities

Our current ATNF facilities, ATCA and Murriyang, will provide larger instantaneous bandwidths than available with the SKA telescopes, long-term monitoring with high cadence observations and smaller-scale PI-driven science. Murriyang will also provide zero-spacing single-dish data sets, while ATCA will provide fast triggered follow-up observations. As foreshadowed by Fender et al. (2024) there is strong scientific benefit of such an array in the southern hemisphere.

SKA-Mid will lack the high resolution required to meet many of its scientific goals. This will come from the SKA telescopes acting as a sensitive element within existing VLBI arrays, or through the follow-up of SKA-led discoveries with independent VLBI arrays. The LBA has already demonstrated effective VLBI networks with the Hartebeesthoek telescope in South Africa and hence will continue to provide the southern hemisphere VLBI network in the SKA era.

Situated alongside SKA-Low, ASKAP will have a direct role in commensal observations. A primary science driver for SKA-Low is the study of space weather, which has both societal applications and astrophysical interest. Through the study of interplanetary scintillation, SKA-Low will probe the magnetic field of coronal mass ejections at relatively large solar radii. Commensally, ASKAP will probe the same events, but at much closer radii. Together they will allow us to probe how space weather events evolve across interplanetary space.

Supporting the community through computing and algorithm development

We continue to take an active role in exploring, implementing and testing new algorithms relevant for next-generation radio astronomy facilities, including high dynamic range wide-field, spectral and polarimetric imaging, transient detection, efficient dedispersion and anomaly detection methods. The primary drivers are increasing the parameter space that we probe with our telescopes, maximising the probability of identifying signals of interest, while minimising the friction between observations and analysis.

Computing, algorithms and data centres are therefore fundamental to our goals. Computing technology evolves fast and the ATNF will maintain a research focus in this area to ensure that our solutions remain compatible with current and future, even speculative, advances. High-performance computing (HPC) and machine learning algorithms will continue to be an important focus, but quantum computing technology is advancing quickly. The dominant technology choice is yet to emerge and the potential applications to radio astronomy still need to be explored.

The SKA regional centres (SRCs) will provide access to the SKA telescopes' data products as well as providing platforms for advanced scientific analysis. The ATNF aims to be a major participant in these data centres and the Australian SKA Regional Centre (AusSRC) is already enhancing its functionality through the processing of ASKAP survey data.

Mitigating the risks of radio frequency interference

Radio frequency interference (RFI) is currently a limiting factor for our ATNF telescopes in many of their primary observing bands. At the ATNF we are developing and implementing mitigation methods through software, hardware or legislative means. This work is essential for continued ground-based radio astronomy and we continue to be at the forefront of research into mitigation strategies. Such work will be invaluable across the coming decade, with our infrastructure ideal for assessing methods.

Upgraded phased array feeds for ASKAP

Our technology and instrumentation development program is world-leading in the development of phased array receivers that have led to wide field-of-view survey instruments. Next-generation phased array feeds (PAFs) installed on the ASKAP antennas would revitalise the telescope in the SKA science era. In particular, we are planning a factor of two improvement in the current system temperature of the ASKAP PAFs. ASKAP will then be comparable to SKA-Mid for wide-area surveys, but with significantly more available observing time, at a tiny fraction of the cost and without the computational overheads required to process the data streams (and hence enable surveys with high-time or high-frequency resolution over wide sky areas). An upgraded ASKAP would be complementary to SKA-Mid, which is better suited for deep, pointed observations. We are currently developing a small-scale demonstration where a single next-generation PAF will be installed on an ASKAP antenna. This will demonstrate the effectiveness of the system prior to a major upgrade of all the antennas.

An all-sky radio monitor

An obvious extension of our phased array technology is an aperture array with sufficient processing capacity to allow a significant section of the sky to be observed from a given site. Continuous monitoring, with sufficient sensitivity and frequency coverage, would complement all existing radio telescopes. Such an instrument would allow the detection of whole populations of transient sources as well as continuous monitoring of known sources from rise to set on a daily cadence. We are exploring the possibility of using LAMBDA (or similar) to form a low-frequency all-sky monitor, which will explore the transients at low frequencies. There is also a long-term goal where an aperture array with the sensitivity of Murriyang in the 0.5 to 1 GHz range and outriggers to > 10 km allows millions of fast radio bursts to be detected and localised. Such datasets would dominate cosmological studies out to high redshift, while being an ideal multi-messenger instrument. These will identify radio events linked to sources detected in any other waveband, and other multi-messenger all sky detectors, such as the gravitational wave instruments.

4.2 New technologies

WG2.4 has identified several areas in which new technologies could play a transformative role in future astronomical instrumentation. These are described briefly below.

4.2.1 Astrophotonics

Astrophotonics (i.e. the manipulation of light within waveguides or other miniature devices for astronomical purposes), has ballooned in importance and interest since the last Decadal Plan. Techniques and infrastructure which have been built up in the telecommunications industry have enabled the highly controlled flow and interference of photons with pupil remapping chips, miniaturised waveguides, optical fibres, photonic lanterns, and more.

Australia has played a leading role in the development of astrophotonics, including the development of fibre Bragg gratings for OH suppression, photonic lanterns, arrayed-waveguide gratings for microspectrographs, pupil remapping for interferometry, beam combination. Some current and future trends in this area include wave-front sensing with photonic lanterns, the scientific exploitation of OH suppression, mid-infrared photonics for planet searches and characterisation, nulling interferometry, and microspectrographs. We note that investment in astrophotonics technologies is increasing across Europe and USA (see the recent Astrophotonics Roadmap[8]). Astrophotonics will only become more important in the era of ELTs, since it provides a way to miniaturise and modularise aspects of otherwise massive instruments, and in which the in-built AO makes the integration of photonic components easier. Photonic devices promise to maximise the science return which can be squeezed out of smaller optical/infrared facilities (e.g. AAT/GNOSIS, AAT/Dragonfly). Photonics were also critical in building the SKA-Mid frequency synchronisation system, and have led to the TeraNet project to carry out high-bandwidth optical communication between ground stations and satellites.

If Australia is to maintain its position as a leader in this field then investment in these activities is needed. Furthermore, Australia is a world leader in photonics research in general, and the astronomical community is well placed to capitalise on this expertise. More astrophotonic groups are now emerging in the U.S. and Europe, and Australia’s position of leadership in photonics will be contingent on maintaining the edge in areas which are complementary to those groups' efforts.

4.2.2 Fibre optics

Australia has many decades of expertise and a world class reputation in fibre optic spectroscopy, including instrumentation, fibre positioners, MOS and IFS. Future massively multiplexed instruments provide an opportunity to exploit and extend this expertise. Opportunities include the development of new positioning technologies (with larger patrol radii, and faster reconfiguration times), and fibres capable of operating beyond 1.8μm. Speciality fibres, such as hexabundles, photonic lanterns and fibre Bragg gratings can be (and have been) developed to extend the traditional applications of fibre spectroscopy to IFS, single mode devices, and atmospheric filtering.

4.2.3 Adaptive optics

AO will be of ever increasing importance in the coming years, in order to fully exploit the angular resolution of the forthcoming ELTs. Areas of technological development for Australia include the extension of AO to wider fields-of-view and shorter wavelengths, the development of new WFS (e.g. based on photonic lanterns), the development of more powerful lasers for brighter, more point-like guide-stars.

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[8] https://iopscience.iop.org/article/10.1088/2515-7647/ace869

4.2.4 Quantum technologies

Satellite to ground communications, using Quantum Key Distribution, can be improved using AO and single-mode fibre coupling to improve downlinks in the presence of atmospheric turbulence. Techniques from quantum computing, including quantum networks and quantum memories offer opportunities for extremely long-baseline optical interferometry.

4.2.5 Detector technologies

New developments in detector technologies offer many advantages over traditional CCDs. For example, lower noise and faster readouts with avalanche photodiode arrays and EMCCDs, zero noise with skipper CCDs, transient monitoring with neuromorphic imaging arrays.

4.2.6 Other emerging technologies

The following topics can be expanded upon by the Working Group upon request)

- AI-driven optical design or other impacts
- Low cost / low power integrated receiver ASIC for massive arrays
- High-performance low-noise amplifiers transistors
- Low-power, massive input beamformer chips for large arrays
- Ultra-wide bandwidth correlators - e.g. For ALMA

5. Findings and Recommendations

The following priorities reflect both the content presented in this White Paper, and the overall sentiments of the Working Group members captured through the regular group meetings and informal community feedback.

Finding 1: Instrumentation is a priority for Australian astronomy

- Australia has an internationally valued track record and capacity for innovation in astronomical instrumentation, with a skilled workforce decades in the making.
- Through the co-development of science and instrument research, this capability enables Australian scientific leadership in the technology-driven research field of astrophysics and space science.
- Building instruments for observatories can enable dedicated access to those facilities, while at the same time developing national capacity in associated technical areas, such as optics, electronics, software and data.

Recommendation: Continue to ensure Australian instrumentation excellence is enabling world-class science in astronomy.

Finding 2: Stable funding is needed to support core groups with key expertise

- Astronomical instrumentation is a specialised area. Growing and maintaining instrumentation groups requires long-term development of the relevant expertise, drawing from a small pool.
- Funding for individual instrumentation projects tends to be stochastic, and varied in scale, inhibiting strategic investment, planning, and recruitment of young talent.
- Project funding does not fund development of emerging technologies for future instrumentation.

Recommendation: Secure stable, dedicated base funding for national-scale instrumentation programs (including those of Astralis and CSIRO) for the next decade, with a broad mandate to both deliver and develop new astronomy instrumentation capabilities with international impact.

Finding 3: Astronomy instrumentation should be aligned, where possible, with major facility investments

- Alignment of instrumentation activities with major facilities builds the engagement of Australian astronomers with Australian instrumentation, maximising the science return of both investments.
- In-kind instrumentation contributions can offset partnership costs to international facilities, reducing the off-shore spend, and increasing return on investment in national instrumentation programs.
- Major facility partnerships typically run over many years, ensuring long-term engagement (scientifically, and financially) well-suited to typical instrumentation projects.

Recommendation: Align national-scale instrumentation program funding with the community's long-term major facility investments, potentially via in-kind arrangements or partnership agreements.

Finding 4: Large, long-term funding mechanisms are needed to engage in next generation instrumentation projects

- Taking a leading or major role in new instruments for next-generation astronomical facilities (e.g. ELT, GMT, or SKA) requires a scale and duration of funding currently not catered for by any national competitive grant scheme.
- Australia has the internationally-competitive workforce and facilities to lead and deliver such projects, but lacks the long-term funding mechanisms to secure them.

Recommendation: Enable access to stable, mid-level ($5-10M p.a.) funding over 5-10 year periods that permits full engagement and leadership of major instrumentation projects for world-class astronomy facilities.

Finding 5: Instrumentation groups, especially in academic institutions, should better support and cater for the diversity of career paths in instrumentation

- The vast majority of the astronomical instrumentation workforce are non-academic technical professionals and engineers with little or no background in astronomy.
- Outside of CSIRO, astronomical instrumentation activity largely happens within University-based groups, supported through limited-term project-based funding.
- Universities generally have limited mechanisms for supporting long-term career development and substantive employment for non-academic staff.
- Limited career stability and progression makes recruitment and retention of highly-trained technical professionals a major challenge.
- Academic careers emphasise a 'publish or perish' pathway that is not well suited to high-risk, high-reward research into new instrumentation, inhibiting the growth of technical research academics within University groups.

Recommendation: Establish sustainable and rewarding career paths within the sector for instrumentation professionals from academic and non-academic/industry backgrounds.

Appendix: Case Studies

In this Appendix we provide some examples of instrumentation projects, giving more project-specific information, including the context of the project development. These case studies can be expanded upon by the Working Group on request, along with supporting materials as needed.

CRACO - Follows on ASKAP success

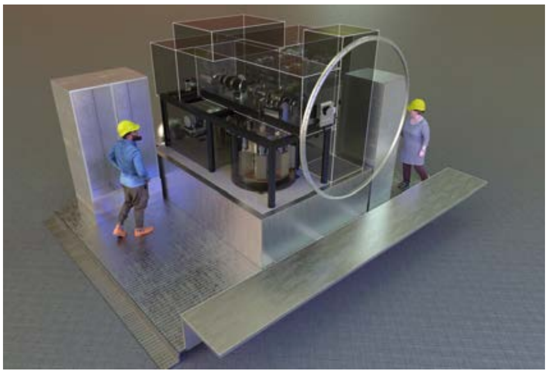
ATNF telescopes and instrumentation has been at the forefront of Fast Radio Burst (FRB) research. The first FRB t was discovered at Murriyang (Parkes) and subsequent confirming bursts were also discovered at Murriyang. With the help of ATNF engineering, a subset of ASKAP antennas were quickly re-purposed during commissioning. At one point, this sub-array held the record for the number of FRBs discovered. ASKAP was the first telescope to localise a once of FRB, a feat for which the team was awarded the Newcomb-Cleveland prize. Encouraged by this success, the ATNF has developed a new FRB antenna-coherent detector for ASKAP, dubbed CRACO. CRACO was funded by university partners and LIEF. CRACO continues the ATNF tradition of handling ambitious data rates: it will process 20 Trilion pixels per second, equivalent to 2 million people watching youtube, and fit in a box the size of a fridge. CRACO is in commissioning and has already discovered a slew of FRBs, ultra-long period sources and very nearby pulsars. It will be made available to any international astronomer via the ASKAP guest science time, which continues Australian radio astronomy's long-held open-access policy.

Long term investment in instrumentation results in export contracts and commercial spinoffs

The ATNF maintains a strong instrumentation group to support its primary facilities: Murriyang (the 64m dish at Parkes), The Australia Telescope Compact Array (ATCA) and the Australian Square Kilometre Array Pathfinder (ASKAP). In order to maintain those facilities at the scientific cutting edge, the ATNF has developed a range of technologies and instrumentation over a long period (30+ years). This instrumentation is world-leading, and highly desirable for upgrades of international facilities and commercial partners. Modified versions have been exported to other telescopes worldwide or technology-transferred to commercial partners. Examples include:

- **Parkes Multibeam:** Adapted to a 9-beam version for the Arecibo telescope, and 19-beam version for Five hundred meter Aperture Spherical Telescope (FAST)
- **ASKAP phased array feed and beamformer**: Exported to the 75m Lovell Telescope in UK and the 100m Effelsburg telescope in Germany
- **Parkes Ultra-wideband low**: Has led to a prototype system to be used on the US-lead next generation Very Large Array (ngVLA).
- **Parkes CryoPAF**: Adapted to the Qasar array for Satellite tracking via spinoff company and technology transfer.
- **CryoPAF beamformer**: FPGA technology deployed for the SKA low correlator / beamformer.
- **ASKAP imaging software:** open sourced as “yandasoft” and improved as part SKA contract.

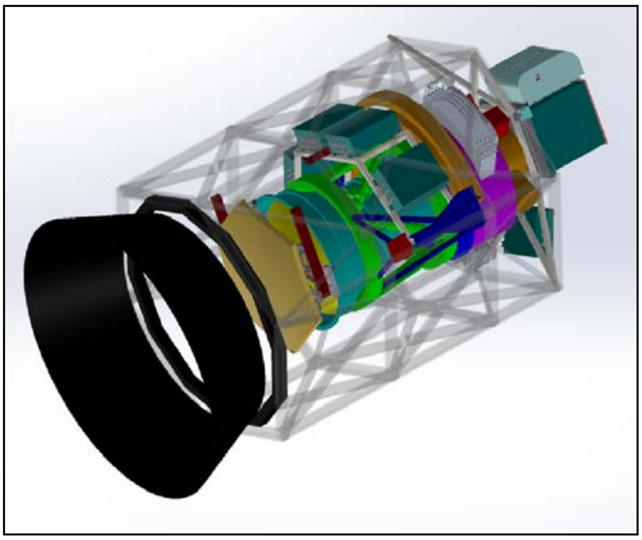
MAVIS (http://www.mavis-ao.org/)



On 1 June 2021 ESO and a consortium of Australian, Italian and French institutions signed an agreement for the design and construction of the MCAO Assisted Visible Imager and Spectrograph (MAVIS). This Very Large Telescope (VLT) instrument will push the frontier of new astronomical instrument technologies to provide, for the first time, wide-field, diffraction-limited angular resolution at visible wavelengths. In combination with the VLT Adaptive Optics Facility, it will use multi-conjugate adaptive optics (MCAO) to feed a 4k × 4k imager covering 30 × 30 arcseconds, as well as an Integral Field Spectrograph (IFS). Angular resolution down to 18 milliarcseconds will be achieved at a wavelength of 550 nm (V band). The IFS will provide four spectral modes, with spectral resolutions from 4,000 to over 15,000 between 370 and 935 nm. This will enable a wide variety of science cases, spanning themes that include the emergence of the Hubble sequence, resolving the contents of nearby galaxies, star clusters over cosmic time and the birth, life, and death of stars and their planets. Delivering visible images and integral-field spectroscopy at an angular resolution two to three times better than that of the Hubble Space Telescope will make MAVIS a powerful complement at visible wavelengths to future facilities like the James Webb Space Telescope and the 30–40-metre-class ground-based telescopes currently under construction, which are all optimised for science at infrared wavelengths.

Australia’s involvement in MAVIS is funded primarily through NCRIS funding administered by AAL, covering labour costs. An additional $2.5M was raised through an ARC LIEF grant, with generous co-funding from seven collaborating Australian institutions. This grant enabled the IFS capability to be funded in full, and increased the amount of guaranteed time returned to the project. The MAVIS project was initiated in 2018 through a community science workshop hosted by PI Francois Rigaut at ANU. First light is currently scheduled for 2030, illustrating the timescale involved in building a complex facility instrument.

Keck Wide-Field Imager (KWFI)



Led by Swinburne, KWFI is a partnership with AAO-Macquarie, ANU-AITC, Caltech, the University of California, and the W. M. Keck Observatory (Keck). KWFI is a UV-sensitive wide-field optical imager. It will be the most powerful optical wide-field imager in the world for 20+ years on the ground or in space. KWFI fills existing, and upcoming, wide-field imaging capability gaps in several areas. UV/blue sensitivity: the only imager with deep u-band imaging (3000-4000A, to m ~ 28-30) enabling many key science cases and new science. Rubin and HSC do not have this sensitivity and cannot reach the needed depth. Overall depth: KWFI sensitivity at 3000 - 10000A goes head-to-head exposure time, depth, and field area with NASA Roman Space Telescope (Rubin and Subaru HSC do not). KWFI has target of opportunity (ToO) capability, and rapid-response capability, whereas HSC does not and Rubin has very limited ToOs (~50 hr/yr for gravitational wave targets, i.e., 99% of all other transients ignored), Multiplexing: KWFI has wide-field imaging with seconds-later data processing and minutes-later spectroscopic capability with a deployable mirror (Rubin and HSC do not have this). Narrowband imaging: KWFI will have access to all 20 Subaru HSC narrowband filters, as well as user narrowband filters (Rubin has only broadband). Very fast imaging: KWFI will have CMOS fast sub-second imaging capability (Rubin and HSC do not have this).

Keck is the only observatory that can host this instrument. Other 8m-class observatories are at lower elevations and have poorer UV atmospheric transmission, have smaller collecting area (~60%), and require costly telescope and/or observatory restructuring. Keck is modular and designed for a wide-field prime focus camera and deployable secondary mirror that enables a fast spectroscopic multiplexing mode not found anywhere else, enabling new science.

KWFI is a workhorse instrument that will progress nearly every area of astronomy, and astronomy at all wavelengths, that will help Australian researchers lead the world. For example, only KWFI can map sources that ionised the Universe (escaping Lyman continuum flux) that requires wide-field, m ~ 28-30 u-band imaging, to directly complement SKA HI mapping of the neutral gas during the Epoch of Reionisation. KWFI will detect faint transients and the most distant transients and their host galaxies for current and next generation radio and gamma-ray telescopes (e.g, SKA, SKA pathfinders, CTA, etc.), high-energy particle detectors (IceCube, KM3Net), and GW detectors (LIGO/Virgo/KAGRA/LIGO-India, LISA, DECIGO, NEMO, Cosmic Explorer, and Einstein Telescope). In addition, KWFI enables the main science aims of Roman and Euclid space telescopes by providing the needed deep, wide-field, optical imaging for their deep fields, in particular m ~ 28-30 in u and g-bands, for accurate photometric redshifts and to help classify events for their transient programs, as well as the 20 other KWFI main science cases.

Guaranteed nights for AU are offered by Keck as part of the project's grant applications. Additional guaranteed nights and Keck access are available via multiple access avenues that include Swinburne partnership nights, large partnership opportunities for Australia, and future instrumentation opportunities. Additional Keck access is available via collaboration through multiple programs and with researchers in Australia and internationally. KWFI offers technological and training opportunities with Caltech, University of California, technological, scientific, and educational opportunities with 20 of the top 100 universities and institutions worldwide.

Industry engagement as part of the KWFI project currently includes Marand Precision Engineering, TNO, Siemens, New Frontier, and JPL. KWFI will progress large dataset and fast (seconds) optical data processing, analysis, and source identification, advance machine learning techniques in galaxy and transient science, and will pioneer industry 4.0 applications to develop the first ‘smart instrument’ with digital twin and smart sensors as a trailblazer for future instruments and for future application to research facilities as a whole for better performance, higher scientific output, lower operating costs, safer environment, improved human/machine interface, and preventative maintenance.