Report of the International and Space Facilities Working Group 2.1 for the Australian Decadal Plan 2026-2035

Co-Chairs:
Simon Driver and Emily Wisnioski

Authors:
Emily Wisnioski, Simon Driver, Andrew Battisti, Jeff Cooke, Taissa Danilovich, Jimi Green, Paul Lasky, Eduardo Trifoni, Aaron Robotham, Gavin Rowell, Rob Sharp

Executive Summary

Over the past decade the Australian Astronomy community has grown in breadth, with strong world-leading capacity existing across optical/infrared astronomy (VLT, Keck, DESI, HST, JWST), radio astronomy (ASKAP, MWA, MeerKat, VLA, VLBI), submm astronomy (APEX, ALMA) and increasingly gravitational-wave astronomy (LIGO), very-high energy (CTAO) and high-energy particle physics (Auger, IceCube). Many of the questions we now look to answer are growing in complexity, requiring not any one facility, but rather a combination of facilities covering a broad range of wavelengths, operational modes, technologies and increasingly involving larger volumes of data and larger allocations of time.

Australia in particular - and in comparison to the global community - has a strong survey-based approach and an equally strong instrumentation capacity. The two often work together with instrument contracts securing large allocations of guaranteed-time observations, allowing us to plan and lead major science endeavours and address BIG questions. This capacity and mindset is world leading, and underpins how we are viewed on the international landscape: Instrument builders and survey leaders. It is demonstrated through our successful leverage of large program time through the ESO strategic partnership with over 88% of our ~60 VLT nights/yr awarded to large programs (r.f. European average of 25%). It is also expressed through Australian-led surveys being conducted with our radio facilities, including ASKAP and MWA, the surveys we are planning with the SKA, the long tradition of large-program surveys on the Anglo-Australian Telescope, our leadership of 4HS and WAVES on 4MOST, our engagements with Rubin C. Observatory's LSST and the scope and scale of our gravitational-wave (OzGrav) and Gamma Ray science programs.

The future for the continuation of our global leadership in survey Astronomy, however, currently hangs in the balance with the question of full ESO membership paramount to our future. ESO is the only global suite of facilities that can provide breadth, capacity and future opportunities for our scientists and instrument builders and secure our continued global leadership.

The coming decade will also see the commencement of operations with the SKA and the final realisation of what will be transformational science led by our radio community. Critical here is for Australia to, at a minimum, safeguard its participation at a consistent level (~14%) as we move from construction to operations, where costs can accumulate, and new partners join. Of equal consideration, is the need to prepare and ensure our teams will have the tools needed to extract the best science from the large quantities of data that the SKA will accumulate.

Looking beyond ESO and SKA is the management of our significant investment in the Giant Magellan Telescope, providing exciting opportunities for our instrument builders (e.g., MANIFEST, GMTIFS) and for our high-fidelity optical community to lead and plan new frontier science at the close of the decade. Within the coming decade, data volumes and their management are likely to be challenging, with the advent of Vera C. Rubin Observatory's LSST, the radio surveys and a number of new Space-telescope facilities (JWST Euclid, SphereX and Roman in particular). Astrophysics will be one of the first sectors to truly hit multiple Peta-byte scale data-flows with excellent opportunities to lead society in data management, optimization, the integration of AI, quantum computing and cross-sector standardisation essential for the information overload era. To achieve this centralised assistance (computing and careers), will be vital in deriving world-leading cross-facility data products that will allow our survey programs to be fully panchromatic and internationally outstanding.

The growing number of international Space telescopes, both small and large, should provide new opportunities to help sustain and expand our instrumentation groups, but first they need to overcome the breakthrough barrier. This is important and will require significant resources, but should not come at the expense of our existing world-leading ground-based instrumentation programs. Hence new funding is critical, and opportunities for new funding streams should be explored for cross-discipline instrumentation development with partners such as Planetary Science, Earth Observation and Solar Physics.

Australia also provides unique opportunities in terms of its longitude and latitude, hosting one third of NASA's and half of ESA deep space tracking dishes, as well as critical Southern Hemisphere follow-up facilities such as MINERVA-Australia and LCO. With the advent of transient astronomy (LSST, GW etc), this is likely to be a global growth area with Australia extremely well positioned to follow-up LSST alerts. A clear opportunity is for Australia to host a Southern Hemisphere gravitational-wave node for ASTAR. Strategic management of this sector is likely to lead to maximum returns.

The final piece of the facility landscape is to support our emerging and burgeoning communities, and in particular the gravitational-wave, very high-energy and high-energy particle scientists. These communities currently obtain international facility access through short-term funding awards. While these communities are likely to continue to secure research awards, because the cases are compelling, this mode of interaction is poor value for money as long-term agreements facilitate broader engagement especially around collaborative instrumentation development and leadership roles.

1 Recommendations

In this section we summarise the recommendations reached within individual sections of this document. The following recommendations have been provided in tiers. Within the individual tiers the recommendations are not ranked but considered on equal footing or to be considered as complimentary.

1.1 Tier 1 Recommendations

- **O/IR:** Australia should join the European Southern Observatory as a full member state
  - Following community consultation membership of ESO remains the overriding top-goal of the community.
  - In the advent that this recommendation is not possible Australia should seek investment in commensurate facility partnerships.

- **Radio**: Australia continues to capitalise on its engagement with the SKA and SKA precursors
  - Australia's share of the SKA should remain consistent with its current level.
  - Sufficient data resources should be maintained to manage and process SKA data.

1.2 Tier 2 Recommendations

- **O/IR:** Australia maintains and protects its current share in the Giant Magellan Telescope (GMT) as a national asset by funding and supporting the completion of GMT instrumentation built in Australia.
  - Australia should not let its current share in the GMT degrade below 3% if we join ESO, or 10% if we do not.

- **Space+Radio+O/IR:** Australia should strengthen its ability to access international ground and space facilities and/or associated data streams and products through data and computing capacity. This national capacity should include the ability to host and process large (PB) datasets, support careers for software engineers, and to integrate multiwavelength datasets that benefit Australia's existing investments.

1.3 Tier 3 Recommendations

- **Space**: By the end of the decade Australian instrumentation teams have grown the capacity to participate in payload development for major NASA/ESA and other agency missions. This should be achieved through the pursuit of new funding pathways that do not undermine our existing ground-based instrumentation programs, in collaboration with adjacent disciplines and with coordination between NCA and NCSS.

- **Space:** That a strategic and coordinated approach is taken to capitalise on Australia's unique location for space-support operations (i.e., communications and follow-on) with a clear goal to leverage greater access, engagement and collaboration with existing and future space-platforms and their science programs.

- Appropriate funds are identified/sought to ensure stable engagement with key facilities important for the Australian community and in particular, long-term membership of:

    - **O/IR:** the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST)

    - **GW:** the Laser Interferometer Gravitational-Wave Observatory (LIGO) and/or Cosmic Explorer

    - **Gamma Ray:** the Cherenkov Telescope Array Observatory (CTAO)

    - **HE particle:** Auger and/or IceCube

- **GW:** Funding options are explored for an Australian-based gravitational-wave observatory.

2 Decadal survey process

2.1 Consultation process

WG2.1 consisted of 30 members of the community including:
A/Prof Emily Wisnioski (ANU), Prof Simon Driver (UWA), Dr Eleanor Sansom (Curtin), Prof Rob Sharp (ANU), Prof Celine D'Orgeville (ANU), Prof Paul Lasky (Monash), Prof Andrew Cole (UTAS), A/Prof Lee Spitler (UMQ), Dr Andrew Battisti (ANU/UWA), Dr Joice Matthew (ANU), Prof Luca Cortese (UWA), Dr Ing Trifoni (ANU), Dr Sarah Sweet (UQ), Prof Francois Rigaut (ANU), Prof Aaron Robotham (UWA), Dr Brent Groves (UWA), A/Prof Francis Bennet (ANU), Dr Sarah Pearce (SKAO), Dr Luke Davies (UWA), Dr Rajan Chhetri (CSIRO), Dr Vanessa Moss (CSIRO), Prof Jeff Cooke (Swin), Prof Cathryn Trott (Curtin), Dr Taissa Danilovich (Monash), Prof Lister Steveley-Smith (UWA), Dr Michael Kriele (UWA), Prof Simon Ellingsen (UWA), Dr Clancy James (Curtin), Prof Tamara Davies (UQ), and Prof Phil Bland (Curtin).

The group met:
25th Jan via Zoom to discuss the scope of work and define three online documents:
26th Jan - 7th May via Google Docs to evolve four discovery papers:

- The International and Space Facilities component of the community questionnaire
- A summary of ongoing or existing financial commitments to facilities
- A summary of future facilities of interest to the community
- Useful figures

7th May a final review of the survey questions
16th June to discuss the results of the survey and review slides for the Town Hall meetings
25th August to discuss and comment on the draft reports

Town Hall meetings were attended by Simon or Emily on/at:

July 18th Swinburne University	Simon in-person, Emily online
July 23rd University of Queensland	Simon in-person, Emily online
July 25th Australian National University	Simon online, Emily in-person
July 29th University of Tasmania	Simon online, Emily online
July 20th University of Sydney	Simon online, Emily online
Aug 1st University of Western Australia	Simon in-person, Emily online
Aug 2nd University of Adelaide	Simon online, Emily online

Information on community usage, priorities, and outcomes have been taken from a number of surveys focused mainly on ESO and optical instrumentation. The surveys are listed in Table 1.

2.2 Decadal Plan Survey Summary

The full results of the community questionnaire are summarised here and presented in more detail in the accompanying Appendix B (provided as a separate document). 374 of the 560 survey participants completed the International and Space Facilities section of which 350 identified as Research or Research & Teaching. The conclusions below are based on the 374 respondents. We recognise that this survey captured only a subset of the Australian community and is thus a limited representation with some biases, as mentioned below.

Table 1: Summary of surveys specific to ground based international facilities

Year of Survey	Survey Title	Organisation leading survey	Number of survey respondents
2019	Australian ESO Users Survey	AAL	16
2020	Australian ESO Users Survey	AAL	24
2021	Australian ESO Users Survey	AAL	15
2022	Australian ESO Users Survey	AAL	11
2023	Evaluation of the Access to World Leading Astronomy Infrastructure (AWLAI) program	ACIL Allen; commissioned by Department of Industry, Science and Resources	124; 25 interviews
2024	Decadal Plan Survey; WG2.1 specific questions	Australian Academy of Science; Decadal Plan Working Group 2.1	558 total respondents 374 for International facilities/space

The Australian community contains significant breadth but with a dominant focus in cosmology/AGN/extragalactic astronomy (43%). This is followed by established activity in instrumentation (15%) and stellar astronomy (13%). Gravitational waves (GW), pulsars, space physics and planetary researchers are represented by 5%, 4%, 4% and 3% respectively. Time domain, astrobiology, mult-imessenger and gamma ray researchers represented <1% of respondents (and clearly under-represented). Our community is dominated by optical/infrared (29%) and radio (18%) astronomers. Researchers self-identifying as theory or computation focused combine to a significant number (28%).

The top most used ground-based international facilities, in rank order, were: ESO(VLT), Keck, MeerKat, VLA, ESO(ALMA), LIGO, Gemini, Subaru and LCO and looking forward the top facilities the community expect to use are: ESO(VLT), SKA, LSST, SKA(MeerKat), Keck, ESO(ALMA), ESO(4MOST), ELTs (ESO/GMRT), VLA/ngVLA and LIGO

The majority of our community has made use of space facilities over the past decade, with 38% responding that have done so at a medium-high to high level of importance. Looking forward this is expected to rise to 48% (medium-high or high). There was no way to judge whether this was in combination with ground-based facilities or standalone. The most common Space facilities were HST, GAIA, JWST, Swift, TESS, Kepler, eROSITA and XMM and looking forward key facilities are: JWST, HST, GAIA, Euclid, Roman, TESS, SWIFT, and Chandra. Of these facilities only Roman is yet to launch (expected 2027).

References to the survey and data therein are made throughout this document.The full summary of the survey, with plots, can be found in the accompanying Appendix B included as a separate document.

3 Access models

When it comes to securing access to international and space based facilities[1], there are a variety of access models that need to be considered and fostered. We highlight these here as they provide context to the discussion that follows.

3.1 Monetary investment

The traditional model for access to most international ground-based facilities (with radio and some space telescopes being exceptions) has been via a monetary contribution. As the scale of ground-based facilities has grown, so too has the associated costs and the sums become significant and beyond the capacity for the University sector to cover. In most cases costs are two-fold with an upfront capital construction cost, and an ongoing operations cost requiring a continuous long-term commitment. Few countries can now afford to run their own major (optical) observatories in the large (8m+) telescope era (the USA and Japan are the two sole exceptions). Hence, it is now typical for most nations to combine resources through the formation of multi-facility observatories such as ESO or the SKA. Membership of observatories such as ESO and SKA requires a significant contribution to cover the investment to date, ongoing construction costs, as well as ongoing operations costs. These costs can now only be reasonably resourced at the governmental level. For smaller endeavours such as LIGO, VRO/LSST or CTAO the costs are more manageable and membership has been achieved through repeated short-term 3-5 year LIEF awards (with some supplement from NCRIS). However, this situation is less than ideal due to the long-term nature of the facilities and the uncertainty associated with support through a short-term peer-review grants program. Consequences of this model include limited access to leadership roles which are unlikely to flow to nations with only short-term memberships. In some cases individual institutions are able to, on occasion, make special arrangements (e.g., the Keck-Swinburne or 4MOST-UWA models) but this is less than ideal as the funding is likely to be time-limited and can create inequity both within and outside the institution. Direct monetary investment is traditionally less applicable to major space based missions which are typically funded through agencies such as NASA or ESA and, like radio astronomy, typically follow an "open skies" policy. However exceptions are now starting to appear with missions like Euclid allowing buy-ins through cash or in-kind effort from non-ESA members.

3.2 In-kind hardware

One way to offset large monetary investments for optical facilities is through instrumentation contracts awarded to national instrumentation capability around Australia. These typically come with guaranteed time observations (GTO) that can be substantial and allow for a ground-breaking major science program to be led by the instrument team and associated scientists, i.e.,100s of hours or nights. In Australia's case, and possibly unique, the GTO time is

[1] Facility is taken here to mean both a traditional facility (e.g., a telescope) and/or an international database (e.g., LSST).

typical made available as a nationwide opportunity, e.g., design effort for DESI, AESOP on 4MOST. The ability to contribute an instrument can be a critical factor when negotiating for longer-term membership to offset costs, or can be a one-off transaction that does not always necessitate long-term access. Australia has been highly successful in this capacity in the past through the world-class instrumentation teams that are an important and integrated part of our community and much of Australia's scientific success is a result of innovative instrument builders. Instrumentation capacity within Australia currently covers a broad wavelength range from UV/optical/infrared/mm and radio. While predominantly focussed on ground-based facilities interest is starting to grow around space-based instruments (e.g., SpIRIT, iLAUNCH, BINAR, TOLIMAN). The growing scale of instruments means growing costs and timescales not well suited to any current funding scheme. The instrument pathway also has significant inherent costs as many instrument contracts do not cover salary FTEs. These are expected to be an in-kind contribution provided by the host institutions. In many cases instrument contracts, including ESO, only cover some portion of the component costs (~50-80%). These issues have been expanded upon in the Instrumentation white paper but are strongly linked to the access models discussed here.

3.3 In-kind software / data processing

Increasingly as we move into the regime of 'big-data,' an additional form of access has become apparent through the provision of data processing capacity, i.e., data centres, with dedicated Data Engineers and the development and application of astronomy software. Recently we have seen this employed successfully to secure access for Australian astronomers to the Vera Rubin Observatory's Large Survey of Space and Time (LSST). Here an ARC LIEF award is providing 3 years of FTE effort of Data Engineers as directed by Rubin Observatory and a LSST data centre in Australia with 1.5PB of storage. It is also an example of the move to purpose-built facilities running dedicated multi-year surveys rather than running an annual proposal-based system. This new model begins to equate access to a facility to access to the data from a facility. This is currently more commonly seen with space-based missions, e.g. Herschel, Euclid. As a further example, Australia was offered membership of the Euclid Consortium with full access to all Euclid data in exchange for Data Engineer support - an opportunity Australia was unable to respond to given the timescale and limited funding resources available. In the coming decade a additional model is possible to envisage data-processed archives taking on the status of a facility in their own right, and can be bartered or exchanged for access to external international datasets. An example of this was the exchange between the Galaxy And Mass Assembly team who managed to barter the 200 nights of data acquired from the Anglo Australian Telescope (AAT) for early access to ESA Herschel, ESO VST KiDS and ESO VISTA VIKING data. As indicated by these examples, Australia already has some capacity in data and computing resources through past and current efforts (e.g. Data Central, ADACS, CSIRO ASKAP Science Data Archive (CASDA), WMA All-Sky Virtual Observatory). The opportunity to use data capabilities as a means of access overlaps considerably with the recommendations from the Data and Computing white paper, particularly with respect to "Platforms," "Software," and "Working Practices and Careers."

4 Optical/IR Facilities
4.1 Progress against 2015-2025 Decadal Plan

Recommendations for this decade were made in a number of documents including the original decadal plan, the mid-term review of the decadal plan, and in the previous white paper on international facilities. The relevant recommendations and progress against them are summarised below.

- "Partnership equating to 30% of an 8-metre class optical/infrared telescope"[1] revised to "Achieve full membership of the European Southern Observatory at the earliest opportunity, and well before the current strategic partnership ends in 2027."[5]

  [Temporarily Achieved] A 30% partnership in a 8m class optical/IR facility was achieved in 2017 with the ESO-Australia 10 year Strategic Partnership which was encompassed by the Access to World Leading Astronomy Infrastructure (AWLAI) program. The current ESO agreement ends in 2027.

- "Partnership equating to 10% of a 30-metre class optical/infrared extremely large telescope (ELT), such as the Giant Magellan Telescope (GMT)"[1] revised to "Protect the substantial national investment by supporting the completion of the Giant Magellan Telescope (GMT), including funding of GMT instrumentation built in Australia."[5]

  [Temporarily Achieved] Partnership equal to 10% of a 30-metre class optical/IR extremely large telescope (ELT) was first achieved in 2008/2009 when AAL and ANU jointly invested funds in 2008/09 to become Founders in the GMT, a 25 metre diameter telescope in Chile. This investment secured a 13% share on the GMT for Australia which was maintained for most of the past decade. However, the final share will be closer to 5% due to increased costs and inclusion of new members in the coming decade.

- "Explore paths to LSST data access from the exchange of time on Australian national facilities, including AAT time (with a suitable suite of AAT instrumentation), time on other Siding Spring Observatory telescopes, and time on national radio facilities including ASKAP, ATCA and Parkes" [5]

  [Temporarily Achieved] Data access to the Legacy Survey of Space and Time survey was achieved in 2024, when a 15-year agreement until 12th June 2039 was formalised and signed by the AAL and the Rubin Observatory. However, while the agreement has been signed funding remains insecure beyond mid-2027. The lack of secure funding puts the investment of Australian resources at risk for achieving their full return.

Additional recommendations were listed in the previous white paper on international facilities.[6] We highlight one recommendation below that did not appear as a top recommendation in the previous decadal plan or midterm review, but persists as a community priority *across the full wavelength spectrum*.

- “There should be a more formalised national scheme to effectively support innovative ‘mid-scale’ projects (defined as ~$1-10M projects). To address the current gap in funding projects at this level, a responsive and recurrent funding scheme needs to be established so that these projects could win funding over the 5-10 year timescales required of major international partnerships. Projects should be selected by competitive peer review. *This scheme would then support innovative programs in frontier astrophysics and gravitational wave astronomy, as well as in O/IR and Radio.*”

  [Not achieved] National scheme to support innovative mid-scale projects (defined as ~$1-10M projects) which could include innovative programs in frontier astrophysics and gravitational wave astronomy, as well as optical/infrared and radio. The situation with respect to funding of mid-scale facility projects has gotten worse due to shifting focus of NCRIS priorities and rising costs of mid-scale projects.

4.2 Current landscape

4.2.1 8m class facilities

While the decade from 2005-2015 saw a decrease of access to 8m class facilities[1], the last decade was one of Australia’s most stable with steady access to the four 8m VLT telescopes from 2017-2025 through the advent of the ESO strategic partnership. The end of this agreement in 2027, putting Australia back to a place of instability and a future with potentially only external collaborator access to 8m class facilities.

During the strategic partnership, the community was awarded an average of 54-68 nights per year on the VLT/I and an additional 190 nights per year on the combination of smaller optical/NIR facilities (NTT, 3.6m, VST, VISTA) and the APEX sub-mm telescope. The community has shown a strong preference in particular for large format integral field spectroscopy and medium to high resolution slit spectroscopy.

A midterm review of the AWLAI program[3], commissioned by the government, was published in March 2024. It reviewed the ESO strategic partnership as well as the AAO transition out of government. The main findings with respect to the ESO strategic partnership are summarised as follows:

- *“The design of AWLAI was effective in positioning Australian astronomers to realise the intended astronomy research outcomes.”*
- The design of AWLAI *“did not position Australia to have the opportunity to best realise industry outcomes.”* This is in part due to the limitations around tendering for contracts within the strategic partnership. An amendment in 2022 was made to allow Australian industry and astronomy institutions to tender for contracts under the ESO Technology Development Program.
- *“Australia’s return on investment based on the investment in and benefits to date from the ESO-SP is neutral,”* comparable with the findings of other international studies (e.g., Canada, UK). The assessment of economic return underestimated the full benefit delivered through the ESO-SP. The report stated that the total benefit to Australia was

likely underestimated. The analysis did not include the broader socio-economic impacts, knowledge advances, and innovations arising from astronomy research, or the delay in outcomes as a result of the four Australian-led large programs and the effects of COVID. If these further benefits and complexities were included, the report made clear that the total benefit to Australia would be considerably higher.

Australia has a long history of large community led projects on our national facilities (e.g. 2dFGRS, GAMA, WiggleZ, SkyMapper, SAMI, DEVILS). This past decade has seen an increase of large community led projects on the ESO facilities of VLT and 4MOST. In recent semesters, 88% of Australia's observing time on the VLT has come from Large Programs. This far exceeds the ~25% average of other ESO member states[3]. The benefits of large projects include high-impact science and opportunities for students and ECRs to engage with large networks of scientists with quality data. Large scale projects were not feasible within previous access agreements with Gemini and Magellan and have only recently been possible with Keck at Swinburne. Any future arrangement for access to 8m class facilities should consider the desire and capability of the Australian community to bid for large programs on 8m+ class facilities.

4.2.2 30m class facilities

The Australian community aims to achieve 10% access to a 30m class optical/NIR facility, commensurate with the shares of other competitive nations in the field of Astrophysics.

Australia joined the GMT partnership in 2009 as a founding member with investment split evenly between the full Australian astronomical community and the Australia National University. The primary goal at the time was to secure Australia as an equal partner with all other founding members, ensuring that no single partner had a controlling interest in the project. This decision was motivated by previous experience with large international collaborations in which a small number of majority partners dominated the agenda and restricted opportunities for the Australian community to have a meaningful say in the scientific priorities pursued by the facility.

Australia has remained fully engaged in the development of GMT since its inception and is currently responsible for three major instrumental components of the observatory: the GMTIFS AO spectrograph, the MANIFEST multi-object fibre feed, and, the Laser tomography launch system and wavefront sensor (LTAO) for high sky coverage adaptive optics.

However, Australia has maintained only limited additional financial investment in GMT over the last decade. This has mostly been via modest additional investment in the Australian instrumentation work packages for which we have claimed in-kind investment credits in the observatory. The Australian partner share has eroded in part due to inflation, but also due to the realisation of additional cost for the wider GMT project which has necessitated the addition of new partner organisations (including discussion with the US National Science Foundation). The current value of Australia's partner share in GMT is estimated to be around ~5%, falling from an initial share of approximately ~13%.

If Australia is to realise the intended 10% investment in GMT, this will required a direct financial contribution to the GMT project. This is estimated to be of order USD170M (AUD~260M) over an approximately ten-year timeframe. This essentially doubles the current financial investment to date. However, following established precedent within the partnership, a significant fraction of this total, perhaps up to 50% (USD85M, AUD~130M) could potentially be provided as in-kind investment through delivery of existing instrumentation programs. The three Australian-led components, GMTIFS, MANIFEST and LTAO, require of order AUD130M investment over the next decade through to delivery to the GMT in Chile. Up to 75% of this investment would be made within Australia to support technical development staff, software and controls engineering, and for fabrication of major optomechanical elements by Australia industry partners. Such an investment secures wide scale access to GMT while building the local economy and securing technical expertise relevant to the advanced manufacturing and high-technology industries.

Operations costs are expected to be $60M USD/yr. A 5% partner would expect to pay ~$4.5M AUD/yr, or ~$9M AUD/yr for a 10% partner, once operations start.

Australia is leading the development of the GMTIFS instrument (ANU), the Laser Tomography Adaptive Optics (LTAO) facility (ANU) and the MANIFEST fibre-feed facility (AAO-Macquarie). Work on the GMT site and mirrors continues with the telescope enclosure passing final design review in 2024. However funding of the GMT through the NSF is uncertain. At the start of 2024, budgetary concerns indicated that the NSF may need to down-select from funding both TMT and GMT to a single facility. The outcome of NSF funding decisions is likely to be known in late 2024. GMT is generally thought to be favoured due to site issues with the TMT.

The ELT being developed by ESO is under construction and surpassed the '50% complete' mark in mid 2023[2]. Given the ESO model, the funding situation is more stable, resulting in the ELT having the most secure future. The opportunity for Australia to contribute the optical arm of first-generation instrument HARMONI arose at the end of 2023. A contribution of this scale would likely serve as a possible in-kind contribution to full ESO membership but requires further significant monetary investment beyond our current investments.

4.2.3 International survey facilities

We are entering a new era of large purpose-built facilities to conduct survey science across wavelengths. Here 'survey facilities' are defined as facilities built or re-purposed with a singular instrument capability and set multi-year projects covering >50% of the available observing time. These facilities mark a shift from facility partnerships to data partnerships (e.g. VRO described below). Australia has a large role to play in these survey facilities given its rich history in optical/NIR spectroscopic surveys, fibre positioner capabilities, and its emerging resources in transient follow-up. In this subsection we focus on the optical/NIR facilities in which Australia has access agreements in place. We include future optical/NIR facilities in Section 4.3 which are under development with strong Australian involvement. Space facilities are not included here but discussed in general terms in 6.2.

[2] https://www.eso.org/public/news/eso2310/

4MOST: The Australian ESO Positioner (AESOP) will be installed on the VISTA telescope in the first quarter of 2025 as the telescope is transformed from a near-infrared imaging facility to a multi-object fibre-fed spectroscopic telescope (4MOST). The upgrade is approximately A$12million in hardware and a further A$48million in FTE with AESOP costing A$6million and with guaranteed-time observations facilitating the Australian-led WAVES survey. The upgrade is being managed by the 4MOST Consortium - a collaboration of over 15 European and 2 Australian Universities - with Australian membership of the Consortium facilitated by the ESO strategic partnership. Operations will commence in the final quarter of 2025 and over 50% of the dark and grey lunation time over the first five years will be allocated to the Australian-led WAVES (GTO time) and 4HS (competitively awarded time). As part of the ROI for contributing AESOP Australia is also entitled to have 8 members of the community (not based at the two member Universities) and their RAs and PhDs participate in any of the 4MOST Consortium surveys. In addition, any astronomers based at UMQ and UWA may join any 4MOST survey. After the first 5 years of operations the consortium access reduces to a 25% share with the remainder offered to the broader ESO community. The Australian consortium of 4MOST members will continue through to the end of the second 5 year observing period with the process managed by UWA.

VRO: The Vera Rubin Observatory (VRO) surveys are expected to commence in 2025. A data rights agreement was formalised in June 2024 which will have a team of software engineers based at Macquarie University in Sydney and Swinburne University of Technology in Melbourne provide vital software for Rubin Observatory, together with storage and processing power for an Australian-based LSST Independent Data Access Centre (IDAC). The software will be developed by Astronomy Data and Computing Services (ADACS) and the IDAC will be managed and hosted by the Swinburne node of ADACS. The agreement allows for the appointment of 47 Australian-based Principal Investigators and 188 “Junior Associates”, across 14 AAL member institutions, who will gain prompt access to LSST data alongside their US and Chilean colleagues and be able to participate in the LSST Science Collaborations. Funding from a LIEF grant and NCIS will end in 2026/2027. Secure access to early VRO data will require continued funding at a comparable level to maintain promised commitments.

DESI: The dark energy spectroscopic instrument is part of the next generation of wide field spectroscopic surveys and will obtain approximately 60 million redshift across the Northern Hemisphere. It uses a 5000 fibre-position system mounted on the 4m Mayall telescope at Kitt Peak National Observatory in the USA. Australian instrumentationists were involved in early design work and this led directly to 2 Australians and their postdocs and students being offered full membership of the DESI program. These members now lead critical aspects of the science analysis from studying the Baryonic Acoustic Oscillations to measurements of neutrino properties and tests of homogeneity. Buy-in for additional members is at the A$250k mark which allows membership for a continuing staff member, two postdocs and unlimited students. DESI, like its predecessor SDSS, will have a strong influence in astrophysics over the coming decade by providing science-ready data, input data for multiple follow-on survey programs, as well as superb synergies with Australian-led radio survey programs where their footprints overlap. DESI data is made publicly available to the global community approximately 2 years after observations through a series of staged releases.

4.3 Future Priorities

4.3.1 The case for ESO

Access to 8m and 30m class optical/NIR facilities remains a top priority for a large component of the Australian Astronomical community and this has been borne out by the Decadal Planning community survey as well as the Town hall meetings (see Section 2). These surveys, in particular the wider-scope Decadal Plan survey indicate that ESO remains, for the second decade, ***the*** top priority for the community.

The clear advantage to full ESO membership is twofold: it's breadth and longevity. ESO membership is a full package deal with access to four 8m telescopes (VLT), an ELT, the world's best sub-mm facility (ALMA), the world's best optical interferometer (VLTI), a high energy array (CTAO; GeV to TeV), a number of smaller facilities (e.g., 4MOST), and future facilities which may include a wide-field dedicated spectroscopic facility (WST) and a new sub-mm facility (AtLAST). The four 8m VLTs and 30m ELT have a diverse range of instruments and the instrumentation design and manufacturing capabilities in Australia are well suited to lead future instrumentation consortium on these telescopes - assuming long-term funding is available (see Instrumentation white paper). Full membership of ESO would provide Australia with access equivalent to approximately a 7% share of the European ELT. While this falls short of the 10% aspired to in the previous decadal plan, when combined with our current share of the GMT would bring Australia's access to ELTs to the commensurate level with other comparable nations.

Crucially, ESO membership provides stability to the community through an on-going treaty level partnership, with access to the governance and future directions of the organisation as an equal peer in a 16 nation Council. ESO membership, as the frontier international facility, provides unparalleled science opportunities for our research community, inspiration for our students and competitiveness for our ECRs. The long-term nature of the agreement promotes fellowship, knowledge transfer, and collaborations with astronomers, data engineers, and instrument scientists across Europe. With 8-30m class instrumentation projects now being on decade-long timescales, the current strategic partnership has highlighted the importance of building process knowledge and maintaining relationships for projects to develop efficiently. ESO membership ensures this knowledge is transferred through project teams reducing overheads. Alternatives to ESO, with respect to just 8m access, are typically short-term based on the current financial need of individual facilities. Agreements or partnerships in these cases come with limited voice and minimal opportunities to influence outcomes, e.g., changes in operations costs.

ESO membership also provides access to facilities that are primarily in the southern hemisphere. Importantly this aligns with other Australian investments, in particular VRO and the SKA. Key Science Projects led from Australia will rely on existing and future optical/NIR based surveys (e.g. 4MOST) for redshifts, source identification, and follow-up science from new discoveries. Any alternative approach to optical/NIR/sub-mm facilities should consider optimising this connection.

Alternatives to ESO:

To meet the needs and aspirations of the current astronomical community without ESO will require a piecemeal approach and potentially a fragmentation of the community as not all of the piecemeal partnership deals necessary to replicate ESO's breadth might eventuate. It would also have an impact on instrument groups by removing the largest contractor of astronomical instrumentation with which we will have spent a decade building relationships and domain knowledge.

Without ESO membership our community would still be able to apply and compete for time on ESO facilities, however external applications for some of ESO's facilities come with restrictions around leadership and with quotas. Hence, the consequences would be significant and without stable and guaranteed access to 8m class facilities there may be difficulties in retaining and recruiting world-leading astronomers. However, the greater impact is really the inability of our instrument teams to be involved in bidding for ESO contracts, or engaging in the frontier design of new facilities (e.g., ELT instrumentation, WST, VLT next generation instruments etc). This in turn would act to suppress collaboration with European astronomers, increasing Australia's isolation. While collaboration is always possible one also has to have something to offer for any collaboration to be symbiotic.

4.3.2 8m class facility alternatives:

Required Capabilities: If we were to look at the past decade to see what key capabilities are required, we see that the optical/NIR community has strong scientific and technical expertise in high resolution spectroscopy and integral field spectroscopy. MUSE, XSHOOTER, and FLAMES being the most sought after instruments during the ESO strategic partnership[3]. This is unsurprising given the alignment with the $30M ASTRO 3D ARC Centre of Excellence ASTRO 3D which specifically focused on the scientific returns of integral field spectroscopy and a three dimensional approach to key science questions. The following describes other 8m class facilities, their alignment with the community, and current community involvement.

Subaru: As of 2019 there are two categories of Subaru partnership, with Subaru still actively looking for partners in 2024. Either option would provide less than half of the access to 8m class facilities as the current ESO partnership. There has been some past engagement with the Subaru community. In 2017, AAL funded ANU and AAO to engage with the Subaru instrumentation program at the level of $400k and gained limited access to Subaru telescope time. Since then no Australian funding has gone towards securing Subaru telescope access. ANU is being paid by NAOJ to design the Laser Guide Star Facility and wavefront sensors for the ULTIMATE Ground Layer Adaptive Optics (GLAO) system on Subaru. No guaranteed time was secured for this arrangement.

Efforts to link the Japanese and Australian astronomical communities have been explored with the SUPER-IRNET consortium, the JSPS program, and the ULTIMATE-Subaru instrumentation team. However, engagement has been low and it is not clear if the Subaru instrumentation suite will serve the same community that benefits from ESO facilities. Subaru lacks an integral field spectroscopic capability and the Japanese community has traditionally been focused on large field imaging. Subaru does however have a wide-field multi-band imager (Hyper Suprime-Cam) and, soon, an optical/near-IR wide-field spectroscopic capability in the form of the Prime Focus Spectrograph (PFS).

From the decadal plan survey, 16% of astronomers who identified as using international facilities (or data from them) reported that they anticipate using Subaru in the next decade with 13% identifying Subaru (or Subaru data) as contributing to their research over the last 5 years. The current use is likely through public imaging surveys while the increase may be due to the advent of PFS.

Keck: Keck includes two 10m optical/IR telescopes located in the northern hemisphere. Swinburne is now a full Keck partner for 2024-2034 and will receive 20 nights per year to serve their community of 133 astronomers (10% of the Australian community). The new partnership includes board membership with voting rights, equal voice in future science and instrumentation direction and contract bidding, Target of Opportunity (ToO) triggers, and access to Director's Discretionary Time. If a similar agreement were available at a national level, as has been indicated, it would need to provide the same number of 8m nights currently being used by the community in the ESO partnership, ~60 nights / yr.

Keck has the most comparable instrumentation suite to ESO instruments including the KCWI (MUSE-like) instrument, laser guide star adaptive optics integral field spectroscopy, imaging, and low-to-high-resolution spectroscopic instruments (OSIRIS, NIRC, NIRES, NIRSPEC, the upcoming LIGER), LRIS, DEIMOS, and MOSFIRE (optical+NIR single- and multi-object spectroscopy), and KPF, a sensitive spectrograph for exo-planets and other science. The Australian-led Keck Wide-Field Imager (KWFI) is a blue/UV-sensitive optical wide field imager concept that will provide wide-field broadband and narrowband images. KWFI is led by Swinburne with broader Australian collaboration and is a partnership between Macquarie-AAO, ANU-AITC, Caltech and the University of California. It comes with guaranteed time for Australians and is in mid-development, with components being built. Keck is also developing a MAVIS(ESO)-like instrument called KOLA, as well as ground-layer adaptive optics to increase performance on most instruments.

Gemini: Gemini includes two 8m optical/IR telescopes, one in each hemisphere. Australia let their previous time access agreement with Gemini lapse in 2016. The general impression from the community is that while the Gemini agreement did give access to 8m class telescopes the outcomes were suboptimal. A number of factors contributed to this including: insufficient number of nights for medium to large programs, low completion rates, lack of alignment of Gemini's priorities with Australian researchers' focus, lack of voice in planning or choice of instrumentation[3]. In the intervening 8 years there has been little change to the Gemini instrumentation suite. However, new instruments are expected to be added in the next two years; a transient follow-up optical/NIR wide-band medium-resolution spectrograph and imager (SCORPIO), a high-resolution near-infrared spectrograph (IGRINS-2), and GIRMOS a multi-object (four) near-infrared spectrograph using GNAO, a new AO system (which Macquarie is a partner in). There is currently little opportunity to join Gemini as a member state and any future opportunities would likely be at a <10% level.

Magellan: Magellan includes two 6.5m optical/IR telescopes in the southern hemisphere. Australia let their previous limited time access agreement with Magellan lapse in 2017. Magellan has a range of instrumentation capabilities including multiple spectroscopic facilities, however it lacks a large-format IFU (MUSE-like). Similar time agreements may be available for Magellan, e.g., 10-20 nights/year across ~3 years. However, full partnership would likely only be possible through the development of a third Magellan telescope with a focus on wide-field multi-object spectroscopy. While this is aligned with the Australian wide-field community the cost of such an endeavour is likely to be significant.

Limited access through in-kind contributions: Australia has a strong reputation for building quality instruments for world leading telescopes. Various institutes are in the process of building components of a number of instruments on 8m class telescopes including MAVIS (VLT); BlueMUSE (VLT); KWFI (Keck); Heimdallr-Asgard (VLTI); ULTIMATE (Subaru), and GNAO (Gemini). While instrument contracts often include some guaranteed nights in return, it does not ensure long-term or national access. It is also worth reiterating that preference is often given to observatory partners and many instrument contracts do not cover FTE costs which in many cases are expected to be borne in exchange for guaranteed time.

4.3.3 30m class facility alternatives and prospects:

Currently the timelines for the ELTs put both GMT and the ESO ELT at ‘first light’ at the end of this decade (2029 and 2028 respectively) with the first generation of non-AO instrumentation available at first light and all AO instrumentation following a couple of years later (2030s). However, currently the ELT instrumentation will all be AO and mostly in the IR.

GMT: The future and timeline of GMT are dependent on the consortium securing the remaining funding needed. To ensure a 10% share in the GMT, Australia would need to more than double its current monetary contribution (to ~$260M AUD) as described in the previous Section.

Limited access through in-kind contributions: Various institutes are in the process of building components for a number of instruments on 30m class telescopes including GMTIFS (GMT); MANIFEST (GMT). There are currently discussions underway for Australia to play a role in building the optical component of HARMONI (ELT). However, in general Australia must be a partner within the ELT consortiums to tender for instruments or instrument components for any of the ELTs. While Australia’s involvement in HARMONI would likely lead to a significant in-kind contribution to full ESO membership, it is unclear if it will lead to significant GTO time or membership in GTO consortia. Currently progress with respect to HARMONI leadership has stalled due to funding constraints.

All ELTs are starting 3rd generation instrument concepts with 2nd generation consortia already formed. These have decade-long development timescales for $30-200M instruments that come in at the same level as facility costs for smaller facilities. There are consortia that Australian teams can join *now*, or we can push for science leadership roles in new ones. However, the level of investment required does mean it needs to be community lead, not just a PI project.

4.3.4 International survey facilities

4MOST: The first 5 years of Consortium and Community surveys will be complete within the coming decade. The decade will also see the transition to the next 5 year period of 4MOST which sees wider community access and the establishment of new surveys. The next set of surveys are well timed with the establishment of SKA Key Science Projects and synergies between the two facilities should be considered. Regardless of the ESO outcome, continued engagement with 4MOST is assured albeit at the consortium not community level with 25% of the time in the second five years going to consortium surveys and the remainder to community surveys.

VRO: The Vera Rubin Observatory in Chile will commence operations from 2025 and take the majority of its core survey data in the coming decade. To take full advantage of Australia's strategic role with respect to data rights, continued funding needs to be secured past 2027. Should Australia not be able to meet this commitment, access to the VRO LSST survey data would be restricted for a two year period - in line with non-member countries - putting Australia at a significant disadvantage in terms of competitive science. VRO is highly complementary to Australia's wide-field spectroscopic and radio surveys providing complementary data that extends and expands the science that can be achieved. Perhaps more importantly, VRO will open a critical new door to time domain astronomy. VRO is expected to detect 10 million transients per night (orders of magnitude more than previously) during its LSST program, but with fragmented information and without follow up. Follow-up observations are, not surprisingly, time-critical, and with Australia's unique geographical location, ~10 hours to the West of Chile as the Earth turns, enables follow-up observations hours after VRO detections for critical early data (important to understand their physics and nature) and before many events fade away forever. Given the logistics, the world will look to Australia to respond to this new era in transients. The global leadership for Australia would be lost if Australians were not full members and excluded from VRO science, including data on the transient's host galaxies, previous history, etc.

WST (ESO[3]): While 4MOST and DESI represent the state-of-the art in 4m telescope design they are arguably the end-of-the-road for 4m surveys, with the next level requiring larger apertures to probe to faint flux limits and ideally near-IR fibre-positioning systems to probe to higher redshifts. In 2021, a large European and Australian consortium was formed under the leadership of Professor Roland Bacon for a concept design of a 10-metre class *Wide-field Spectroscopic Telescope (WST)* devoted to spectroscopic surveys and to be hosted at Paranal. The current WST design would have simultaneous operation of a large optical field-of-view, a

[3] Not currently a planned ESO facility but has growing support from the ESO community.

high multiplex multi-object spectrograph (MOS) including both low- and high-resolution modes, and a giant panoramic central IFS.

Currently WST is envisaged to be purely optical with an upgrade path to near-IR and for which Australian groups are developing a design concept. WST is likely to cost upwards of A$600 million and will not be operational during the 2025-2035 decade *but the ESO selection, critical design work and the lion's share of the construction are all likely to happen during the decade.* The instrumentation suite will be limited to one instrument with multiple modes of operation. Early participation from Australian institutes could guarantee later access through the GTO consortium or as in-kind contributions to full ESO membership.

A successful EU Horizon grant for 3M Euro over three years was awarded in 2024. This does not include any funding for Australia but includes 6 Australian partner institutes who collectively are contributing 16 FTE yrs in-kind to the design study. This includes 4 FTE of in-kind effort (1 FTE as lead) towards the WST science work packages. In addition, the Astralis Instrumentation Consortium has committed 12 FTE of in-kind effort (10 FTE as leads) towards WST technical work packages. Australians have contributed significantly to the science white paper published earlier this year[7]. There are 4 Australian astronomers on the WST Steering Committee.

MSE: In comparison to WST, the Mauna Kea Spectroscopic Explorer (MSE) has seen little development in recent years either in funding or Australian engagement. This is in part due to the cultural implications of building on the Mauna Kea summit in Hawaii, although the MSE design is to go into the existing CFHT observatory dome, resulting in no new construction). By the midterm review in 2020, the Australian led fibre positioner concept, Sphinx, was selected for MSE. However with the lack of funding or site clarification, no work has begun and funding partners yet to be identified. Australia maintains a representative on the MSE Management Group. The current focus of that group is for a pathfinder instrument to go on CFHT which would not require any change of telescope structure. Funding applications are pending.

4.4 Optical/IR recommendations

By far the largest uncertainty confronting the community in the international and space facility domain is that of security in access and partnerships. This is an overarching theme throughout this document and underlies most top-level recommendations. For the second decade running ESO remains the overwhelming aspiration and is the single action that would benefit the broadest section of the community and ensure Australia remains at the frontier of Astrophysics. The recent ACIL Allen report highlighted that at worst it is cost neutral and at best culturally enriching with benefits and returns that extend well outside the Astrophysics domain. Membership of ESO provides both front-rank research capacity, but just as important is the opportunity for our instrumentation community to participate in the research and development of the world-leading astronomical instruments on the world's best telescopes and an equal partnership share in the future direction of the observatory. It is necessary to provide our students and ECRs with the best possible opportunities and has been a conscious decision of over 16 nations who recognise that alone they cannot compete internationally but together then can. It is therefore uncontroversial to state clearly that:

O/IR recommendation 1: All pathways should be pursued to bring about Australian membership of the European Southern Observatory.

However, the uncertainty in ESO access affects not only the optical/NIR/sub-mm communities but has a carry-on effect in funding uncertainty for other Australian investments and younger sectors of the Australian community: space, gravitational-wave science, very-high energy science, etc. Given the risk presented by continual contract renewals and access agreements it is prudent for some effort to be invested in exploring alternatives to ESO membership. Such alternative plans are essentially an attempt to replace the functionality of ESO through multiple piecemeal agreements. This almost certainly will require a strong pivot from partnership in the world's premier observatory to having minor memberships of multiple facilities in which our influence is likely to be that of a minor partner. The concept of multiple minor partnerships and a limited market for our instrumentationalists to operate in is undesirable. Precise alternatives cannot be clearly specified at any time as it will depend on the needs of the individual facilities with opportunities opening and closing regularly. Appendix A outlines a possible alternative plan with approximate costings based on information available at the time of writing this report. Hence a second recommendation is:

O/IR recommendation 1b: Should membership of ESO not be possible, every effort should be made to implement an appropriate alternative arrangement, with emphasis on longevity, to provide partnership to facilities comparable to ESO in terms of 8m access, ELT access, and sub-mm access**.**

One missing ingredient in the current ESO complement and outlook is that of deep wide-field imaging such as that which will be provided by the VRO LSST. ESO on the whole provides frontier facilities to study the very detailed properties of modest samples of galaxies. 4MOST represents ESO's advance into wide-field astronomy yet critical to this aspiration and to our radio astronomers is deep wide-field optical imaging. At present ESO provides only modest depth imaging through the 2.5m VST telescope. The state of the art from 2025 will be the VRO LSST 8m facility that will provide the ultimate supporting data for our wide-field optical wide-field radio and transient communities. Australia's membership of the VRO LSST is currently funded through to 2026, further funding is needed to ensure that over 60 Australian Astronomers will benefit from immediate access to LSST data. Hence a final recommendation from the Optical/IR domain is:

O/IR recommendation 2: Long-term funding is sought to ensure Australian membership of the VRO.

While ESO membership and 8m access is at a pivot point, we continue to hold a percentage share in the Giant Magellan Telescope. By investing in the GMT early we were able to secure a 13% share. This is degrading with time due to costs and new partnerships. The future of the GMT has some uncertainty due to funding decisions of the National Science Foundation (NSF) in the United States. Decisions on the future of the GMT are expected within the year. Assuming that the GMT is supported by the NSF, and moves forward, Australia must maintain its current partnership agreement and deliver on the three instruments that it is leading. If Australia were to join ESO it would be in the unique position of having access to two ELT facilities and the expected ~5% share would complement the ~7% share of the European ELT that ESO membership would afford us. However, if Australia does not ascend to full ESO members we will fall behind comparable nations with a less than 10% share in an ELT. In this case we recommend to pursue a 10% share of the GMT, building on current investments.

O/IR recommendation 3: Australia maintains and protects its current share in the GMT as a national asset by funding and supporting the completion of GMT instrumentation built in Australia.

Table 2: Summary of 8-10m Partnership Categories

Partnership type	ESO Strategic Partnership	ESO membership	Keck Partnership	Subaru Associate (SA)	Subaru Partner (SP)
# of 8m	4	4	2	1	1
Cost (to be redacted)	[redacted]				
Joining fee	No	Yes	No	No	?
Access (nights)	54-68 nights / yr[1]	% of contribution	Up to 60 nights / yr (+ 20 n/yr Swinburne)	4.4 - 4.8 nights / yr	22 - 24 nights / yr
Term	10 years	Ongoing	Long-term, 10yrs?	>= 2yrs	>= 3 yrs
In-kind contributions accepted?	No	Yes (maximum of 25%)	No scheme now, but possible (e.g., instrumentation)	No	Yes (additional and <50% cash contributions)
Additional benefits	Access to: - Some governance roles - Large programs, - VLT instrumentation and computing contract opportunities, - submm (APEX; limited), - 4m (NTT, 3.6m, VST, VISTA) - Interferometer (VLTI)	Access to: - Full governance role - Large programs - All instrumentation / computing contracts[2] - all current facilities access (e.g. – ELT, – submm (ALMA) – 4m (NTT, 3.6m, VST, VISTA) – CTA (5%) – Interferometer (VLTI) – All future facilities (e.g. WST?/AtLast?)	Access to: - Full governance role - Large programs - Instrumentation and computing opportunities - Access to pool Target of Opportunity triggers - Access to Subaru exchange time	Access to: - Multi-partner program access	Access to: - Multi-partner program access - Large program access - Instrumentation contracts

[1] VLT nights only; an additional ~190 nights / yr have been obtained on other ESO facilities

[2] Expectation that competitive contracts should average ~70% of the annual contribution

5 Radio and Sub-mm Facilities

5.1 Progress against 2015-2025 Decadal Plan

- "Continued development and operations of Square Kilometre Array (SKA) precursors, the Australian SKA Pathfinder (ASKAP) and Murchison Widefield Array (MWA) at the Murchison Radio-astronomy Observatory (MRO), and membership of the SKA telescope"[1] modified to "Pursue realisation of the full Square Kilometre Array Observatory, while continuing to exploit its ASKAP and MWA pathfinders."[5]

  [Achieved] Continued development and operations of Square Kilometre Array (SKA) precursors, the Australian SKA Pathfinder (ASKAP) and Murchison Widefield Array (MWA) at the Murchison Radio-astronomy Observatory (MRO) was achieved in this decade. The updated recommendation from the Mid-term review to continue to exploit ASKAP and MWA pathfinders with consideration of cost-effective enhancements to maintain their scientific capability has also been achieved.The five-year ASKAP surveys have commenced with the full array, and the MWA has received a correlator upgrade. The MWA is in the process of installing new receivers to further improve the signal chain, and continues science operations. MWA infrastructure and signal chains have also been used to help with prototyping of SKA-Low stations, in a bid to support SKA construction.

  [Achieved] Australia has continued to invest in the SKA. Australia was one of the first countries to ratify the SKAO Treaty, and Australia is a full member of the SKAO Intergovernmental Organisation. Australia has a 14% share in the Observatory. SKA-Low is currently under construction at Inyarrimanha Ilgari Bundara, CSIRO's Murchison Radio Astronomy Observatory, with a Science Operations Centre in Perth and an Engineering Operations Centre in Geraldton.

5.2 Current landscape

5.2.1 SKA
The Square Kilometre Array Observatory (SKAO) is a three-site, two telescope radio observatory run through an International Intergovernmental Organisation (IGO) and defined by treaty. The SKA-Mid telescope in South Africa (350 MHz - 15 GHz) and the SKA-Low telescope in Australia (50 MHz - 350 MHz) are currently under construction, and in early commissioning phases. The two telescopes aim to be in full science operations by 2030, with early shared-risk science available from 2026-2027 through partial array releases. Australia is the host country for the SKA-Low telescope, housing both the Science and Engineering Operations Centres, and has a 14% share in the project overall, providing 14% community access to the telescope.

5.2.2 SKA precursors
SKA and its national precursors have historically been linked. In this decade we will see the long anticipated operations of the SKA. We briefly mention SKA precursors used most by Australian astronomers to provide some context to the transition to the full SKA over the next decade. As

noted in Section 5.2.3, Australian radio astronomers take advantage of a number of international facilities.

Murriyang/Parkes: In addition to conducting science geared towards the priorities of the SKAO, including discovering Fast Radio Bursts, and conducting long term pulsar timing programmes, the Murriyang telescope was recognised in 2016 as an SKA Pathfinder on the basis of phased array and wide-bandwidth feed technology development, examples being the Ultra-Wide bandwidth Low frequency receiver ('UWL') and the Cryogenically cooled phased array feed ('Cryo-PAF').

Murchison Widefield Array (MWA): The MWA resides at Inyarrimanha Ilgari Bundara. Curtin University owns and operates the MWA on behalf of an international consortium (currently, Australian consortium, US Consortium, Swiss Consortium, Japan, China, Canada). Members allocated per country based on contributions to the project. Australian access in Guaranteed Time is limited to Australia's individual members (from 6 institutions + CSIRO). NCRIS funding supports operations cost. There is an open call each semester for the telescope, in one of two array configurations (compact for EoR observing; extended for radio galaxy/continuum). There are Guaranteed Time (members) and Open Access categories. Data is publicly available 18 months after observation (18 months after end of observing semester for EoR data).

ASKAP: The Australian SKA Pathfinder (ASKAP) is a wide-field radio survey telescope located in Western Australia at Inyarrimanha Ilgari Bundara, CSIRO's Murchison Radio-astronomy Observatory. This radio-quiet site is also the location of the SKA-Low telescope. ASKAP is operated by CSIRO as part of the Australia Telescope National Facility (ATNF), and also receives some support through the NCRIS program administered by AAL. ASKAP is currently observing a 5-year program of large community-led surveys. ASKAP has an open skies policy, and an automated data pipeline provides processed data that is available through the public CASDA archive with no proprietary period. The current and future usage of ASKAP is discussed in the national facilities white paper.

MeerKAT: The MeerKAT radio telescope with 64 antennas is located in South Africa. There is an open call for proposals each year. According to the Decadal Plan Survey, MeerKAT data has been used regularly by the Australian community over the last 5 years, at a higher level than the VLA or ALMA. Of the international facilities that the survey respondents expect to use in the coming decade, MeerKAT ranks 4th behind the (1)VLT, (2)SKA, and (3)VRO.

5.2.3 International radio facilities

A large faction of the community uses international radio facilities for their research through open skies and collaborations. These facilities include but are not limited to the JVLA, VLBA, VLBI, EVN, FAST, Green Bank Telescope, GMRT, LOFAR, MeerKAT, and previously Arecibo. Some additional limited access is provided to the 70 metre dish at the Canberra Deep Space Communications Centre in Tidbinbilla. Australia Telescope National Facility continues to coordinate with Australian Universities in the operation of the Long Baseline Array, which in turn can include international radio facilities for longer baselines.

5.2.4 Millimetre and submillimetre:

There are currently no international facilities in which Australia has an official stake. There is most notably a lack of access to facilities operating above ~200 GHz as shown in Figure 1. Some international facilities, including ALMA, offer open time which Australians do compete to access with some success. Australian astronomers regularly use ALMA data (65 users that responded[4]) in their research accessed through a combination of collaboration, archive, and open skies. However, Australians are not able to lead large programs on ALMA. With no stake in higher-frequency facilities, Australia cannot directly participate in international high-profile projects such as the Event Horizon Telescope (EHT).

For a short period APEX could be accessed through the ESO strategic partnership (826 hours awarded over 3.5 yrs with a 100% success rate) however APEX is no longer operated by ESO. Since 2023, APEX is under the sole operational responsibility of the Max Planck Society and is expected to continue operations until at least 2028.

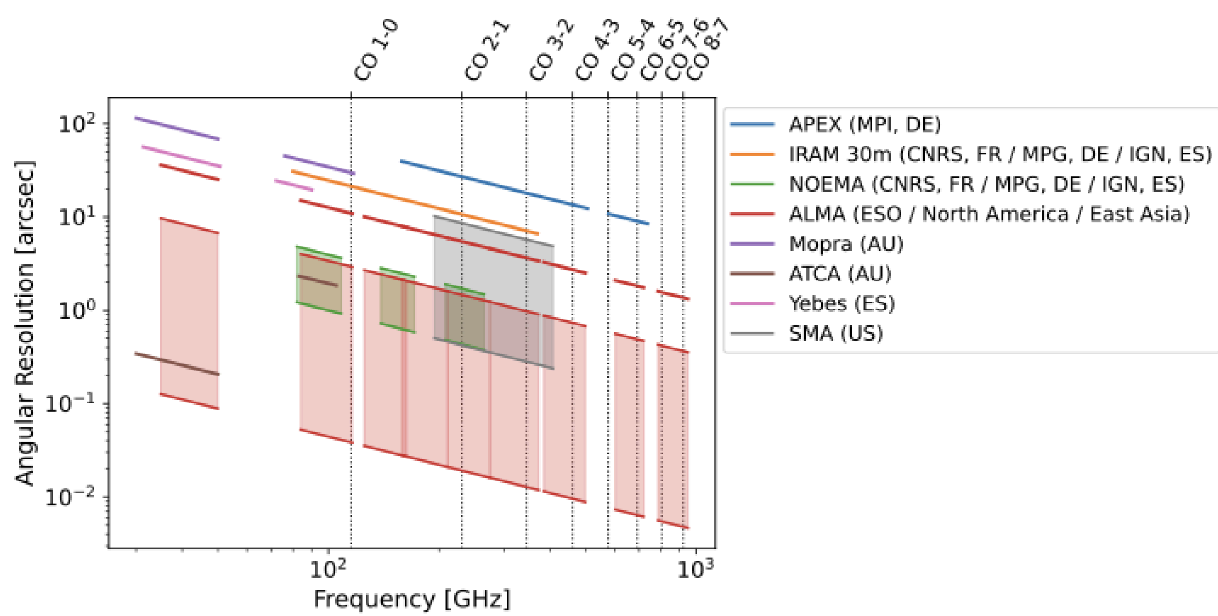

Figure 1: Angular resolution vs. frequency of mm and sub-mm national (ATCA, Mopra) and international facilities (e.g. ALMA, APEX, IRAM). The rest frequencies of carbon monoxide (CO) rotational transition lines are indicated by the dotted vertical lines.

5.3 Future Priorities

5.3.1 SKA

The SKA Observatory, including both the SKA-Low telescope in Australia and the SKA-Mid telescope in South Africa, remains Australia's highest-priority radio facility for the next Decadal Plan period. Australia has made significant financial investment into the construction and operation of the SKA Observatory, and as such holds a significant share of the Observatory as a founding member country and host country.

SKAO in collaboration with CSIRO, will operate the SKA-Low telescope in Western Australia, and preparations for this facility have seen significant personnel investment at the Science Operations Centre (Perth), the Engineering Operations Centre (Geraldton), and the Boolardy Accommodation Facility (Inyarrimanha Ilgari Bundara, SKA-Low telescope site). Australia has also invested in the Australian SKA Regional Centre (‘AusSRC’) for data processing, pipeline development and scientific analysis, a key interface between the observatory and the astronomy community.

The start of the coming decade will see ‘first light’ of the SKA and the establishment of the Key Science Projects. Primary science cases for the Australian community include Epoch of Reionisation and Cosmic Dawn, pulsars, transients, our Galaxy, and galaxy evolution through HI and radio continuum, which span both telescopes. Australia should aim to maintain or increase its share of the SKAO, and work to ensure strong Australian representation in the leadership teams of key science projects. Australia should also leverage the SKA Regional Centre Network including the Australian node (AusSRC) to ensure that we maximise the scientific return on the data taken with the SKA-Low in Australia, and the SKA-Mid facility in South Africa (with membership providing access to both). Early science verification data will be available with Array Assembly 2 (AA2) in 2026/2027, with full science operations and key science projects to start ~2029/2030.

It is essential for Australia to be involved in the development of innovative instrumentation and software for future SKA upgrades, and this requires long-term support for radio astronomy instrumentation groups to ensure that we continue to drive innovation both for SKA itself and for our unique national facility telescopes like Parkes and ASKAP in the SKA era.

Although there is a strong science case for Very Long Baseline Interferometry (VLBI) with SKA on continental and intercontinental baselines, funding limitations mean that a VLBI capability is not part of the SKA baseline design. There are future opportunities for Australia, together with international partners, to develop VLBI as an upgrade path for both SKA-Mid and SKA-Low.

5.3.2 SKA Precursors

The SKA precursor telescopes MWA and ASKAP are unique national facilities that will continue operations into the new Decadal Plan era as SKA operations ramp up. To continue to exploit the SKA pathfinders as we transition to the SKA era the following upgrades are planned.

(MWA - Phase III *upgrade*): Receivers are being upgraded in 2024-2025 to produce a new signal chain and connect all 256 tiles of the array at one time, increasing science capability and sensitivity.

ASKAP (future *upgrades*): A major upgrade to ASKAP is planned within the next five years, following the completion of the current program of large surveys. This upgrade will focus on improving the sensitivity of the telescope through the provision of new phased-array feeds (PAF) with significantly lower noise than the current PAF receivers. Such an upgrade would position ASKAP as a sensitive wide-field radio survey facility that directly complements the science carried out with the SKA telescopes in areas such as time-domain astronomy. Development of the new PAFs began in 2024, with the goal of carrying out an on-telescope demonstration of a single receiver by 2026. If this demonstration is successful, new infrastructure funding will be needed to roll out the upgrade to the full ASKAP array.

5.3.3 International radio facilities

The coming decade will see pathways to upgrading many of the facilities highlighted in the current landscape for international radio facilities, for example, the evolution of JVLA to ngVLA and LOFAR to LOFAR 2.0, as well as the construction of new facilities. International radio facilities of particular relevance to the Australian community in the coming decade as outlined in the demographics survey include (in order of number of mentions): SKA, MeerKAT, VLA, ngVLA, FAST, GMRT, VLBA, CHIME, DSA-2000, GBT, LOFAR, Effelsberg and JBO.

The Australian astronomical community has a long history of collaborating closely with international radio facilities both scientifically and via productive exchange of technical expertise, and we expect this will continue into the next decade. This will continue to provide avenues for the transfer of national expertise into the international community, as well as opportunities to collaboratively utilise, optimise and further develop the suite of national and university facilities.

5.3.4 Millimetre and submillimetre:

ALMA was mentioned extensively in the white paper of this working group one decade ago. While there was overwhelming support from the community for access to ALMA there was also push back with respect to the capacity that our limited community has for being experts in all types of instrumentations and wavelengths.

These concerns are fading due to the shift to multi-wavelength, multi-messenger astronomy in the last decade, as well as, the shift to big data with observatories doing much of the processing before delivering data to proposers. From the Decadal Plan survey, 18% of current researchers using international facilities have used ALMA in the last 5 years, while 26% of current researchers using international facilities expect to use ALMA in the next 10 years. This is comparable to the expected number of Keck (25%) and ELT[4] users (21%) in the next 10 years. The majority of current (71%) and prospective (79%) ALMA users are also using 8m-class optical/NIR facilities. For the radio community, cross-correlation of CO and CII star-forming tracers at high-redshift with 21cm emission provides one of the key tests for confirming a 21cm EoR detection, as well as providing key information to link star forming galaxy properties to IGM ionisation. For this, ALMA's small field-of-view makes direct cross-correlation challenging, but other line intensity mapping facilities may provide resolution-matched datasets.

[4] It is noted that some respondents may have not considered the ELTs would be operational within 10yrs

Australians' lack of priority access to ALMA has been noted as a limitation in multiple surveys[3,4]. Full access to ALMA would result from ascension to full membership of ESO. There are no comparable facilities to ALMA with respect to sensitivity and frequency range with which to partner (Figure 1). ALMA access outside of joining ESO may be a possibility (e.g. Korea joined the East Asian Regional Centre in 2014) but has not been explored previously and would likely include both a one-time ascension fee and an annual fee comparable to a partnership with an 8m consortium (See Appendix A). Alternatively, there may be willingness within the Max Planck Society to discuss Australia joining APEX however the sensitivity and resolution limitations do not serve the community at the same level as ALMA.

While ALMA remains the preeminent submillimetre facilities. New submillimeter facility designs are underway, this includes the European-led single dish concept, the Atacama Large Aperture Submillimeter Telescope (AtLAST). The AtLAST concept, also at the design phase with a EU Horizon grant, is for a 50m class single dish facility to be built on the Atacama Plateau (within either the wider Atacama Astronomy Park or the ALMA concession) which will have a large focal plane, be able to observe in the same atmospheric windows as ALMA and host up to 6 large format (highly-multiplexed) instruments. There is currently no notable Australian involvement in AtLAST.

5.4 Radio and sub-millimetre recommendations

Radio recommendation 1: Australia continues to capitalise on its engagement with the SKA and SKA precursors:

- Australia's share of the SKA should remain consistent with its current level.
- Sufficient data resources should be available to the community for individuals to conduct their science with SKA data.

Radio recommendation 2: Should Australia not join ESO every effort should be made to join one of the ALMA regional centres.

6 Space

6.1 Progress against 2015-2025 Decadal Plan

Recommendations from the 2015-2025 Decadal Plan mid-term review published in 2020:

1. Explore mechanisms to build stronger ties between the Australian astronomy community, the wider Australia space science community, and the new Australian Space Agency.
[Not Achieved] While meetings and communications have occurred between the ASA and the Australian Astronomy community the ties cannot be considered strong. This is very much due to ASA's focus on industry engagement. The two areas which have been successful have been engagements around the development of the SpIRIT mission (see item below) and the development of space laser communications. ASA had the opportunity to request membership for Australian Astronomy to Euclid, following the funding and ground-breaking of NNO3 (the dish which will support Roman) but declined to do so. In the questionnaire <1% of Astronomers felt they were supported by the ASA in any way.

2. Develop capabilities in space missions though affordable small satellite technology and the new Australian Space Agency.
[Partially Achieved] The standout success in the Australian Astronomy space sector was the funding of SpIRIT by the ASA (A$6million) with matching contributions from U Melbourne and industry partners. The telescope went from design to operation in 5 years on a A$10million budget. However, this did not translate to support across the sector, nor the establishment of ongoing funding streams necessary to develop this area. With a number of ASA budget items recently de-funded the outlook is for the moment bleak.

3. **Explore arrangements that would allow Australian groups to engage with international small- to mid-scale mission opportunities (along the lines of NASA's Mission of Opportunity scheme). These could potentially leverage value from Australian strengths in instrumentation and ground station services.**
[Not Achieved] Australian did not manage to engage with any NASA MIssion or Opportunity missions).

4. Continue to utilise Australia's global location for ground station services, where those services provide Australian scientists with access to otherwise proprietary space facilities.
[Not Achieved] Australia through CSIRO continues to provide day-to-day operational support for both NASA and ESA deep space tracking stations as a service provision. A bilateral agreement between the Australia and US government around space-tracking and communications was signed for a further 25 year period on 17th Oct 2017. No discussion or engagement with Australian Astronomers occurred that might have enabled Australian Astronomers to leverage any benefit from this agreement. The ASA recently invested A$4.4

million towards the construction of a new European Space Agency deep space tracking dish at New Norcia (NNO3). While the dish will downlink for Roman (ironically a NASA mission), no attempt to negotiate access for Australian Astronomers to NASA or ESA facilities by ASA was undertaken. Minister Husic indicated he hoped the new dish might stop the brain drain, it will not as no advantage was obtained or attempted to be obtained for Australian scientists during negotiations. On the positive side U Tas have demonstrated the capacity to commercially sell downlink time through their radio dish network albeit for commercial applications not astronomy missions.

6.2 Current landscape

6.2.1 The International Space Telescope Landscape

In recent years (2021, 2022) we have seen the high-profile launch of two flagship missions from NASA and the European Space Agency, namely the James Webb Space Telescope (JWST) and Euclid. In 2025 we expect the launch of NASA/SphereX and in 2026 the launch of NASA/Roman with a steady list of future launches planned at a rate of about 1 major space-telescope per year throughout the decade.

These facilities follow a steady stream of major international space-based platforms that operate as: dedicated experiments, e.g., Kepler, TESS, GAIA, WMAP, Plank, Euclid and SphereX; common-user facilities with annual time allocation committees, e.g., Fermi-LAT, XMM, Chandra, SWIFT, HST, and JWST; or hybrid facilities running large programs, e.g., GALEX, WISE, Herschel and Roman. Generally the instrument payloads are constructed by international consortia, with NASA or ESA or other agencies responsible for the launch vehicle, launch and operations. In general, data is "Open Access" immediately or becomes public after some proprietary period. As is also common practice for ground-based instrumentation, significant guaranteed time observations (GTO) are allocated to the instrument building teams, allowing the definition of major science "frontier" programs providing preferential advantage to nations contributing towards mission payloads.

In many (most) cases, communications to and from Space missions are managed through the NASA and ESA Deep Space Tracking stations in Australia via Tidbinbilla, ACT, or New Norcia, WA under contract to CSIRO. For example JWST downlinks 8hrs a day through Tidbinbilla and the upcoming Roman facility will downlink through New Norcia highlighting Australia's critical importance for deep space operations in general.

In addition to the fleet of Astronomy-focussed space-telescopes, comparable numbers of new missions are exploring the Solar System, studying the Sun, and observing the Earth. Increasingly, missions can be mixed, and it is worth highlighting the recent frontier study of the extragalactic background from the New Horizons LORRI camera, built for the Pluto fly-by. This represents an Astronomy science program piggybacking off of a planetary-science mission, highlighting discipline entanglement. In the future, it is likely that major Planetary Missions heading to the outer system could carry modest low-cost space-telescopes to get beyond the impact of inner Solar System dust.

Telescopes operating from the ISS represent a further example of lower cost endeavours e.g., the China Space Telescope to be installed on Xuntian, as might future mix-discipline efforts to develop telescopes operating in the Lunar orbit or from the Lunar surface. The opportunity for joint missions, highlights a strong need for greater cross-discipline communications. Space-platforms can and will cut across multiple disciplines while also acting as generic technology demonstrators for the Space sector. Similarly the industry connections are broad, covering payload, launch, operation and communication sectors.

Over the last decade, a growing number of individual nation agencies such as JAXA, DLR and ISRO, have successfully launched, operated and made available, data from smaller missions such as AKARI, XRISM, eROSITA and AstroSat, with China shortly launching the Chinese Space Telescope to attach to the Xuntian Space Station. These agencies are generally open to partnerships with instrument teams that have demonstrated in-space capacity.

The coming decade will see a significant number of new facilities in space (SphereX, Roman, LISA, Athena etc), with this diversity in space being matched by diversity on the ground in terms of increasingly complex instrumentation in ground-based optical facilities (MUSE, MANIFEST, AESOP), large ground-based facilities (ELT, GMT), high data-rate facilities (LSST), expansive radio arrays (SKA, VLBI, ET), gravitational wave detectors (LIGO, ASTAR) and very high energy facilities (CTA, Auger).

6.2.2. The Local Space-Environment

The standout success in the Space sector, and supported by the ASA, has been the development and launch of the SpIRIT and BINAR space-telescope programs. Both are small "shoebox" sized low-Earth orbit platforms in which the focus is on the development of sovereign technologies that demonstrate fledgling capability that are helping to grow the research *and* industry space-sector, including the National Space Test Facility (NSTF) which has supported the qualification tests of both programs. Neither, at this stage, are competitive space-telescope facilities in a purely Astrophysics sense. Nevertheless the rapidity, advent and success of these two programs is remarkable, and demonstrates the emergence of a capability upon which to build. A critical role for the coming decade will be to identify a pathway to connect these emerging capabilities to the next-generation frontier space-telescope missions.

Outside the ASA, the community is engaging on an individual institutional or science-driven basis. Obvious examples are the expert engagements at or being provided by:

- the University of Sydney in the development of the aperture masking interferometer installed on the James Webb Space Telescope,
- the establishment of the Minerva-Australis Observatory at the University of Southern Queensland's Mt John observatory in support of the NASA TESS mission,
- the establishment of a James Webb Australian Data Centre at the University of Swinburne to support Australia-wide activities with JWST,

- a number of Australian Universities (ANU/UQ/UWA/UA) engaging with the upcoming approved ESA LISA gravitational wave mission (launching at the start of the next decade in 2035),
- the establishment of commercial ground-support activities by the University of Tasmania,
- the pursuit of optical laser communications to space occurring both at InSpace, ANU and the International Space Centre, UWA,

6.3 Future Priorities

Space-based data provides multi-wavelength high-resolution imaging (including parallaxes), to greater sensitivity or over larger areas than is possible from the ground due to limitations of geography, sky glow, opacity, atmospheric distortions and increasingly Low Earth Orbit (LEO) operations. Conversely, but not exclusively, ground-based data provides extra-galactic distances, radial velocity, high spectral resolution, image slicing (including IFU), longer-wavelength (mm/radio) and multi-messenger information. Hence Space and ground based data are *highly complementary* and their routine combination is now a requirement for many science objectives. Obvious synergistic matches include: JWST, ALMA and ELT; 4MOST, Euclid and SKA; LIGO, Euclid and VLT etc.

A clear direction for the future is not to pivot towards or away from space-telescopes. Rather, frontier science in the coming decade will necessitate access to optical, radio *and* space platforms to better understand the broader picture and answer the bigger science questions. Add to this the advent and rise in the importance of multi-messenger astronomy, including gravitational wave detectors (LIGO & ASTAR) and high-energy particle detectors (CTA) and the message really is one of growing diversity and complexity, and the need for Australia to be able to operate across a broad range of facilities, wavelengths and operational modes in a seamless manner commensurate with the Astronomy portfolio budget.

6.3.1 The growing data volumes from space and other facilities

The upcoming space telescopes: Euclid, Roman and SphereX, in particular (see Appendix B), essentially provide their data for free (2 year proprietary for Euclid) in rudimentary form. However, few institutions, or even nation communities, can manage the data volumes, rendering the data inaccessible except for small areas or small samples. In the case of space, and these facilities in particular, international facility access is only enabled by national data management capacity. This is a new concept for the global community and highlights in particular a growing need to discuss how to engage with these data and in particular how to integrate these data with our leading national surveys.

Many of our critical science goals and surveys, originating from ESO, SKA, LSST and other facilities will benefit strongly from easy access to these data and the ability to fuse into a coherent sample. Few countries let alone institutions are geared up to manage this in the coming decade.

Table 3: Estimates of anticipated data volumes from both space-platforms and ground-based facilities: e.g., Euclid, LSST and SKA, and highlighting the data barrier to international facility access. The goal is to

identify how to allow the Astrophysics community to focus on science and not be swamped by data logistics best left to professional data engineers.

Domain	Data Volume	Host
ESO and AAT datasets		
One night of ELT data	<1TB	ESO
One week of ESO 8m	<1TB	ESO
One night of ALMA data	<1TB	ESO
SAMI IFU database	20GB	Data Central
Hector IFU database	60GB	Data Central
ESO MUSE MAGPI database	4TB	Data Central
GAMA Spectra	30GB	Data Central
GAMA panchromatic	3TB	Data Central
LSST, 4MOST & DESI		
4MOST/4HS spectra	8TB	4MOST
4MOST/WAVES spectra	4TB	4MOST
LSST 1800 sq deg	3PB	LSST Corp
DESI spectra	50TB	DESI
Space-based facilities		
HST 1 orbit	<1TB	StSCI
HST SkySurf (20sq deg, 15 band)	20TB	StSCI
JWST 1hr	200GB	StSCI
JWST Cosmos-Web	80TB	StSCI
Euclid/WAVES (800 sq deg	150TB	ESA
Euclid (15000 sq deg)	2.5PB*	ESA
SphereX	50TB*	IPAC
Roman (2000 sq deg)	1PB*	StSCI
Fermi-LAT	<10TB	Fermi

Table3: continued

Domain	Data Volume	Host
Radio-based		
ASKAP/EMU	1TB	CASDA/Aus SRC
ASKAP/WALLABY	1PB	CASDA/Aus SRC
ASKAP/DINGO	2PB	CASDA/Aus SRC
SKA/SRC	Many PB	SKAO
Gamma Ray-based datasets		
CTAO	<10TB	CTAO
Gravitational-wave datasets		
LIGO	1Tb	OzGrav CoE
Australian requirements		
4MOST/DESI+WALLABY/EMU+Euclid/Roman+LSST	10PB	?

**Note: Data is uncompressed and covers static images only (i.e., no time-dependent data). Roman/Euclid and SphereX are scaled from LSST where LSST has been quoted by LSST Corp as 2.7TB for 2 16-bit stacks (all data & good seeing data) covering 18000 sq deg in 6 filters at 0.2”x0.2” resolution.*

Australia is reasonably well placed through the existence of capacity in the form of Data Central established 9 years ago. Data Central have uniquely built the infrastructure needed to manage large datasets with a current capacity of 1.2PB that will double in the next year. Even doing this is still not enough to cope with the expected combination of facilities (see Table 3). Currently Data Central is orientated around the hosting of national facilities, i.e., not international-facility facing, and not adequately resourced to manage the influx of these upcoming international facility data flows. As the need goes beyond hosting, but rather the combining of these data with critical Australian surveys, an additional capacity is also needed to bring code to the data (as recommended in the Data and HPC white paper).

Facilities such as LSST, Euclid and Roman will produce final reduced data having gone through the process of massively inflating the data to reach this point. This initial reduction brings the data to what we might call Level 1 where the instrument systematics have been removed and repeat data stacked. Level 2 data consists of cross-facility data measurements, e.g., fluxes measuring from LSST to Euclid using a single defined aperture, and Level 3 the derivation of physical parameters useful for science, e.g., a photometric redshift, stellar mass, and star-formation rate.

The clever part for Australia would be to focus on Level 2 and 3. Fusing data to produce Level 2 requires significantly less inflation. Similarly, once parameters have been extracted the derivation of Level 3 products requires cpu's in close physical proximity to the data store. Hence a clever approach is to focus effort and resources into the multi-facility Level 2 and 3 domains. This can only be achieved through some centralised national repository and analysis capability. Data Central currently fills this niche but their funding is unstable, limited and restricted to data serving not data analysis. Currently Data Central has storage capacity of 1.2PB which they hope to double over the next year but no further plans due to lack of long-term funding.

6.3.2. The inability to engage in major astronomy missions

Astronomy from Space is thriving globally with a greater rate of space-platforms being launched than ever before. Most notable has been the launch of JWST and Euclid, with SphereX and Roman shortly to follow (see Appendix B), in addition are a host of small facilities driven by small agencies. Space facilities require instrumentation and at present Australia is at a disadvantage because of limited prior experience with major space missions.

As mentioned in Section 6.2.2 the advert of SpIRIT and BINAR represents two University-led programs which are focussing on the far cheaper LEO sector to demonstrate capability. These two programs are to be commended in how much they have achieved in such a short period of time. They are also highly complementary in that SpIRIT[5] has focussed on payloads while BINAR[6] on the platform.

To advance to the international level we need to connect the technological "dots" from our existing instrumentation programs, to LEO and beyond. In doing so we can and will demonstrate our readiness to engage as partners in large international space missions. This process is starting, but progress is slow due to limited funding opportunities. While investment is critical it is important that it does not jeopardise or undermine our existing ground-based instrument capabilities which are themselves under resourcing pressure. This means new funding and new funding pathways are needed to support the development of space instrumentation. Success in this area is likely to be achieved by working in collaboration with aligned disciplines and industry partners through strategic coordination between NCA, NCSS and other relevant bodies (e.g., ASA, CSIRO etc).

6.3.3 Space-infrastructure in Australia

The final piece in the Australian Space puzzle, is to capitalise fully on our unique and established role as part of the global support infrastructure for Space. This includes the critical operation of ground stations, development of high-bandwidth communications, as well as time-critical follow-up capacity from Australian-based observatories. Note that the high bandwidth is being driven by increasing data rates with missions such as Euclid and Roman downlinking 1TB/day (or @1Mbps). Future facilities will likely require higher rates still necessitating a shift from radio towards infrared laser-communications. Similarly Australia's

---

5 SpIRIT

6 Binar Space

Southern Hemisphere location and longitude provide unique opportunities for the location of follow-up facilities as embodied by the Minerva-Australis observatory supporting TESS. Our unique longitude, clear skies and technological expertise all provide distinct accelerants in this area. CSIRO ground-support stands on a long tradition running for over 60 years from before the Apollo mission and is built on a deep relationship between CSIRO and NASA, and a bilateral agreement between Australia and the USA. This treaty was recently renewed for a further 20 years. Both New Norcia and Tidbinbilla are currently operating at capacity. The investment into these sites is approximately A$1 billion and A$200 million respectively, with a likely need to renew and increase capacity in the coming decade, i.e., one might expect a similar level of new investment by mid 2035 especially with the upcoming aspirations by NASA and ESA to establish permanent settlements on the Moon and Mars.

The sector is clearly flourishing but while Australian scientists and engineers are providing a critical role in supporting many space telescope missions, it has not translated into any engagement with the science being conducted by these platforms. A good parallel is perhaps the 10% time access return that Chile enjoys for hosting ESO, however this is built into major investment by Chile into ESO, including the donation of Public land. An obvious opportunity for the Australian Astronomy community is to better coordinate across this sector and look to identify opportunities around space similar to that enjoyed by Chile around ESO. One opportunity in the future might be the allocation of some of Australia's radio dishes towards communications in exchange for guaranteed time observations or similar.

6.4 Space recommendations

The three recommendations below, come out of broad discussions of the Working Group as well as discussions at the Town Hall meetings, insight from the AAL Space Science Leads Committee, and ideas that have been discussed over the past year. They are in no particular priority order:

Space recommendation 1: Australia should strengthen its ability to access international ground and space facilities and/or associated data streams and products through data and computing capacity. This national capacity should include the ability to host and process large (PB) datasets, support careers for software engineers, and to integrate multiwavelength datasets that benefit Australia's existing investments.

Space recommendation 2: That by the end of the decade Australian instrumentation teams have grown the capacity to participate in payload development for major NASA/ESA and other agency missions. This should be achieved through the pursuit of new funding pathways that do not undermine our existing ground-based instrumentation programs, in collaboration with adjacent disciplines and with coordination between NCA and NCSS.

Space recommendation 3: That a strategic and coordinated approach is taken to capitalise on Australia's unique location for space-support operations (i.e., communications and follow-on) with a clear goal to leverage greater access, engagement and collaboration with existing and future space-platforms and their science programs.

7 Gravitational Wave Astronomy

7.1 Progress against 2015-2026 Decadal Plan

- The Mid-term review recommended: “Fund the design and development of an Australian gravitational wave pathfinder to lay the foundations for a future southern hemisphere detector hosted by Australia.”

  [Partially Achieved] The Australian Gravitational-wave Observatory Project Office was established in 2022, initially through the development of an Executive Committee that was subsequently funded (~$0.5M) through an NCRIS grant and also by the OzGrav Centre of Excellence. The initial focus is a study into the feasibility, science, and business case for a Southern Hemisphere gravitational- wave observatory hosted in Australia. This work is being facilitated by OzGrav members, including performing technological options assessments and initial site selection studies, to be delivered early in 2026.

7.2 Current landscape

The field of gravitational-wave astronomy has undergone a major transition since the writing of the previous decadal plan. At that time, gravitational waves had not yet been discovered. Since the first detection in 2015, the LIGO-Virgo-KAGRA gravitational-wave observatories have detected almost 200 merging black hole and neutron star systems. Australia has 119 active members of the LIGO-Virgo-KAGRA collaboration covering instrumentation, data, astrophysics, and fundamental physics. Pulsar Timing Arrays, including Australia’s Parkes Pulsar Timing Array, have published tantalising evidence for the discovery of nanohertz gravitational waves from the superposition of signals coming from coalescing supermassive binary black holes throughout the Universe.

The second ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) was funded in 2023, and began operating in 2024. The $35M ARC contribution is supplemented by $6.7M University cash, guaranteeing the ~300 strong workforce in gravitational-wave astronomy through to the year 2031. Approximately half of the Australian-based OzGrav members are not part of LIGO, however, they do rely heavily on the data and science being produced by LIGO, and they and contribute to Gravitational Wave Astrophysics in a number of ways. This includes members working on the ultra-low frequency gravitational wave band accessed by Pulsar Timing using facilities such as radio telescopes such as Parkes, Meerkat and ASKAP, as well as, members that work on electromagnetic and multi-messenger follow-up using optical, radio, x-ray, and high-energy particle observations.

LIGO: Australia is a major stake-holder in the Laser Interferometer Gravitational-wave Observatory (LIGO). LIGO is part of a global network of gravitational-wave observatories including Virgo in Italy, KAGRA in Japan, and LIGO-India (under construction).

As of January, 2024, the 119 members of the Australian LIGO group are currently managed by OzGrav. Of these, 81 meet the strict requirements for authorship (including a ≥50% FTE contribution to LIGO science). As members of the LIGO Scientific Collaboration, the Australian community gains access to proprietary data before it becomes public. Australian researchers play integral roles in the analysis of LIGO data and the construction and commissioning of instrumentation including technology such as the quantum squeezer and the new sensors and actuators for adaptive optics.

Membership in LIGO, and support for commissioning, has historically been underwritten through LIEF grants. This is currently being done through a four-year LIEF grant which is up for renewal with LE25. The last LIEF was $3M over four years. This is not a sustainable solution for a consortium that provides significant and valued contributions to the global partnership and has a guaranteed sustained workforce through to 2031.

As of August 2024, LIGO-Virgo-KAGRA's fourth observing run O4 is underway. Following O4, the observatories will go offline for commissioning in preparation for O5, scheduled to run from 2027-2029. After that, the observatory will likely go offline for further upgrades including significantly increased test masses and circulating laser power that will ultimately see a broadband sensitivity improvement of a factor of two from O5, implying an increase in event rates by a factor of eight (gravitational-wave strain sensitivity is inversely proportional to horizon distance). OzGrav scientists are committed to provide commissioning and delivery of improved subsystems to each of these upgrades.

7.3 Future Priorities

The international gravitational-wave community is developing plans for the next-generation of gravitational-wave observatories, slated for operation in the mid-to-late 2030s. These include the Einstein Telescope in Europe and Cosmic Explorer in the US. These "third-generation" observatories will have broadband sensitivity improvements of more than an order of magnitude over the current generation, implying they will observe every black hole and neutron star merger throughout the Universe; e.g., they can observe a 10+10-solar-mass black hole merger out to redshift 100. These observatories will also open the window on new sources of gravitational waves including supernovae and isolated neutron stars, as well as more speculative sources such as cosmic strings and other inflationary relics.

OzGrav scientists are members of the Cosmic Explorer consortium, and are contributing major technological research and development including in quantum squeezing, laser technology, thermal compensation, suspension systems and instability control and mitigation, and many other areas. They are also making significant contributions to the astrophysics and fundamental physics science case, and driving forward data-analysis methods for future observatories including detection and astrophysical inference capabilities.

The Cosmic Explorer "Horizon Study"[7] presented three global network options, with clearly the most valuable being one that includes a gravitational-wave observatory in Australia to improve

[7] https://arxiv.org/abs/2109.09882

sky localisation of all gravitational-wave sources, and hence significantly improve the synergy between gravitational-wave observatories and electromagnetic facilities.

The Australian gravitational-wave community has $0.5M seed funding through the Australian Gravitational-Wave Observatory Project to develop the science, technology, and business case for an Australian observatory. While such an observatory would likely not come online until after the period of the current decadal plan, the infrastructure development must occur in the coming decades to ensure the burgeoning field of gravitational-wave astronomy continues to grow and thrive.

LISA: The space-based observatory Laser Interferometer Space Antenna (LISA) is scheduled to fly in 2037. Australia has a long history of contributing to testing and development of instrumentation for LISA, as well as spin-off technologies e.g., for NASA's GRACE and GRACE Follow-On missions that measure Earth's mass and water changes. Australia's efforts in astrophysical forecasting and data analysis are currently small, however there is a concerted effort within OzGrav to increase participation in this and instrumentation contributions and capabilities as LISA's launch date draws near.

7.4 Gravitational-waves recommendation

GW recommendation 1: Appropriate funds are identified/sought to ensure stable engagement for long-term membership of international gravitational-wave facilities including LIGO and Cosmic Explorer.

GW recommendation 2: Funding pathways are sought for the design and development of a third-generation Southern-Hemisphere observatory.

8 Gamma-Ray Astronomy

8.1 Progress against 2015-2026 Decadal Plan

Relevant recommendations from the Mid-Term review are:

1. **[Temporarily Achieved]** Build on existing engagements with international projects (such as CTA and eROSITA) from which high impact outcomes can be achieved with a modest investment.
2. **[Temporarily Achieved]** Encourage new collaborations between astronomers and particle physicists in this emerging area, including with the Centre of Excellence for Dark Matter Particle Physics.

Additional Mid-Term review statements were also made in relation to the emerging multi-messenger and astroparticle physics fields:

3. *There are significant and important synergies between astroparticle physics and traditional observational astrophysics facilities from the radio to the optical. To get a complete picture of the processes operating in the Universe we need to understand the full gamut of energetic particles, and this requires enhanced collaboration between the high-energy and particle community, and the observational and theoretical astronomical community.*

4. *In coming years the astroparticle community will seek to expand involvement in the large international facilities with which they currently engage: CTA, IceCube, KM3Net and the Pierre Auger Observatory. Each of these leverages substantial international investment and enables significant Australian involvement and leadership for relatively modest cost.*

Australia’s growing gamma-ray astronomy community in the Cherenkov Telescope Array Observatory (CTAO), currently about 30 scientists from seven institutions led by the University of Adelaide, has enabled it to reach NCRIS-supported status via AAL. AAL provides Australia’s formal representation on CTAO’s various governance committees, and contributes about $100k/year to Australia’s CTAO membership. In tandem, three ARC LIEF projects have so far provided Australia’s construction funding (about $5M including salaries for FTE in-kind effort).

CTAO’s anticipated performance will push TeV gamma-ray astronomy to the forefront of many astrophysical challenges relating to the origin of cosmic rays in extreme environments, high-energy transients, particle cosmology, and in probing the particle makeup of dark matter. As a result, significant new opportunities to link with Australia’s radio, optical and gravitational wave communities have arisen.

The new Astronomical Society of Australia and Australian Institute of Physics (ASA+AIP) supported Group for Astroparticle Physics (GAP) commenced in 2021 and now has over 100 members from both societies. The GAP has started to bring together the somewhat separate astronomy and particle physics communities in Australia to boost all aspects of astroparticle physics studies spanning radio to gamma rays, gravitational waves and particles (neutrinos and cosmic rays). The GAP now has influence in determining the makeup of the major AIP Congress and ASA ASM meetings held annually.

8.2 Current landscape

The High Energy Stereoscopic System (HESS) is the currently operating TeV gamma-ray observatory with Australian membership (Uni. Adelaide, West. Syd. Uni.). While these data are initially private, many opportunities for joint programmes (e.g. in transients studies and follow-up campaigns) with radio, optical, X-ray etc. facilities have been set up. Some examples are joint gamma-ray and radio studies of GRBs, FRBs, and AGN (e.g. with Parkes, ATCA and ASKAP), plus radio imaging observations of gamma-ray supernova remnants, pulsar-wind-nebulae and unidentified sources. High level HESS results (spectra, FITs images etc) are fully public once published. HESS is guaranteed to run at least to 2025 but operations are likely to extend to 2028. The space-based Fermi-LAT telescope, covering the 0.1 GeV to 1 TeV range, continues to operate via NASA funding. Data are publicly available within 24hrs to scientists world-wide. NASA will continue to fund the telescope at least until 2028.

CTAO's construction phase is well underway with its first telescope at CTAO-North producing science, and the CTAO-South site being prepared. A 4th pending LIEF proposal aims to partially cover (with NCRIS) Australia's operational cost obligations for CTAO, which are about 200k Euro/yr out to 2029/30. As a member of CTAO, Australia has access to the CTAO Key Science Projects which account for about half of CTA's observing time in its first 10 years of operation, plus guest-observer time for small-scale proposals. The current LIEF funding for CTA construction contributes to the development of the detector cameras for over 40 of CTAO's telescopes. This will likely include hardware components directly from Australian industry with a value approaching $1M. FTE efforts are also devoted to CTAO's analysis techniques and optimising its observational programme. The latter task involves some seconded FTE effort to CTAO which allows Australia to accumulate 'credit' towards its operational cost obligations.

CTAO estimates over 1000 hr/yr of coverage in the optical and radio domains will be required to support its Key Science Projects over the coming decades. This is especially the case for studies of transients, since CTAO will be over 10,000x more sensitive than Fermi-LAT in their overlapping energy range (about 20 to 1 TeV). CTAO is expected to open up the transient gamma-ray sky. For this reason, efforts by the CTA-Australia group are now devoted to ensuring Australia's radio and optical facilities can play leading roles in providing the necessary multi-wavelength coverage. For example, CTA-Australia is developing a new optical polarimeter instrument for the ANU 2.3m telescope (which was recently automated) aimed at studies of jets from AGN, GRBs and TDUs (where polarisation reveals important insights into accelerated particle properties and hence gamma-ray flares). The ANU is upgrading the telescope to host this instrument at its Cassegrain focus. The CTAO-SKAO MoU signed by both facilities will map out future linkages as they enter their full operations phase from 2029/30. Similarly, discussions are underway to develop science white papers outlining CTAO-SKAO and CTAO-ESO synergies. Efforts are also devoted to training students and preparing them for the analysis of CTAO data using the officially supported ‘gammapy’ software package. A recent *gammapy* school was organised online and attracted over 30 students and postdocs from Australia and beyond.

Complementary to CTAO, the Southern Widefield Gamma ray Observatory (SWGO) aims to provide 24hr coverage of the full Southern sky in the 0.1 to 100 TeV gamma ray band. SWGO is under development with final decisions on its site (>4000m above sea level either in Peru, Chile or Argentina) expected by early 2025. Uni. Adelaide has one associate member (now adjunct) of SWGO. Most importantly, Australian industry leads development of crucial hardware aspects of the SWGO detectors which may lead to a contract of over $50M in value.

8.3 Future Priorities

While Australia’s contribution to CTAO construction is secure, it needs funding for CTAO’s operations phase well into the next decade and beyond (CTAO is a 20-30 year project). The present situation relies on a NCRIS+LIEF combination (based on the estimated 200k Euro/yr cost). This presents a long-term risk to Australia’s involvement, given both of these funding schemes operate on a maximum 5-year cycle and renewal is not guaranteed. Australian leadership, co-leadership, and influence in CTAO’s Key Science Projects along with the related multiwavelength opportunities for radio and optical facilities relies heavily on stable long-term funding. A similar situation applies to any funding associated with the SWGO.

Since involvement in CTAO is a top priority for high-energy astronomy, *a long-term funding scheme (e.g. 10 year duration with 5-year review period) specifically for international facility membership or subscription should be developed.*

8.4 Gamma-ray Astronomy Recommendation

Gamma Ray recommendation 1: Appropriate funds are identified/sought to ensure stable engagement for CTAO

9 High-Energy Particle Astronomy (Neutrinos, Cosmic Rays)

9.1 Progress against 2015-2025 Decadal Plan

The relevant facilities with Australian involvements are IceCube and KM3Net (neutrinos), and, Pierre Auger Observatory (Auger, cosmic rays). The Mid-Term review statements #3 and #4 mentioned above in Section 8 apply here. They note the importance of a multi-messenger approach to tackling the key astrophysical questions posed in the Decadal Plan. In particular the upgrades to IceCube and Auger offer rich new opportunities.

9.2 Current landscape

The University of Adelaide is a founding member of Auger (since the 1990's) and continues to have important influence in the facility's science output (via analysis improvement and calibration updates). The latest results from Auger clearly establish a directionality (anisotropy) in the ultra-high-energy cosmic-ray directions (above 10^{18} eV) with growing links to star forming galaxies as a population plus local hotspots such as the AGN Centaurus-A. Adelaide is also a member of the IceCube facility (since about 2010), which leads neutrino astronomy in the TeV to PeV energy band. Following indications for neutrino emission from a flaring AGN, IceCube has since firmly established neutrino emission from a nearby active galaxy and most recently, revealed diffuse neutrino emission from the Galactic Plane. These results provide further critical clues on the origin of cosmic rays in galaxies, linking them to the evolution of massive stars. IceCube also automatically issues alerts on individual neutrino events to the world-wide community. Such alerts often prompt rapid radio, optical and X-ray follow-up observations, given transient neutrino emission could be expected from many astrophysical source classes. Recent neutrino events potentially linked to a tidal disruption event (TDE) attracted particular attention. Australian involvement in KM3Net is via Western Sydney University. KM3NeT is under construction in the Mediterranean Sea with major funding via various European countries.

Auger was recently upgraded (Auger-Prime) which has significantly improved its ability to measure cosmic-ray elemental composition (plus energy and directions). This is critically important for cosmic-ray source identification. Auger-Prime operations are expected to continue at least until 2034. IceCube has funding for a first-step upgrade (IceCube-Upgrade) as a stepping stone for a planned expansion (IceCube Gen2) by a factor 10x or so in detector volume (and sensitivity to both northern. IceCube-Upgrade will utilise detector modules using the latest technology and will be deployed over the next 5 years or so. Improvements in neutrino event reconstruction will then be used to refine the design of IceCube-Gen2 to build the case for NSF-funding approval from about 2029/30.

9.3 Future Priorities

Access to the Auger and IceCube facilities are essential to ensure Australian researchers can take advantage of their field-leading performance over the coming decade. The challenge here is similar to that faced in accessing the CTAO in that a long-term funding avenue devoted to facilities access remains the top priority.

9.4 High-energy particle physics recommendation

HE particle recommendation 1: Appropriate funds are identified/sought to ensure stable engagement for Auger and/or IceCube

10. Prioritisation

Overall we provide 12 recommendations that cover the Astronomy landscape but without sufficient time for due consideration of the science white papers. In providing our final ranked recommendations in three Tiers we adopt the principle of how many people in the community might benefit from the activity, the level of investment to date, and the outcomes of the questionnaire and town halls. The size of the relevant communities may be better captured by the demographics working group. We note considerable overlap in communities, as most astronomers no longer identify as 100% to any individual wavelength or science case.

Recommendation	Community	Investment history	Future opportunities
Top Tier Recommendations			
O/IR recommendation 1a: All pathways should be pursued to bring about Australian membership of the European Southern Observatory.	optical, sub-mm and Gamma Ray, radio communities, IFU and wide-field, instrumentation	ESO 10yr strategic partnership	Future instrumentation contracts. Engagement in design and construction of WST
O/IR recommendation 1b, Radio recommendation 2: Should membership of ESO not be possible, every effort should be made to implement an appropriate alternative arrangement, with emphasis on longevity, to provide partnership to facilities comparable to ESO in terms of 8m access, ELT access, and sub-mm access.	Same	GMT and 8m investment over past decade	Unknown
Radio recommendation 1 (part a): Australia continues to capitalise on its engagement with the SKA and SKA precursors	Radio and multiwavelength wide-field communities	ASKAP, MWA and SKA investment	Transformational science. Global leadership role through SKA-low.

Second Tier Recommendations			
O/IR recommendation 3: Australia maintains and protects its current share in the GMT as a national asset by funding and supporting the completion of GMT instrumentation built in Australia.	Instrumentation and O/IR high-fidelity community	A$250 million	Instrumentation contracts. Frontier science
Space recommendation 1: Australia should strengthen its ability to access international ground and space facilities and/or associated data streams and products through data and computing capacity. This national capacity should include the ability to host and process large (PB) datasets, support careers for software engineers, and to integrate multiwavelength datasets that benefit Australia's existing investments.	Space, O/IR and radio wide-field and multiwavelength communities	0$ but arguably A$5M investment in Data Central over the past 9 years to develop the necessary infrastructure to achieve this.	Capacity to analyse key data flows from international facilities relevant to Australian Surveys. World leadership in data fusion.
O/IR recommendation 2: Long-term funding is sought to ensure Australian membership of the VRO.	~250 members of community	Combination of NCRIS, A$3M LIEF	2yr lead in data access over non-partnership
Third Tier Recommendations			
O/IR recommendation 2: Long-term funding is sought to ensure Australian membership of the VRO.	~250 members of community	Combination of NCRIS, A$3M LIEF	2yr lead in data access over non-partnership
Space recommendation 2: That by the end of the decade Australian instrumentation teams have grown the capacity to participate in payload	Instrumentation teams, science groups able to lead GTO programs on space-facilities.	0$	Aspiration to develop world-leading capacity in space instrumentation

development for major NASA/ESA and other agency missions. This should be achieved through the pursuit of new funding pathways that do not undermine our existing ground-based instrumentation programs, in collaboration with adjacent disciplines and with coordination between NCA and NCSS.			
Space recommendation 3: That a strategic and coordinated approach is taken to capitalise on Australia's unique location for space-support operations (i.e., communications and follow-on) with a clear goal to leverage greater access, engagement and collaboration with existing and future space-platforms and their science programs.	Space and transient communities.	0$	Leverage of access to Space facilities. Critical role in support of space science.
GW recommendation 1: Appropriate funds are identified/sought to ensure stable engagement for long-term membership of international gravitational-wave facilities including LIGO and/or Cosmic Explorer.	Gravitational wave community	Series of ~$A3M LIEF; OzGrav ($35M ARC contribution is supplemented by $6.7M University cash)	Capacity to engage in instrumentation development and leadership roles
Gamma Ray recommendation 1: Appropriate funds are identified/sought to ensure stable engagement for CTAO		LIEF grants ~$5M	Capacity to engage in instrumentation development and leadership roles
HE particle recommendation 1: Appropriate funds are identified/sought to ensure	HE particle physics community		Capacity to engage in instrumentation development and

stable engagement for Auger and/or IceCub			leadership roles
GW recommendation 2: Funding pathways are sought for the design and development of a third-generation Southern-Hemisphere observatory.	GW community	A$0.5M	Prominent role in global experiment and potential for Australian leadership

Resources:

[1] *“Australia in the era of global astronomy, The decadal plan for Australian astronomy 2016–2025”*; July 2015; Australian Academy of Science

[2] *“New Horizons, A Decadal Plan for Australian Astronomy 2006 – 2015”*; November 2005; Australian Academy of Science

[3] *“Evaluation of the Access to World Leading Astronomy Infrastructure (AWLAI) program - Final report”*; 26 March 2024; ACIL ALLEN

[4] Survey for this decadal plan

[5] *“Decadal plan for Australian astronomy 2016-2025; Mid-term review”*; July 2020; Australian Academy of Science

[6] *“Report of the International Scale Facilities Working Group 2.1 for the Australian Astronomy 2016-2025 Strategic Plan”*; 2014

[7] *“The Wide-field Spectroscopic Telescope (WST) Science White Paper”;* Mainieri, V. et al. 2024, arXiv:2403.05398; https://ui.adsabs.harvard.edu/abs/2024arXiv240305398M/abstract

Glossary:

4MOST - 4-metre Multi-Object Spectroscopic Telescope
ALMA - Atacama Large Millimetre/Submillimetre Array
APEX - Atacama Pathfinder Experiment
ASA - Australian Space Agency
ASKAP - Australian SKA Pathfinder
ATCA - Australian Telescope Compact Array
AtLAST -Atacama Large Aperture Submillimetre Telescope
ATNF - Australia Telescope National Facility
AusSRC - Australian SKA Regional Centre
AWLAI - Access to World Leading Astronomy Infrastructure
CTAO - Cherenkov Telescope Array Observatory
DLR - German space agency
Euclid - The Euclid Space Telescope
ELT - Extremely Large Telescope
ESA - European Space Agency
ESO - European Southern Observatory
EU - European Union
FTE - Full Time Equivalent
GMT - Giant Magellan Telescope
GTO - Guaranteed Time Observations
ISRO - Indian Space Research Organisation
JAXA - Japanese Space Agency
JWST - James Webb Space Telescope
LEO - Low Earth Orbit
LIGO - Laser Interferometer Gravitational-Wave Observatory
LISA - Laser Interferometer Space Antenna
LIEF - Linkage Infrastructure, Equipment, and Facilities
LSST - Legacy Survey of Space and Time
MSE - Maunakea Spectroscopic Explorer
MUSE - Multi Unit Spectroscopic Explorer
NASA - National Aeronautics and Space Administration
Roman - The Nancy Grace Roman Space Telescope
SphereX -
SKAO - Square Kilometre Array Observatory
VLT - Very Large Telescope
VRO - Vera C. Rubin Observatory
WST - Wide-field Spectroscopic Telescope

Appendix A: Cost estimates for alternative partnerships to ESO

Capability	Facility	Cost (investment)	Cost (annual)	ESO Equivalent
10% share of **30m optical / NIR telescope**	GMT (Current 5% share not included)	[redacted]	[redacted]	ELT (7% share)
30% share of **8m optical / NIR telescope(s)**[1][2]	Keck (2 telescopes 60nts/yr; USA, access to Subaru exchange nts)	[redacted]	[redacted]	VLT (4 telescopes)
4m telescope(s)	Continued SSO investment (3 telescopes; Australia)	[redacted]	[redacted]	NTT / 3.6m / VST / VISTA / 4MOST (some of these are being returned to owners…)
8m optical interferometer	No equivalent	[redacted]	[redacted]	VLTI
Sub-mm array	ALMA access agreement through the one of the regional centres (e.g. North America, Europe, East Asia)	[redacted]	[redacted]	ALMA
Future access to **dedicated spectroscopic facility**	*MSE*[3] *(10% share)* *3rd Magellan*[4] *(10%share)* *Subaru PFS (?)*	[redacted]	[redacted]	WST
Additional facilities support through AAL to manage multiple contracts (previously ITSO[6])		[redacted]	[redacted]	
Total Cost		[redacted]	[redacted]	

[1] This is likely not achievable within one partnership to meet the annual use of the VLT during the ESO SP. Multiple partnerships would be required to meet the need
[2] Must be partnership to enable access to governance and instrumentation contracts
[3] MSE is not funded and struggling to find partners and complexity of site location. Wrong Hemisphere.
[4] Some preliminary discussions are underway about the possibility of a 3rd Magellan but no firm plans as yet
[5] Numbers in parentheses are guesswork
[6] International Telescope Support Office

Appendix B: Space facilities relevant to Table 3.

JWST: The James Webb Space Telescope (JWST) is the most significant astronomy telescope since the Hubble Space Telescope, with the US$12b NASA project launching successfully in late 2021 with an aim to answer fundamental questions about our Universe. With a primary mirror of 6.5m in diameter it is by far the largest space-based telescope, and has allowed astronomers to peer into the infrared at high-resolution for the first time. JWST is an extremely complex telescope, with instruments offering many modes of operation (imaging and spectra) over a huge dynamic range of wavelength. The new capabilities achieved by JWST are a genuine step change in capability for many different astronomy communities, with scientists discovering new signs or water vapour in exoplanets and the oldest ever galaxies directly observed by humanity. In just a few years of operation JWST has challenged established theories, and is already the most in-demand facility ever constructed for astronomy. Multiple Australian Universities are highly engaged with JWST science, and many Australian researchers are leading major programmes on JWST through NASA's liberal open-sky policies.

Euclid: The Euclid space telescope is an M-class €1b ESA mission to survey the entire extragalactic sky unaffected by the Earth's turbulent atmosphere. It launched in 2023, and is already operating its challenging 5-year mission survey to create the deepest wide-area images ever created. It is a highly specialised 1.2m diameter telescope with a focus on broadband imaging in the optical and near-infrared, and also a coarse grism mode that allows astronomers to estimate the distance of luminous galaxies. The core aim of the mission is to produce a dark matter map of the Universe by measuring the weak-lensing distortions of background galaxies through dark matter halos, but such is the quality of the data (both depth and resolution) a huge number of ancillary projects are planned by extra-galactic astronomers. These include searching for extreme low surface brightness galaxies, and measuring the morphological structures of galaxies over almost all cosmic time. Australia has limited access to Euclid through a number of legacy science projects that were established to target particular regions of the sky, but separate to such proprietary access Euclid data will be released publicly after a ~2 yr delay to allow internal analysis. The data volumes are immense however, with petabytes of data being made available, and individual frames being tens of gigabytes. This will fundamentally change how we approach astronomy, since downloading all of the data to a local machine and analysing it there is not feasible.

SphereX: The SphereX space telescope is an all sky spectral telescope. It is a NASA Medium Explore mission funded (US$100million) in 2019 and on schedule for launch in 2025. It is managed and led by JPL with a number of University and industry partners. The facility consists of a 20cm mirror with a 3.5x11 degree field of view and size 2kx2k mHgCdTe detectors. It will operate in low-earth orbit for 25 months and during this period it will obtain imaging in 96 bands from 0.75 to 5 micron across the full sky with a spatial resolution of 6 arcseconds. A novel feature of SPhereX is that it has no moving parts but instead makes use of innovative linear variable filter technologies. Its key focus is to obtain low-resolution spectroscopy for redshift identification of approximately 500 million objects, as well as indicators of elements vital for life in stellar spectra and in particular the origin of water in planetary systems. SphereX data will be processed by CalTech-IPAC and made available immediately via the IPAC archive. Catalogues of redshift and other information to follow. The resolution of SphereX is well aligned with that from radio and X-ray surveys.

Roman: The Nancy Grace Roman mission is NASA's next flagship mission scheduled for launch in 2027 and supported through the ESA deep space tracking station at New Norcia, WA. The facility, initially funded for US$255 million, will operate from L2 and consists of a 2.4m aperture telescope with two instruments. The wide-field instrument containing a 300-megapixel camera covering a field of view of 0.3 sq deg with a range of filters operating from optical to near infrared wavelengths (including grisms) and the Coronographic instrument representing a high-contrast small field of view using novel starlight suppression technologies to obtain direct spectroscopy of extra-solar planet atmospheres. The CGI is mainly here as a technology demonstrator for a future large mission. The goal of the primary Roman mission is to study the growth of structure in the Universe, i.e., dark energy, by conducting a series of surveys including a wide-area (4000 sg degree) survey. Roman's field of view is approximately 100 times larger than that of Hubble's. Roman data will be processed and released through a series of public data dumps with a final data volume expected to be in the 40PB ball-park (including the time-series data).