Report of the International Scale Facilities Working Group 2.1 for the Australian Astronomy 2016-2025 Strategic Plan

V1.7 31/8/2014

WG2.1 Executive Committee:

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Structure of this report

The rest of this report is broken in to the following sections:

1. Discussion and summary of key recommendations
2. Decadal Survey process
3. Optical/IR facilities
4. Radio facilities (including ALMA)
5. 'Frontier Astrophysics' (including other portions of the EM spectrum and smaller research fields)
6. Gravitational Wave astronomy
7. Discussion of 'mid-scale funding'

The general structure of each section is to start with (i) review progress against the previous decadal plan (ii) summary of current landscape, (iii) discussion of the recommendations for the next decade based on our survey of the community.

1 The Key Recommendations

1.1 Top Priority Recommendations (summary of the summary)

In this section we summarise the top priority recommendations across the full portfolio of the WG.

- **Access equivalent to 20-30% of the time on a single 8-m telescope** with a broad suite of instrumentation, **and 10-20% of an ELT** via membership of international consortia. **8-m telescope access is the most critical unmet need in the community and the major unrealised goal of the previous Decadal plan** (in that membership of Gemini is about to expire and current access levels fall below community need).
- **Australian development of the pathfinder ASKAP in to SKA Phase** 1 via international engagement. We should continue to develop mid-frequency (GHz) technologies, where Australia has established leadership, and the emerging area of low-frequency astronomy which has a strongly developing community within Australia and whose infrastructure Australia will host for SKA1.
- That there should be a more formalised national **scheme to support more effectively 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.
- Key areas of the latter that **we consider highly competitive** for implementation at the start of this decade under a **mid-scale program**:
    - Partnership in THz and/or 2μm telescopes at Dome A taking advantage of site conditions unique on Earth
    - Partnership in a large galaxy spectroscopic survey such as 4MOST.
    - Subscription to LSST.
    - Instrumentation contributions to telescopes such as the Maunakea spectroscopic explorer.
    - Upgrade of the MWA to a significantly increased collecting area and longer baselines.
    - Membership of Pierre Auger, CHARA and CTA consortia
    - Partnership in a long baseline Gravitational Wave antennae global array.

  These priorities should be revisited at the mid-term review of the Decadal Plan.

These recommendations arise from both the community consultation and from the changing usage profile of the community as captured by the bibliometrics facilities '*Australian Astronomy Publication and Facilities Survey*' report conducted by Brian Schmidt. Both are in accord and this is discussed in detail in Section 2.

The full set of recommendations are given in the following subsections, broken down according to optical/IR, radio, frontier astrophysics and gravitational wave astronomy. The logic and motivation of this approach (which is fairly conventional) is explained in Section 2. **We also outline in Section 1.6 some indicative costs.**

1.2 Optical/IR Recommendations.

We recommend as **first priority**:

- Access to 30% equivalent of a single 8-m class telescope (minimum: 20%) and 20% equivalent of a 24m ELT (minimum: 10%) via membership of international consortia. Having access to both types of telescope at this level of access is absolutely crucial as it facilitates different but highly complementary internationally competitive research programs. Besides being the ideal vehicle for many larger observing programs, access to ample amount of 8m telescope time is required to provide suitable targets for detailed follow-up studies with ELTs. Providing this capability could be shared among more than one 8m-class telescope, and this would in fact be desirable to increase the access to diverse instrumentation.

- One strongly preferred option as to how this can be realised is through Australia joining the European Southern Observatory (ESO) as a partner, which would also have the added benefit of gaining access to many additional front-line optical, infrared and sub-mm facilities. The optimum time frame to do this is by 2017. If ESO membership is not possible due to the necessary government funding not being forthcoming on a suitable time-scale, an alternative route to gaining the necessary telescope access is to pursue partnership on other 8m telescopes (Keck and Magellan would be preferred community options if a partnership opportunity arose) together with an increased share of GMT. We recommend that all options should be actively pursued at this stage since there are no guarantees which combination of facilities will be the most advantageous scientifically and strategically in the future. We emphasize that it is crucial to have a broad and diverse portfolio of front-line capabilities in terms of telescope aperture and instrumentation in order to meet the diverse scientific interests of the Australian OIR community.

- That a competitive scheme be put in place to enable funding of medium-scale international facilities and experiments. Such a scheme could fund community access and/or instrumentation contributions to projects such as LSST, DESI, KDUST and 4MOST, giving Australia great value for money by providing access to international front-line facilities largely constructed by overseas organizations. Such a scheme would also be for building instrumentation for national facilities.

We recommend as **second priority**:

- Australia engages in developing a 10m-class wide-field spectroscopic telescope to become ready for science towards the second half of the decade covered by this DP. One such option would be the proposed Maunakea Spectroscopic Explorer (MSE, originally stemming from the CFHT collaboration) or a similar Australian-led 10m facility in the southern hemisphere (Chile?) to optimize the synergies with SKA and LSST.

- Australian membership of the Large Synoptic Survey Telescope (LSST) consortium should be explored, as it would benefit a very large fraction of the community. The LSST, funded largely by the NSF and about to commence construction on Cerro Pachon in Chile, is scheduled to commence science operations in 2022. LSST would, especially in combination with a large, wide-field optical/infrared spectroscopic survey facility, provide excellent synergies with for example the next generation of radio facilities (ASKAP, SKA).

1.3 Radio Recommendations

- We recommend the highest priority continue to be placed on ASKAP and the SKA. The next decade will see delivery of the scientific benefits of ASKAP, demonstrating the power of this innovative survey instrument. Construction of SKA1-survey and SKA1-low will also occur during this period, putting Australia at the centre of this 'mega-science' project. We judge it critical that the highest priority be placed on successful delivery of these instruments and positioning Australia to exploit their scientific potential.

- We recommend new, but modest, investment in low-frequency radio astronomy. This would allow a limited growth of MWA, to continue surveys of the low frequency radio sky in the period before SKA1-low comes on line. We support current exploration by the MWA consortium of options for this expansion.

- We recommend the continuity of funding streams (such as NCRIS) that allow participation in high-priority, mid-level international science projects. This would benefit a few key areas of science related to radio astronomy that are not under the SKA banner, potentially including Antarctic Astronomy. Such a scheme could also allow direct comparison between international and national projects of similar scale.

- We recommend that the principle of 'open skies' be adhered to for future radio facilities as far as possible. Open skies allows Australian astronomers access to the highest quality facilities worldwide, and ensures the best possible science is done on Australia's instruments. We consider that this principle is worth retaining, although it will undoubtedly come under pressure in this decade.

- We regard the provision of user-ready data and post-processing facilities for the SKA and pathfinders as vital to their scientific utilisation. We strongly encourage the SKA project and the Australian community to develop a plan for SKA data management that enables Australian astronomers to best use SKA data when it becomes available.

- We recommend engagement with new southern hemisphere widefield optical/IR imaging and spectroscopic facilities, and deep southern hemisphere spectroscopic facilities and continued engagement with ALMA at the current level (supporting travel to Regional Centres and local workshops).

1.4 Recommendations for Frontier Astrophysics.

- Continued productivity in Frontier Astrophysics requires access to competitive funding schemes that acknowledge the leverage provided by international investment and collaboration. We recommend this access be continued, and more broadly and formally supported.

- Given that they leverage major investments world-wide and science return for a modest cost, there is no need to prioritise particular Australian activities in Frontier Astrophysics for major investment.

- We recommend two scales of support for international Frontier Astrophysics:
    - A mechanism for small (~$30K) membership or access fees to be paid, enabling high-impact science from individual Australian researchers.
    - The ability to occasionally compete in mid-scale funding ($1M to $10M) opportunities to become a partner in new international major research investments.

1.5 Recommendations for Gravitational Wave Astronomy.

We recommend:

- Continuation of Australia's partnership in Advanced LIGO and LIGO-India and their upgrades at the level of $500K p.a. throughout the decade and supporting the installation and commissioning of KAGRA over the period 2016-2020 ($10M over 5 years) via the envisioned mid-scale program.

- Investment in the development of gravitational wave and multi-messenger astronomy and the required data analysis and computing infrastructure (hardware and Virtual Laboratory software) ($600K p.a.).

- *That following first detection*, Australia considers participation in the construction of a third-generation detector in Australia at an investment level of 20-30%.

1.6 Indicative costs of main recommendations.

It is not possible to include a table of costs, this would not be nuanced enough and would erroneously imply too much definitiveness. Costs are highly uncertain due to the different maturity stages of different facilities and potential variations of exchange rates and inflation. Nevertheless we include the following discussion of indicative costs, all converted to AUD.

- ESO membership. It is currently estimated that the joining fee is €110M (about $150M) and the annual contribution would be €13M ($18M). In-kind is notionally capped at 25% of this.

- SKA: Australia will pay 14% of Phase 1 (capped at €650M), which is $120M, plus 14% of operations costs. (*Source: OzSKA wiki July 2014*). These we estimate at $12-15M p.a.

- Alternative 8m. We take the Keck telescope as an example, the total value of the asset has been estimated by the NSF[1] as $290M with $16M in operations. However much of the asset cost is amortised over the past 30 years, how much would clearly be negotiable. If we take a 15% AU share (i.e. 30% of one telescope) and assume 50% amortisation the membership fee would be $22M and the operations share $2.4M p.a. This may underestimate the market value. True cost would likely be within a factor of two to be worth considering.

- Mid-scale program. Estimated at $30M over the decade for 3-4 medium-scale and 5-10 small-scale projects.

- Development of a 10m-class wide-field spectroscopic telescope (~10-20% share) is likely to be at the $25-50M level over the decade. (Note MSE is costed at $220M in their Feasibility Report[2]). Possibly the first phase of this would be viable as a mid-scale project.

- Development of Gravitational Wave astronomy is estimated at $20M over the decade. Following first detection then engagement of Australia in a major new local observatory would be $100-150M.

[1] http://ast.noao.edu/system/tsip/more-info/time-calc-keck

[2] http://www.cfht.hawaii.edu/en/news/MSE/docs/Feasibility_Technical_Final.pdf

- GMT operations (which includes new instrumentation development) Australian contribution is estimated to be $4-5M p.a. in order to maintain ~10% access share.

- Development of low-frequency radio pre-SKA, optical survey projects and Frontier programs are covered by the recommended mid-scale program.

2 Decadal survey process

2.1 Consultation process

The consultation of our Working Group (WG) was extensive. We conducted a series of Town Halls during Mar/Apr of 2014 where issues were presented and group consultation was done in a round-robin fashion with other WGs. The locations were Sydney (CSIRO), Melbourne (Swinburne)[3], Canberra (RSAA) and Perth (ICRAR UWA). The WG Chair attended every Town Hall meeting and there was at least one other executive member at each Town Hall. Several note takers were identified for each meeting and notes were all reviewed by the Chair and executive.

We also invited online solicitations of white papers. These can be found at:

https://sites.google.com/site/australiandecadalplanwg21/white-papers

The WG Executive met in Sydney on June 5th and 6th and completed a preliminary draft of the report. The final draft report was circulated on the ASA exploder before the ASA 2014 meeting at Macquarie University and the report was presented at the ASA by the Chair. There was a panel discussion session at the ASA and a further invitation for feedback. Many individual emails were received in response to the draft report and their points were carefully considered.

In August we also received the bibliometrics facilities '*Australian Astronomy Publication and Facilities Survey*' report conducted by Brian Schmidt, together with responses to specific queries on the data the WG formulated, and we factored key points of this in to the report. In the last week of August we reviewed the penultimate drafts of the Science WG reports to check their facilities priorities against our report and found them broadly in accord. We also asked the Chairs of the Science WGs to complete a table of ranking of desired international facilities capabilities in a common format. This will be provided separately to the editorial committee at a later date when it is completed satisfactorily.

The revised draft was circulated to the full WG on 25/8/2014 for final comments and the final report submitted to the Editorial Board on 31/8/2014.

2.2 Report Principles

The report is structured along fairly conventional divisions of optical/IR astronomy, radio astronomy, what we have termed 'frontier astrophysics' and also gravitational wave astronomy. This reflects the broad structure of our community and it's facilities and this structure was also adopted to make the

[3] We provided an option to stream the Melbourne Town Hall but it was not taken up.

work task manageable. In particular the focus, chapter leads and expertise of the WG executive was:

- O/IR: Karl Glazebrook, Martin Asplund, Stuart Ryder
- Radio: Lister Staveley-Smith, Sarah Pearce, Naomi McClure-Griffiths
- Frontier Astrophysics & Gravitational Wave Astronomy: David McClelland, Michael Ireland

We decided to include the sub-mm/THz discussion in the radio section but also address this in the Frontier Astrophysics chapter.

To justify this division we note that according to the Decadal '*Australian Astronomy Publication and Facilities Survey*' theory, optical and radio together add up to 93.5% of the impact weighted (their Case 6) scientific output of our community. The breakdown is:

- Theory 42%
- O/IR 42%
- Radio 20%
- High Energy 4%
- Gravitational wave 0.7%

It is significant that 'theory' has grown to 42% from only 11% in 2005. Currently there are no international-scale facilities associated with theory (e.g. HPC or data centres) but that is in our view likely to change as the scale of such activities grow. However since there is a separate WG specifically on e-Science (WG 2.3) we decided to defer such considerations to them. Hence we restrict our report to international observational facilities. In the next section we analyse the survey further to see if it accords with the consultative feedback and primary recommendations.

It is also worth discussing our views on two other points:

'What is an international facility?' Typically we are discussing something which is >$5M in capital cost and >20% in overseas funding/scientific collaboration. We specifically identify AAT, SSO, ATNF, Parkes, ASKAP and MWA as being within the domain of WG2.2 on National Facilities and not ours. However (esp. in Frontier) we inevitably discuss some smaller scale projects. Also our key recommendation of a mid-scale program is intended to cross the $5M divide and capture a number of the smaller-scale programs.

Frontier Astrophysics. This is obviously something of a catch-all section where we discuss a number of diverse and different projects. The general theme here is that 'Frontier' facilities generally share one or more of the following list of attributes (i) experimental, (ii) project specific, (iii) only engaging a small fraction of the community, (iv) non-common user facility, (v) not O/IR or radio.

2.3 Analysis of the Australian Astronomy Publication and Facilities Survey'

The survey of the community (Schmidt 2014) analysed all papers published in the previous decade and asked authors to estimate contributions from different classes of facility to the science. We believe that what the survey calls 'Case 2' (publications attributable normalised by Australian authors), and 'Case 6' (citation impact adjusted for year and normalised by Australian authors) are the most relevant metrics for us. Schmidt provided numbers for us specifically related to key questions we had. The general report is also in line with the following conclusions and it also concurs with the feedback during the consultative process.

A key question for us was for the Optical/IR how much has the usage shifted from 4m to 8m class facilities? The feedback during the consultation indicated to us that 8m's had become the 'workhorse facilities'. The numbers are laid out in Table 1. Clearly the impact of domestic small telescopes (4m and below) has shrunk from 52% to 26% whereas the impact of 8m-class telescope science has grown from 13% to 25%. We expect this trend to continue as small telescopes move to a specialist survey role with specialist instrumentation (the majority of AAT time is now used for large surveys, if it wasn't for this it is likely that AAT impact would be lower) whilst the general-purpose diverse science instrument capability resides on the 8m telescopes.

What is remarkable is this increase in science output from the largest telescopes has happened at the same as Australia's share of large telescope time has shrunk dramatically (Figure 1). These statistics along with the voice of the community during the consultation motivate our recommendation for access to 20-30% of an 8m telescope.

We can make a similar analysis for radio facilities (Table 2). It can be seen that the usage of ATCA and Parkes has shrunk substantially as a share of community publications, though we note that a deeper analysis of the data shows this is due to an overall growth in community output with these remaining constant. Since ASKAP has not yet begun operations it is hard to similarly assess whether impact and usage will shift to this facility, but it is clear that usage of overseas facilities has increased greatly which likely reflects usage following technology upgrades and development.

We can also use the survey to estimate the breakdown of the community (Table 3). Given these statistics the focus of our recommendations on optical/IR and radio are logical. We note that though 'Theory' scores high most of this is not HPC-based (large national facilities account for 9% of the theory impact). Attention should be paid to the recommendations of the e-Science WG 2.3 here, noting that HPC is now also essential to reduce radio observations. High-energy is also a large fraction, we believe support for this area (including engagement in overseas experiments such as cosmic rays and gamma rays) are captured in our mid-scale funding recommendation.

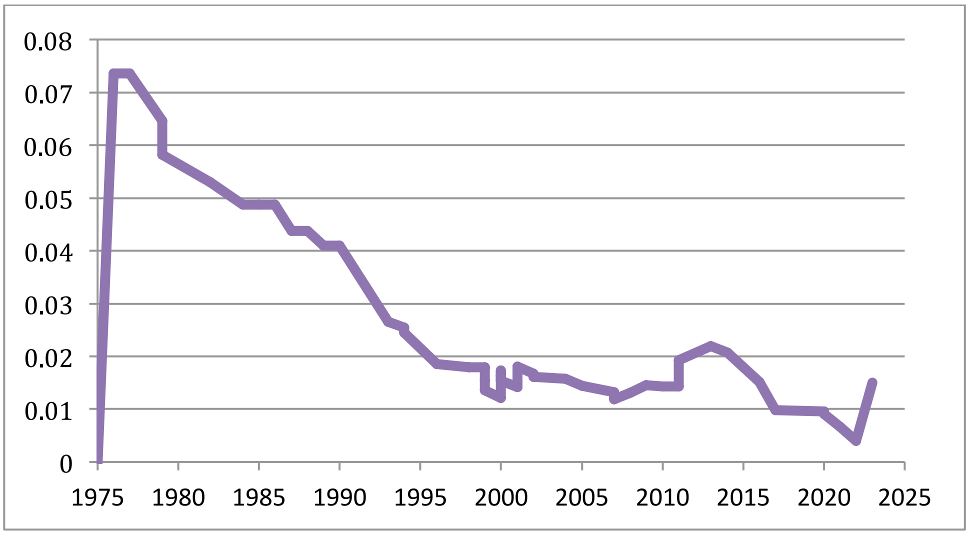

Figure 1: Australia's fraction of world's telescope collecting area (for scientifically productive telescopes over 2m in size) showing the severe decline of Australian access to large optical/IR telescopes. *(Source: Brian Schmidt 2014, based on projections of new facilities coming online)*.

Table1: Impact (Case 6) of various optical/IR facilities.

	2005	**2014**
AAT 4m	27%	17%
Other domestic O/IR	25%	9%
Australian 8m access	0.4%	7%
Other 8m access	13%	18%
Other foreign O/IR	34%	49%

Table2: Impact (Case 6) of various radio facilities.

	2005	**2014**
ATCA	40%	27%
Parkes	39%	30%
Other AU radio	5%	11%
Foreign radio	16%	31%

Table 3: Number of astronomers submitted at least one paper with the following contributions (noting many report in multiple categories).

Field of publication	Number of astronomers	Fraction
Optical/IR	224	33%
Radio	170	25%
Theory	163	24%
High Energy	102	15%
Gravitational Wave	21	3%

3 Optical/IR Facilities

3.1 Progress against 2006-2015 Decadal Plan

The 2006–2015 Decadal Plan prioritised a tiered investment in optical and infrared (OIR) infrastructure based around a hierarchy of increasingly large telescopes. These included fully supporting the 4-metre Anglo-Australian Telescope and Observatory through to 2018; providing the equivalent of 20 per cent access to an 8-metre class telescope; and supporting investment at a 10 per cent level in an Extremely Large Telescope (ELT) program. **Progress has been made against the Decadal Plan's goals for international-scale OIR astronomy facilities over the past decade, but realities have not reached our aspirations in the OIR area.**

1. On 1 July 2010, the Anglo-Australian Observatory transitioned to become the Australian Astronomical Observatory (AAO), a division of the Commonwealth government's Department of Industry, and has achieved security of funding until at least 2018. The Mid-Term Review recommended that "*Over the next several years, a forward-looking strategic plan for the AAO and the facilities it manages needs to be developed that foresees how the AAO can best serve the community in the future.*" The AAO released its Forward Look to 2015 document in June 2012. With regard to supporting large offshore telescopes, the AAO undertook to continue to find ways of adding value to Australian astronomers' access to these facilities; to pursue opportunities to build instruments for Gemini; and to determine what contributions the AAO could make towards joining ESO, and supporting Australian users of ESO facilities.

2. Involvement in 8-metre class telescopes has consistently fallen short of the Decadal Plan goal. Even after the advent of the first ELTs, 8-metre telescopes will remain at the core of any world-class astronomical program. Since 2007 Australian astronomers have had access equivalent to only a 16.5 percent share in an 8-metre class telescope via our membership in Gemini, and through the purchase of Magellan nights by AAL.

3. Australia has maintained its world leadership in the development of innovative technologies in optical and infrared astronomy. The Research School of Astronomy and Astrophysics (RSAA) of the Australian National University delivered its second instrument, the Gemini South Adaptive Optics Imager to Gemini South in Oct 2006.

4. Australia is now a well-established partner in an ELT program, the Giant Magellan Telescope (GMT). An initial co-investment by AAL with the Australian National University secured a 10 per cent share in the GMT Design & Development Phase. Australia has already invested US$41.5M in GMT construction from EIF funds, with a further AU$26.9M to be invested if and when a decision is taken to commence construction. Owing to

indexation to reward an early investment, this could lead to an ~15% share of GMT observing time, split 50:50 between AAL members and ANU. However it is worth noting that even a 15% share of the GMT equates to barely 2% of the ultimate collecting area of all 3 ELTs, if built.

3.2 Current Landscape

Since the conclusion of the NCRIS program in 2011, **no *long-term* (i.e. >3 years) funding program of science infrastructure has been announced that could sustain the existing 8-metre telescope access arrangements**. As a result Australia has been precluded from being able to commit to a new Gemini partnership agreement beginning in 2016. It is also true that the Gemini partnership and instrument capabilities over the past decade have not fully met the research requirements within the greater Australian astronomy community and as such Gemini has not been an ideal match to our 8m aspirations. While AAL has successfully been able to fund and negotiate access agreements for 15 nights per year on Magellan, and a further 10 nights per year on Keck through the end of 2017, this will see Australia starting the next Decadal Plan period with *even less 8-metre access than it has utilised throughout the current period*.

So serious is this shortfall in 8m access that first Swinburne, and more recently ANU have moved to ensure their own staff can have some surety of access by temporarily purchasing 15 night per year each on the 10m Keck telescopes. AAL has now secured similar access to Keck for the entire Australian community during 2016-2017, but the ability to undertake high-impact, ambitious science with such short-term access is severely hampered.

With regard to current instrumentation activity, RSAA is leading an upgrade of the natural guide star wavefront sensors of the Gemini Multi-conjugate adaptive optics System (GeMS) which feeds GSAOI. The AAO, in partnership with RSAA and the NRC Herzberg in Canada, has been awarded a contract by the Gemini Observatory to deliver the Gemini High-resolution Optical SpecTrograph (GHOST) by 2018. Although Australia will no longer be a full partner in Gemini by then, access through guaranteed time or via the purchase of classical nights remains an option. The AAO is also in discussion with Subaru and with the Maunakea Spectroscopic Explorer project office to contribute their optical fibre positioner expertise and technology for future survey facilities on these 8–10m class telescopes.

The GMT has now passed both its Preliminary Design Review and its Cost and Organizational Review and is looking at a phased approach with Phase A (four mirrors) costing ~$650M, while the full GMT would cost $1050M (as spent USD including inflation). Phase A is expected to achieve first light by 2020 with the full capabilities now foreseen to be available in

2023. GMT has a good chance of being the first ELT coming online and thus reaping many of the highest-impact science, especially given GMT's chosen first-generation instrumentation. Australia is leading in cutting-edge GMT technology: the GMT Integral Field Spectrograph (GMTIFS) and Laser Tomography Adaptive Optics system are being developed by RSAA as a first-generation instrument for GMT, while the AAO is refining its Starbugs focal plane positioning technology for the MANIFEST fibre-feed facility to be used by the G-CLEF (high-resolution optical spectrograph for exo-planet discovery/characterisation, Galactic archaeology etc.) and GMACS (multi-object optical spectrograph for studies of galaxy formation and evolution) first-generation instruments. Australia has invested AUD$23.4M to support this instrumentation development and enhanced laboratory facilities at RSAA.

3.3 O/IR Future Priorities

3.3.1 Key Capabilities Required

Today 8m class telescopes (actual range 6-10m in diameter of primary mirror) are the workhorses of the Australian OIR astronomy community for leading new scientific frontiers. From 2020 onwards, ELTs will become the next peak facilities with 8m telescopes still playing a vital role. In order to stay internationally competitive in the field, the requirements in terms of facility access are:

1. Access to a significant share of a modern 8-m telescope (goal: equivalent 30% of an 8m aperture, minimum 20%) equipped with a diverse and front-line set of instrumentation**.** This implies a variety of imaging and spectroscopic resolutions in the optical and infrared regime, including both single- and multi-object instrumentation. This could be achieved either through membership in ESO or through a portfolio of other telescopes (e.g. Keck, Magellan, Subaru, Gemini, MSE) that together provides the necessary broad instrumentation suite.

2. Access to significant ELT capability by the end of the decade (goal: 20% of a 22m aperture or 70 nights per annum, minimum: 10%/35 nights). Australia and ANU are currently members of the 24m Giant Magellan Telescope at a level of 10% together. To reach this goal, we envision either joining ESO and their 39m E-ELT project (benefits: larger aperture, access to complementary instrumentation, hedging) or an increased share in GMT (benefits: established Australian involvement, larger influence as a bigger partner).

3. It is critical that these capabilities are delivered in such a way that Australia has a strategic say in the management of these facilities as early on as possible and that the arrangement is secure and stable to allow long-term planning.

4. There needs to be a regular, competitive funding scheme that will fund access and memberships for smaller scale but high-profile international projects (typically $1-10M spread over 5-10 years). Such a scheme could fund Australian engagement in projects such as LSST, DESI, KDUST and 4MOST.

3.3.2 Implementation and Key Recommendation for ESO Membership

The majority consensus of the community as expressed in the Mid-Term Review of the previous Decadal Plan is that membership of the European Southern Observatory was the key strategic priority in optical/infrared astronomy. ESO membership does provide several benefits:

- ESO provides secure long-term access to the next generation of large telescope capability, and arguably currently the best comprehensive suite of instrumentation capability available worldwide.

- Membership of ESO connects Australia with an inter-government treaty-level scientific organization, which enables significant international opportunities for our scientific and technical community and enables long-term astronomical development infrastructure planning.

- Access to ESO's four VLT telescopes will secure our goal for 8-m class telescopes (at the level of 25-30% equivalent of one telescope). The fact that the access is split across four such telescopes means that the suite of instrumentation capability is very diverse and world-leading in terms of technological sophistication.

- Access to the 39m E-ELT will secure our goal for ELT access together with our existing GMT involvement. Australia's participation in ESO would correspond to the level of 18% equivalent of the 24m GMT in terms of light-gathering capability in addition to our existing 10% share of GMT.

- Membership is currently on the table under terms that would allow partial cost offsets by making existing world-leading Australian infrastructure (the AAT and in particular the new HERMES facility) available to the ESO community. In addition, ESO is currently actively seeking new partners to enable the commencement of construction of the E-ELT, making it reasonable to expect more favourable financial terms in the near future compared with a delayed entry.

In order to have maximum influence and involvement in the €1 billion E-ELT design, construction and first-generation instrumentation, it would be highly desirable to join ESO as early as possible. Delaying joining ESO as a member would both increase the entry price as the investment by other ESO countries increases with time and will diminish the construction and development contracts flowing back to Australia (though not to zero as ESO has an ongoing program of instrumentation development for their facilities). Another crucial consideration is that further delay in joining ESO could result in the missing out of other strategic alternatives. On balance we conclude **that the optimum time to join ESO is within the next two years**, **after that ESO should be reassessed** against other alternatives and it is likely that the landscape will have evolved.

3.3.3 Strategic Alternatives to ESO

In order to meet our aspirations in the era of ELTs, we recommend to further increase our share of GMT should ESO not be a viable way forward. It is likely that GMT will be the first ELT to become operational and as such will dominate the early science from the next generation of ground-based optical telescopes. It therefore makes sense to maximize Australia's involvement in this peak facility. Being a larger partner would also give Australia larger influence into any decisions regarding its strategic future, such as new instrumentation.

If ESO membership proves not be possible in the near term, then we recommend as alternate first priority that Australia secures a deeper engagement in other 8m and ELT projects, preferably as full members rather than only buying time on such telescopes. In the 8m telescope area there are several options (albeit none straightforward) today: Keck, Magellan, Subaru and Gemini. All of these telescopes provide very good instrument capabilities, which are well matched to our community. Based on feedback at our WG Town Hall meetings and elsewhere, **there is a preference to join Keck and/or Magellan as full members** even if currently at least there is no mechanism to do so. Australia is currently a member of the Gemini partnership, but has not been able to commit to the new partnership past 2016 and its membership will then lapse. In terms of instrumentation Subaru would be very attractive but there is no obvious way into this Japanese project with no further memberships being solicited or foreseen.

Why do we emphasize membership in one or more of these projects? Membership is the key to a strategic long-term relationship where our community is involved in the governance of a facility. It is also important for the instrumentation science community in Australia. The work in astrophotonics, fibre optics, adaptive optics, and optical interferometry requires access to the largest telescopes for these to lead to scientific breakthroughs. Return to Australia in this technological investment comes via contracts, which are generally let only to facility members. A final, not so obvious point, is that facility access is of most benefit for early career researchers (ECRs) trying to establish innovative new areas of research. Senior scientists can access telescope time via overseas collaborations, however reliance on this greatly discriminates against ECRs without developed networks and ultimately undermines the long-term future of the discipline. The importance of membership has been heavily re-affirmed in our extensive consultation process.

We note that the existing Keck operating agreement expires in 2018 and it is possible that a new partner opportunity may arise when the University of California will reduce to only paying half the operating costs (Keck currently costs ~$16M p.a. to operate). Furthermore it is possible that Magellan partners may be looking to sell a share to fund GMT costs and thus opening up the possibility for Australia to join as a partner or buy telescope time. We also recommend continuing to monitor the situation with Subaru and Gemini for future opportunities in the 8m area. Gemini have been emphasizing that there are likely opportunities to either purchase time or form limited-term partnerships. This would enable future access to Australian-built instrumentation such as GSAOI and GHOST.

Finally we note that a future 'Pan-Pacific Observatory' (PPO) may ultimately emerge from a federation of observatories on Mauna Kea (engaging Australia, Canada, U.S.A, Japan, China and Korea) and would rival ESO in scientific grasp. Membership in one of these facilities (e.g. Keck or MSE) would position Australia to participate in such a PPO.

3.3.4 International Survey Facilities

An ultra-wide field 10m-class spectroscopic telescope is a very compelling scientific concept that has been mooted by many scientific groups. It is also well matched to the Australian emphasis on survey science both in the optical and in the radio. Partnership in such a facility would partially address the strategic and instrument science goals of a large facility membership. However it does not meet all of the science goals of the Australian astronomy community by itself and as such would still have to be combined with purchasing time on other facilities such as Keck and Magellan to meet our diverse science requirements. The 'Maunakea Spectroscopic Explorer' (MSE) on Hawaii proposed by the CFHT community is one concept gaining momentum, while the 'Dream Machine' proposed in the Driver et al. white paper is currently only at the idea stage but its southern hemisphere location would be advantageous for the Australian community given our other optical and radio facilities. If built, such dedicated spectroscopic 10m telescopes would at the earliest see first light during the second half of the considered decade, i.e. after 2020, which necessitates a stop-gap solution before then. As already noted, such spectroscopic survey facilities, while scientifically of great interest, do not meet all scientific interests of the whole Australian community due to the limited instrument suite. We recommend Australia stay engaged in the development of one of these projects with the goal of playing a leading role.

The Large Synoptic Survey Telescope is an 8m-class specialist wide-field imaging-only telescope under construction in Chile by the United States, funded primarily by the NSF and DOE. Whilst access to this is distinct from the general 8m-access need (*and does not satisfy this requirement*) the data it provides will be extremely valuable for the surveys being done by our community, both in the optical (e.g. HERMES/WAVES/2dFlens spectroscopic surveys) and in the radio (source matching with ASKAP and MWA surveys). Early and guaranteed access to such data via membership would greatly enhance the value of this science. We recommend that our community explore ways to become members in LSST. We note that the current 'per person' membership model proposed by LSST does not seem appropriate for a national-level access, and we recommend more flexible and innovative arrangements be explored perhaps on an agency-to-agency basis. As for the above-mentioned 10m spectroscopic survey telescope, LSST only addresses parts of the scientific interests within the community, being a purely wide-field imaging facility. As such we see it by necessity only as part of a telescope portfolio rather than as a one-stop solution.

Finally we note that a set of smaller-scale international O/IR projects are becoming available for interested subsets of our community to participate in (e.g. KDUST, DESI, 4MOST etc.) often via subscriptions. This approach to science projects is a trending area and should be formally supported. A clear consensus has emerged in the WG and from the consultations that access to these should be on a competitive peer-reviewed basis (see further discussion in 'mid-scale funding' section).

3.3.5 O/IR Astronomy in the Antarctic

There has been some success during the last decade in developing infrastructure to take advantage of the unique conditions of the high Antarctic plateau (see Section 5.1.1. under 'Frontier'), in particular the successful operation of the PLATO autonomous observatory.

For the next decade we look forward to further progress, at the Dome A site where this development has shifted too, in partnership with China. This is seen as a key future strategic linkage. Seed projects such as PLATO and AST3 should continue to be supported, via competitive review against other projects via the LIEF scheme and/or any future mid-scale scheme. A future 2-4m telescope such as the proposed KDUST currently looks very attractive for both optical (excellent seeing) and infrared (low 2.4μm background) work in excellent niche science areas. Australia's contribution would we envision fall under the recommended mid-scale program to be competitively assessed at the appropriate time.

4 Radio Facilities

4.1 Progress against 2006-2015 Decadal Plan

The previous Decadal Plan *New Horizons: A Decadal Plan for Australian Astronomy 2006 – 2015* included preparation and engagement with the Square Kilometre Array as its highest priority, the apex of the pyramid of astronomy investment in Australia. More specifically, the community aspired towards 10% participation in the SKA from Australia, flagging in particular the development of radio astronomy infrastructure in Western Australia as a potential means of achieving this, although of course the site for the SKA had yet to be chosen.

Development towards the SKA was to be staged, with an engineering demonstrator (xNTD) leading towards an internationally funded SKA Stage 1, in a risk management approach that ensured useful scientific facilities at each stage. The plan noted potential for industry engagement in SKA, the likely lead role of ATNF in Australian SKA, and the desirability of Australian participation in refinement of science cases, design and prototyping. Finally, the likelihood that resources would need to be redirected towards SKA was considered, with consequent reduction in capability at existing facilities.

The plan explicitly recommended against investment from Australia in the Atacama Large Millimetre Array, noting that, "A nation of Australia's size cannot compete on every playing field in international astronomy." However, the plan looked forward to Australian astronomers being able to win time on ALMA.

4.2 Mid-term review

The Mid-term Review reaffirmed the goals set out in the Decadal Plan. By this stage, Australia's plan for an SKA technology demonstrator, xNTD, was being realised with the construction of the Australian SKA Pathfinder (ASKAP), and funding had been allocated for the Pawsey High-Performance Computing Centre for SKA Science in Perth. The review reinforced the need for the community to ensure Australia was well placed to participate in and host the SKA, including continued development of ASKAP and the Murchison Widefield Array (MWA). In particular, the review stressed the scientific quality of the MRO, and protection of radio quiet at the site.

The mid-term review noted that engagement with ALMA should continue.

4.3 Current landscape

4.3.1 SKA in Australia

Many of the goals of the previous decadal plan have now been achieved in radio astronomy, albeit not exactly as envisaged in 2005. The SKA site decision in 2012 resulted in a split site, with three instruments to be distributed across the

Australian site at the MRO, and the South African site in the Karoo. For the first phase of SKA (SKA1), this division is:

- SKA1_MID, with 190 antennas equipped with single pixel feed receivers, integrated with the 64 antennas of the MeerKAT instrument in the Karoo.
- SKA1_SURVEY, with 60 antennas equipped with phased array feeds. These will be integrated with the 36 ASKAP antennas at the MRO.
- SKA1_LOW, with 250,000 dipoles at the MRO.

This site decision will lead to approximately half the first stage of SKA being built in Australia. Australia is currently positioned to be at least a 10% partner in SKA

The MRO has been established as the world's leading site for radio astronomy, with outstanding radio quiet protection and three instruments currently on site (ASKAP, MWA, EDGES).

Australia's mid-frequency technology demonstrator for SKA is CSIRO's ASKAP project. Infrastructure on site for ASKAP is complete, including all 36 antennas and a highly shielded control building. The six antennas and phased array feeds (PAFs) that comprise the BETA array are now well into their commissioning process. The remaining 30 PAFs, with improved capabilities, will be built and installed over the next two years, with early science expected to start in mid-2015.

MWA is the low-frequency SKA precursor located at the MRO, consisting of 128 dual-polarisation aperture array tiles with a frequency range of 80 – 300 MHz. Led by Curtin University, the MWA consortium has 13 partners in four countries. Its operational phase commenced in July 2013, with the instrument operated as a national facility for Australian users. Importantly, the MWA has demonstrated the quality of the MRO for low frequency radio astronomy, and led to a dynamic and growing low frequency community in Australia that will be critical for SKA1_LOW.

4.3.2 SKA internationally

The international SKA project has made considerable progress since the last plan, although less quickly than hoped in 2005. Eleven countries are currently full members, the project HQ has been established at Jodrell Bank and design work for SKA1 has begun as part of SKA Pre-construction, a three year phase from 2013 -2016. Much of the technical work for pre-construction is taking place within eleven international design consortia, funded from within the member states. In Australia, the Department of Industry made $18m of funding available over the pre-construction phase to consortium partners. Australia leads two of the design consortia (Dish, Australian Infrastructure), and plays a major role several others, including Low Frequency Aperture Array.

As part of planning for SKA1, the SKA Organisation has set a cost cap of €650m. This will require a descope of the current baseline design, which is due to take place in early 2015.

4.3.3 ALMA and sub-mm astronomy

ALMA began early science operations with Cycle 0 in 2011, and is currently in Cycle 2. Australian astronomers are able to lead proposals for time as part of the 'Rest of the World' allocation, and have been incredibly successful in all three cycles to date, despite extremely high oversubscription rates. To date, Australian astronomers have been PIs of 7 high-priority proposals and CoIs for many more. There have been several Australian ALMA workshops with >70 astronomers attending. It is envisaged that access through this allocation and strategic collaborations will remain the most effective means of obtaining ALMA time for Australian astronomers. Possibilities of extending our current ALMA engagement (such as CSIRO establishing an ALMA office) were discussed during our consultation but it was concluded that current activities were mostly sufficient as long as they can continue to be funded.

The previous decadal plan did not prioritise sub-mm astronomy, and indeed stated that Australia is "unique amongst the major industrial nations (US, Canada, Europe, Japan) in that it has … chosen not to participate in the Atacama Large Millimeter Array (ALMA)". The science subgroups in this decadal plan have comments such as:

- *WG2.1* "Over the next decade, the ALMA telescope is likely to revolutionise our understanding of molecular gas and star formation in high-redshift galaxies". Conclusion: "access to ALMA is essential".
- *WG2.2* A key recommendation was "Access to the new generation of sub-millimetre facilities now under constructions overseas, in particular the Atacama Large Millimetre Array (ALMA)".
- *WG2.3* "Although ALMA and SKA are two major international facilities that will have pivotal impact on many areas of astronomical research, the Working Group on Stars and Planets does not place participation in these projects at as high a priority as the above items. "

The decision not to prioritise sub-mm astronomy within Australia has therefore lead to an under-representation of Australian astronomers utilising this wavelength regime. Now that sub-mm astronomy is becoming mainstream and is applicable to multi-wavelength studies across almost all science areas, the lack of expertise within Australia could become a concern, and support for sub-mm should be revisited at the mid-term review.

4.3.4 JVLA and other facilities

The VLA was renamed the Jansky VLA (JVLA) in 2012 following a significant upgrade to its receivers and correlator, which have improved its sensitivity by a factor of ten and frequency coverage by a factor of three. The JVLA is the most sensitive radio interferometer in the world and will remain so into the next decade. Other current large-scale international radio facilities include LOFAR in The Netherlands, and the US Green Bank and Arecibo radio telescopes. The future of both Green Bank and Arecibo are uncertain. Australian astronomers have access to the JVLA and most other facilities via the "open skies" principle.

4.4 Future Priorities

4.4.1 Capabilities required

Since the opening of the Parkes radio telescopes more than 50 years ago, Australia has been at the forefront of radio astronomy. Engagement with international facilities in the coming decade will be critical to ensure this continues. Required capabilities are in three main areas:

- With the Murchison Radio-astronomy Observatory in Western Australia, Australia now hosts one of the premier radio observatories in the world. As the radio spectrum becomes ever more crowded in the next decade, its remote environment will be critical to delivering the radio quiet necessary for the most sensitive instruments.
- ASKAP will demonstrate the power of wide-field surveys of the Southern sky. Extension of ASKAP, as proposed through the SKA1-survey instrument, will allow a hundred-fold increase in our knowledge of the radio sky.
- MWA is developing powerful new capabilities for radio astronomy and heliospheric science at low frequencies, optimized for extremely wide fields of view and unprecedented sensitivity at those frequencies. Continued exploration of the epoch of reionization will require extension of MWA, to the enormous increase in capability offered by the hundreds of thousands of antennas on SKA1_LOW.

4.4.2 SKA and its precursors

Priorities for the coming decade are dominated by the national and international SKA pathfinders and phase 1 of the SKA. These are world-class facilities, major components of which (such as ASKAP and part of the SKA) will be constructed in Australia. These telescopes will all make their debut in the 2016-2025 decade, with early SKA science coming towards the end of the decade. Massive commitments by Federal and State Governments, AAL and CSIRO have already ensured early technical successes with MWA and ASKAP, with full commissioning of the latter expected to be complete in the early part of the decade. Organisations such as ICRAR and CAASTRO, which were established in the last decade, will continue to operate in the first half of the coming decade with the scientific use, and technical development, of the SKA and their pathfinders as their leading justification. Consultation with the community suggests very strong support for the path leading to SKA in Australia.

We recommend continued prioritisation of ASKAP and the SKA. The next decade will see the scientific benefits of ASKAP, demonstrating the power of this innovative survey instrument. Construction of SKA1_SURVEY and

SKA1_LOW will also occur during this period, putting Australia at the centre of this 'mega-science' project. We judge it critical that the highest priority be placed on successful delivery of these instruments and positioning Australia to exploit their scientific potential.

Whilst the SKA1_SURVEY instrument is a natural progression from ASKAP, there is currently a long gap between the scheduled end of AAL-supported MWA operations (2015) and SKA1_LOW (currently scheduled to be complete in 2023). The radio community sees a tremendous opportunity to leverage its current investment and increase its leadership in low-frequency astronomy with a modest investment in a low-frequency facility that paves the way to the SKA. The natural choice is a limited expansion of the capabilities of the MWA. The main scientific goals realised through expansion would be resolving the time-evolution of the epoch of reionisation (assuming that the current MWA is able to make a detection), and understanding galaxy and black hole evolution through surveys of the low-frequency sky at unprecedented resolution and sensitivity. Alternative investments may involve a prototype SKA instrument or participation in other international mid-scale instruments. These investments are of much lower cost than the SKA, but would serve to maintain, if not increase, Australia's leadership credentials in the field.

We recommend new, but modest, investment in low-frequency radio astronomy. This would allow a limited growth of MWA, to continue surveys of the low frequency radio sky in the period before SKA1_LOW comes on line. We support current exploration by the MWA consortium of options for this expansion.

In general, the funding of mid-scale international (or national) projects has been problematic in Australia. Competitive small-scale projects are well-served by the ARC schemes, particularly LIEF. However, construction, subscription and operating costs of larger facilities (total investment $1-10M) has been more problematic, with schemes like NCRIS having operated on an *ad hoc* basis for the last few years. The lack of continuity in these schemes could jeopardise Australia's ability to take full advantage of SKA both scientifically and technically.

A mid-scale investment program would also allow areas such as Antarctic Astronomy to compete for funding with other, similar programs. There is now a working THz observatory on the Antarctic plateau (HEAT), its data cubes are publicly available, and its first science publications are being released this year. The proposed development of Antarctic Astronomy, through partnering with China on the KDUST and DATE5 projects, would be a potential mid-scale investment.

We recommend the continuity of funding streams (such as NCRIS) that allow participation in high-priority, mid-level international science projects. This would benefit a few key areas of science related to radio astronomy that are not under the SKA banner, potentially including Antarctic Astronomy. Such a scheme could also allow direct comparison between international and national projects of similar scale.

Australian radio astronomers have benefitted from the 'Open Skies' policies of major international radio observatories such as the JVLA and ALMA. This has permitted our access to the world's best radio telescopes at cm and mm wavelengths. In return, international astronomers have used Australian facilities, such as the Parkes and Mopra telescopes and the ATCA, with good effect. In doing so, increased levels of collaboration between Australian and international radio astronomers have been facilitated. It is therefore essential that the SKA and future radio facilities operate in a similar manner. Whilst it is appreciated that there is pressure to sell or trade observing time in return for access to other closed facilities, the radio community feels that the precedents set by the world's premier astronomy facilities such as NASA's Great Observatories and NRAO's radio telescopes are the gold standard to which we should aspire.

We recommend that the principle of 'open skies' be adhered to for future radio facilities as far as possible. Open skies allows Australian astronomers access to the highest quality facilities worldwide, and ensures the best possible science is done on Australia's instruments. We consider that this principle is worth retaining, although it will undoubtedly come under pressure in this decade.

It is not clear to what extent the central SKA project will include support for local astronomers, or how far this will be the responsibility of the country or region. However, access to highly processed data, and the ability to re-process or post-process large data sets will be a key to scientific utilisation of the SKA. There are a number of approaches that will allow such support, such as regional centres (ALMA), a central processing centre or a federated approach (CERN). Access to such facilities is important for the competitiveness of Australian astronomy, particularly for the engagement with large surveys, if not provided as part of the SKA project.

We regard the provision of user-ready data and post-processing facilities for the SKA and pathfinders as vital to their scientific utilisation. We strongly encourage the SKA project and the Australian community to develop a plan for SKA data management that enables Australian astronomers to best use SKA data when it becomes available.

4.4.3 Multi-wavelength recommendations

Access to world-class multi-wavelength data is vital for the scientific interpretation and publication of radio astronomy data. Australia's reputation in astronomy has largely derived from being a flexible collaborative community with access to a broad range of facilities. From the point of view of complementary optical/IR facilities, the radio community needs access to large-scale surveys from widefield imaging telescopes such as SkyMapper and LSST, to 20-m class facilities for deep follow-up, particularly spectroscopy. Access to widefield spectroscopic facilities such as the AAT/AAOmega has been extremely productive in the past, and we envisage that access to better facilities in the 4-12-m class in the future will be required.

We recommend engagement with new southern hemisphere widefield optical/IR imaging and spectroscopic facilities, and deep southern hemisphere spectroscopic facilities.

The sub-mm array ALMA will be extremely significant in the coming decade due to its unique capabilities of high spatial resolution, high dynamic range and high-sensitivity. It is very complementary to both classical radio and optical/IR wavelength regimes. Small investments to support Australian work with ALMA from open time would bring enormous value for money.

Continued support of ALMA is highly recommended at a modest financial level to provide (i) travel to ALMA Regional Centres, (ii) training and workshops in Australia, (iii) support for collaboration and joint postdoctoral positions with Chile. This should be re-assessed at the mid-term review.

5 Frontier Astrophysics

5.1 Progress against the previous Decadal Plan

The different sub-fields of *Frontier Astrophysics* had a widely varying presence in the previous decadal plan.

5.1.1 Antarctic Astronomy

Antarctic astronomy was supported in the last Decadal Plan, with the key—and ambitious—recommendation being the construction of the Pathfinder for an International Large Optical Telescope (PILOT). Australia completed a Phase A design study for PILOT, and this document and the surrounding science case published in three refereed papers in PASA, has been used by China and France in developing their own PILOT-like proposals.

By the time of the mid-term review it was clear that PILOT was too expensive for Australia to build on its own, so the review made four key recommendations:

(1) to continue support for the PLATO program in order to maintain Australian leadership,

(2) to explore international collaborations for an Antarctic optical/near-IR telescope for transient science,

(3) put on hold plans for a 2-4m optical/IR pathfinder telescope until an international partner can be identified to help with detailed design and costing, and

(4) to build a THz observatory in Antarctica.

All of the objectives of the mid-term review have now been met or exceeded.

The PLATO project (objective 1) was supported with NCRIS and EIF funding managed through AAL, with contributions from UNSW and AAO. PLATO remains the only observatory capable of running through the year at the best sites on the high Antarctic plateau. Its success has directly led to Australia strengthening its collaborative position with China, the US, and Japan in Antarctica.

The 0.5m aperture AST3-1 telescope (objective 2) showed promising early commissioning data (~0.5 millimag photometry) and the CSTAR telescope has been successful despite its small size. A near-infrared camera for the AST3-3 telescope is being considered. The leading candidate for a 2-4m optical/IR pathfinder (objective 3) is involvement in KDUST via a Chinese collaboration. This has been recommended to the Chinese Academy of Sciences, along with the DATE-5 THz telescope, as the only large astronomy program to be supported in the next five years. With a fast evolving competitive landscape in wide-field imaging, including the in-progress VISTA Hemispheric Survey, GLAO systems to improve seeing at temperate sites and a planned space-based wide-field infrared survey telescope (WFIRST), this larger-scale optical/IR part of Antarctic Astronomy should be considered competitively alongside other medium-scale investments for the coming decade.

THz is discussed below noting that the deployment of HEAT fulfils objective 4.

5.1.2 THz/submm Astronomy

Operation of the ALMA sub-mm telescope in Chile has begun, this is discussed in Section 4 under 'Radio'. At higher THz frequencies we have seen the Pre-HEAT pathfinder and the HEAT dish deployed to Ridge-A. HEAT is a collaboration with US partners (that started in 2012) to deploy a 0.62m THz telescope in the Antarctic. US NSF funding for this project was $1.5M, with additional logistical support from the US Antarctic program valued at $9M.

We note is considerable frequency overlap between the 'sub-mm' and 'THz' regimes. The Antarctic site offers significantly lower precipitable water vapour and thus much greater sensitivity per unit collecting area at higher frequencies. However there are currently no plans to construct an interferometer array in Antarctica and thus attain high spatial resolutions.

5.1.3 Gamma-Ray Astronomy

The previous decadal plan prioritised continued funding of the Australian institutional-scale facility CANGAROO. The Mid-Term Review recommended a continuation of Australian access to H.E.S.S., which by that point had capabilities that significantly superseded CANGAROO, due to increased international investment.

5.1.4 High-energy Particle Astronomy

The Pierre Auger observatory was mentioned as an international project of the type that competitive grant funding could be used for, especially in the type of programs that *leverage international collaboration and support*. The University of Adelaide was able to maintain collaboration membership in this world-leading high-energy particle observatory through funds including the EIF and NCRIS schemes.

5.1.5 Long Baseline Optical/IR Interferometry

Long baseline optical/IR interferometry only formed part of the previous decadal review in the context of University-scale facilities (i.e. the Sydney University Stellar Interferometer, SUSI).

5.1.6 Vacuum UV and X-Ray Astronomy

These fields were only mentioned in the last decadal plan and mid-term review in the context of the need for multi-wavelength and multi-messenger astronomy: part of the wide variety of tools available to astronomers. Specific Australian involvement (beyond that available publicly) did not form part of the plan.

5.2 Current Landscape.

Australia has a vibrant community of researchers in many Frontier fields of astrophysics, including gamma-ray astronomy to neutrino astronomy to long-baseline optical/IR interferometry. This community both conducts specialised experiments in astrophysics to answer narrow science goals, and also supports multi-wavelength and multi-messenger astronomy. Australia's involvement throughout these fields is moving from institutional scale facilities to international facilities, where Australia provides expertise, specialised instrumentation and access/membership fees in exchange for access to facilities and data.

5.2.1 THz Astronomy

Key current THz facilities used by Australian astronomers are NANTEN2 (Chile) and HEAT (Antarctica).

HEAT has successfully operated at Ridge A for three years, with 90 days of good THz weather per year, compared to only 5 days at the ALMA site. HEAT has tripled the amount of ground-based THz data ever taken, with the data now publically available and the first science papers published this year.

5.2.2 Gamma-Ray Astronomy

Gamma-ray astronomy is split between satellite missions (e.g. SWIFT, Fermi) and ground-based facilities (e.g. H.E.S.S.). The boundary between the two types of observatories is at the ~10s of GeV level, with ground-based gamma-ray astronomy focusing on the higher energies. The lower energies that are observable from small space telescopes do not have specific funded Australian involvement, and for this report are in the same category as X-ray astronomy. Australian involvement in H.E.S.S. II is at the institutional scale, via the University of Adelaide.

5.2.3 High-energy Particle Astronomy

The Pierre Auger observatory remains the world leader in high energy particle astronomy, and researchers at the University of Adelaide are able to participate in this highly productive international facility.

IceCube, a ~$0.5B international project at South Pole, has Australian involvement through the University of Adelaide. This field was not mentioned in the last decadal plan, despite an expectation of neutrinos from gamma-ray bursts. These detections did not eventuate, but the collaboration is now identifying high-energy neutrinos from astrophysical sources. Papers from IceCube are extremely well cited, demonstrating its impact, but the majority of this impact so far remains in the particle physics community.

5.2.4 Long Baseline Optical/IR Interferometry

The Australian institutional facility, the Sydney University Stellar Interferometer (SUSI) is still operational, but approaching the end of its scientifically useful life. This is especially due to the wide range of facilities and increasing operational efficiency of the Very-Large Telescope Interferometer (VLTI). There are currently 3 major world interferometers – the VLTI, the Center for High Angular Resolution Astronomy (CHARA) array and the US Navy Precision Optical Interferometer (NPOI). Australian astronomers are able to apply for open VLTI time, and researchers at the University of Sydney and ANU are able to access CHARA due to previous Australian investment funded through the ARC. The CHARA array now has a mature, scientifically productive first-generation instrument suite, with many current publications combining data from many sources (e.g. the Kepler satellite).

5.2.5 Vacuum UV and X-Ray Astronomy

A section of the community (CAASTRO) has negotiated access to the extended ROentgen Survey with an Imaging Telescope Array (eROSITA) all sky survey in X-rays, via a data sharing arrangement.

5.3 Future Priorities

5.3.1 Capabilities Needed

Frontier astrophysics is the centrepiece in the continuing trend towards multi-messenger astronomy. In order for Australian astronomy to have science reach in this context, representation is required across Frontier fields. Continued access to Pierre Auger, IceCube and CHARA is needed, as well as becoming a full member of:

- The Cherenkov Telescope Array (CTA)
- The DATE-5 THz telescope in Antarctica

Towards the end of the decade, there may be opportunities to invest in a next-generation particle astronomy instrument (e.g. Askaryan Radio Array) or the Planet Formation Imager.

5.3.2 Implementation

Ability to Compete for Mid-Scale funding: Where the minimum investment to become part of a world-leading instrument exceeds a LIEF, a pathway to access these larger (>$1-2M) infrastructure funds is required.

Membership/access fees: Where a researcher's primary instrument is a ~$10M to $0.5B international instrument that Australia did not contribute to, a common theme is that science exploitation is often still possible for a small membership or access fee. While competitive access to $100k or more of telescope time per researcher may be possible for large optical or radio telescopes, a common theme in Frontier astrophysics is that ongoing access fees are difficult to fund through normal (e.g. ARC, institutional) funding routes. A dedicated, competitive but enlarged scheme along the lines of AMFRP would remove this issue – the expected cost across Frontier astrophysics is of order $300K per year, leveraging access to many billions of dollars of international investment.

Workshops: Even where data are public, a barrier to science exploitation in Frontier Astrophysics is sharing of knowledge with non-experts. Within other international communities, there are often workshops or schools to help with this (e.g. the VLTI school, and an X-ray astronomy school through Chandra). Within Australia, this sort of collaboration mostly happens through the national observatories (e.g. AusGO workshop, Synthesis Imaging Workshop). A funding stream to set up these kinds of specialised workshops outside the traditional scope of the national observatories has the potential to greatly increase Australia's science exploitation of Frontier astrophysics.

5.3.3 THz Astronomy

New opportunities come in the form of THz astronomy – in the near term this is "Following the Carbon Trail" as described by Michael Burton in the ISM whitepaper. Carbon I critically probes temperatures in-between H-I and molecular cloud temperatures, which was previously a near-invisible stage of star formation. Australian membership in DATE-5 via a Chinese collaboration is the most promising mechanism to ensure access to this new frontier and would be a very compelling mid-scale project.

Development of THz astronomy would also arise naturally from Australian engagement of its sister-field of sub-mm astronomy via ALMA as recommended in Section 4.

Potential Antarctic long baseline interferometric projects are also to be considered amongst other international projects for the next decade.

5.3.4 Gamma-Ray Astronomy

The Cherenkov Telescope Array (CTA) is the most prominent next generation project – an international project at the $0.5B level. Australia is a member of this consortium, building on the CANGAROO project and H.E.S.S. Full membership in CTA is the single biggest priority for the Gamma-Ray community, which is in the range of several $M this decade.

5.3.5 High-energy Particle Astronomy

Continued membership of Pierre Auger and IceCube by Australian experts is a priority for at least the first part of this decade. It is likely that the next generation of cosmic ray observatories will be planned in the second part of this decade (e.g. a 20,000 square kilometre cosmic ray observatory and the Askaryan Radio Array). Australian leadership in these projects is not currently envisioned as a priority, but the ability for strong Australian participation is a priority.

5.3.6 Long Baseline Optical/IR Interferometry

Continued access to CHARA is the first priority over the first part of the decade, with this likely requiring access fees. If Australia is not to become part of ESO, continued access to CHARA in the second part of the decade will remain the top priority, due to anticipated gains from major upgrades underway (especially adaptive optics).

Over the early part of the next decade, much of the international optical/IR interferometry community is participating in a planning stage of the Planet Formation Imager (planetformationimager.org). This is a facility approaching the scale of an ELT, addressing key science questions in the Stars and Planets working group, and possibly other groups. One of the designs being put forward at this early stage requires the cold, dry conditions of Antarctica and would therefore have synergies with Australia's prior involvement in Antarctica. Although Australian involvement in this may become a priority, this facility falls outside the current decade. It is important for Australia to continue leadership in the astrophotonics technologies that are likely to form the basis of this facility, and to be able to compete for mid-scale funding for PFI membership as early as the end of the coming decade.

5.3.7 Vacuum UV and X-Ray Astronomy

The eROSITA initiative of CAASTRO is one priority that will give Australian access in the early part of the decade. Both India and China have in-progress and planned missions (Astrosat and SVOM), and future missions are possible within the decade. Australia should be positioned to utilise any major international investment in these fields to maximise the reach of multi-wavelength astronomy, but does not have specific priorities in this field.

6 Gravitational Wave Astronomy

6.1 Progress against the 2006-2015 Decadal Plan

Recommendation in the 2006-15 Decadal Plan:

1. Australian Astronomy supported Australia gaining a partnership in Advanced LIGO (aLIGO). Australian partnership in Advanced LIGO (aLIGO) was funded by ARC LIEF grants, the Australian National University and the University of Adelaide, from 2009-2016 at ~$500K p.a. These funds were used to deliver, install and commission hardware. This was very successful, earning for Australia full partnership recognition along with the USA, UK and Germany in aLIGO.

2. Upgrading AIGO, an 80m baseline high optical power test facility at Gingin in WA, to a 1km long detector. This was not pursued as analysis showed that such an instrument could never be sensitive enough to enhance, in any meaningful way, the performance of a global array of long baseline detectors.

6.2 Current Landscape

The Australian GW community is coordinated by ACIGA, the Australian Consortium for Interferometric Gravitational wave Astronomy. It currently has 50 members (including staff and graduate students) from six universities (ANU, UWA, UA, Melbourne, Monash, CSU) and CSIRO. The majority (75%) of the community members are currently instrument scientists, reflecting the pre-detection state of the field.

The construction and commissioning of Advanced LIGO (aLIGO) and Advanced Virgo detectors is proceeding on budget and on schedule. 'First light' was achieved a complete Advanced LIGO detector in May 2014. The first science run at about 25% of full sensitivity is scheduled for the last three months in 2015. Over 60 optical and radio projects worldwide (including Australia) have signed MOUs to be ready to follow-up on transient triggers from aLIGO during this first science run. With the expected sensitivity and short duration of the first run, GW detection is possible but not likely. Science runs scheduled for 2016 and 2017 are anticipated to detect GWs based on realistic estimate of binary neutron star event rates.

During the decade (2010) Australia was offered a full-scale (4km) advanced detector by the US LIGO Project, valued at $100M. This led to a proper analysis being performed to estimate the cost of building the infrastructure to house it. That estimate came in at $140M plus $5M p.a. to operate. The total cost of the facility then amounted to $240M, 40% effectively funded by the USA. A comprehensive analysis of the benefits of a southern hemisphere detector was performed, showing that, averaged over the entire sky, a factor of 5 improvement in pointing over the funded LIGO (USA) – Virgo (Italy) array would be achieved.

A bid to the Australian Government for $140M was unsuccessful, coming at a time when, driven by the global financial crisis, Australia had just spent over $1B in research infrastructure.

What came from this activity is that this LIGO detector will be sited in India. LIGO-India is scheduled to be operational by 2022. Furthermore, in 2010, construction of the Japanese KAGRA Project, a 3km baseline laser interferometer inside a mountain near the west coast of Japan, commenced. KAGRA anticipates reaching useful sensitivity by 2020. Both India and Japan have looked to Australia for assistance with their projects. India had no experimental heritage in the field, while Japan has a funding shortfall.

The actual funding on audio-band GW research over the past decade was around $11M, consisting of:

Partnership in Advanced LIGO,	ARC LIEF + unis,	$3.5M
Gingin High Power Research Facility	ARC LIEF + unis,	$2M
Research Instrumentation	ARC DP, Fellowships	$4.5M
Research Data Analysis	ARC DP, Fellowships	$1M

Outcomes from our research programs are driving upgrade paths for advanced detectors and ensuring leadership in a number GW search programs.

6.3 Future Priorities

The next decade will see the advent of gravitational wave astronomy. The first direct detection of GWs could happen as early as 2016 using audio-band receivers, with multiple detections per week by 2020. Pulsar timing arrays will have observed GWs from a stochastic background of massive black hole binaries. The signature of primordial GWs imprinted on the microwave background will have definitively been found or refuted, and planning for space-based detectors will be well advanced. Multi-band multi-messenger astronomy will be in its infancy, with Australia playing a key role in interrogating transient southern hemisphere GW sources using our optical and radio telescopes. During this birth of gravitational wave astronomy, the number of astronomers in the gravitational wave community (as opposed to instrument scientists) is anticipated to increase significantly.

6.3.1 Capabilities Required

Gravitational waves span over 20 orders of magnitude in frequency.
Exploration of the audio-band requires access to an array of ground based long baseline laser interferometer based detectors.

milli-Hz signals can only be extracted from space based interferometers. nHz-band signals and ultra-low frequency gravitational waves from the inflationary period use data from electro-magnetic telescopes.

6.3.2 Audio-band Gravitational Wave Antennae

To ensure a high profile in the rich early-science rewards from GW detection, the health of the field in the Asia-Pacific region, and the ability to contribute to and reap the rewards from being a key player in multi-messenger astronomy requires:

- On-going support for partnership in a full-scale international detector such as Advanced LIGO.
- Support for the commissioning of the Japanese KAGRA.
- Engagement with China.
- The necessary data analysis and computing infrastructure (hardware and Virtual Laboratory software).
- Early engagement of on-shore Australian electromagnetic telescopes in the follow-up of transient GW signals.

Access to data from the global array currently requires a financial commitment to detector staffing during observing runs (~$60K p.a. from Australian groups) and a Memorandum of Understanding to carry out agreed research with the data or instrument development.

A seat on the international oversight committee with the ability to influence detector operations, science, designs and future locations only comes with full partnership.

The strength and frequency content of audio-band signals will be used to inform the design of instruments ten times more sensitive, increasing the range for neutron-star binary coalescences to 8 Gpc (z~2) and ten-solar-mass black-hole coalescences at redshifts z>5. However, discoveries will be limited by both the resolution of the global array and its duty cycle.

Adding a detector in the southern hemisphere would improve the pointing of the LIGO/LIGO-India/Virgo/KAGRA array by, on average, a factor of 2; double the duty cycle of a 4 detector network (needed to optimise the GW information extracted) and hence double the science output from all detectors. **Post direct detection, optimising the global array will become a priority of the international GW community.**

With its ideal location within the southern hemisphere, availability of large tracks of stable flat land away from human-induced disturbances, and teams of leading EM and GW astronomers, Australia is a compelling site for a gravitational wave telescope.

A third-generation detector is likely to carry a price tag approaching half a billion dollars. Given the global nature of its impact, the funding of this instrument would need to come from an international consortium, with the cost to the host country on the order of 20% to 30%, i.e. $100-150M plus a share in the operating costs. The economic, social and scientific benefits of such a large international investment in Australia are obvious.

6.3.3 Space-based mHz-band GW antenna

Space-based GW detectors operating in the mHz to 0.1 Hz frequency band should observe thousands of in-spiral events including massive black hole (10^6 M_S), neutron star and white dwarf binaries and be well positioned to do cosmology. For the first time, eLISA has a programmed launch date of 2034 as an ESA L3 mission. Whilst the timeline is well outside the scope of this decadal plan, Australia has significant capability in satellite laser ranging through its involvement in the GRACE Follow-on earth observation mission, the Space Environment Research Centre and with a number of expatriates in JPL science/engineering positions. Australia should maintain a watching brief on this field and encourage continuing R&D supported through ARC and other programs.

6.3.4 nHz-band GW astronomy using Pulsar Timing Arrays

The detection of nano-Hz GW signals does not need dedicated radio telescope facilities and so does not fall under the brief of the International Facilities working group. Australia is recognised as leader in this field using the Parkes telescope and we urge that that telescope continue to be supported over the decade.

7 Mid-scale funding

Our key recommendations on optical/IR and radio concern large international facilities upon which it is desirable that the Australian community reach a consensus. However there are several common themes in funding small to medium-scale projects that have emerged in this report that deserve discussing together.

Firstly there are a quite a number of projects that groups of Australians can subscribe to as international members. Examples on the small scale are items such as membership of cosmic ray experiments (total decadal cost <$300K p.a.), examples on the medium scale are experiments such as 4MOST or KDUST (total decadal cost < $5-10M). There is a definite growing international trend for projects to raise funding in this way via consortia with membership subscriptions. Secondly there are often opportunities to build specific instruments for overseas telescopes where added funding is required at the $5-10M level and scientific return accrues to a subset of the community.

On the small-scale funding can be secured competitively via the ARC LIEF scheme (though we note this can be difficult if the timeline goes beyond several years). **The medium scale has no particular ARC funding scheme; however it has been funded by NCRIS and NCRIS2 in the past decade under a somewhat ad hoc process.** We have already supported mid-scale projects such as MWA, AAT upgrades and Antarctic astronomy this way. However the timetable has been irregular and the rules have been different each time (for example the last two rounds have not allowed proposals for new facilities) and it has been insufficiently open and competitive. In the future such a mid-scale scheme could be funded through NCIRS, perhaps via AAL, or CSIRO or ARC could support such a program.

The number and variety of small to medium scale projects is such that we do not think the decadal plan should make specific recommendations as to which to support. **Rather we have reached a consensus that the peer-review process is the best way to ensure that the most compelling such ideas can be supported in a rapidly evolving landscape**. There should also be a mechanism for providing seed funding for developing mid-scale ideas (which would fit in as 'small-scale').

Recommendation: we have concluded that such projects should be funded by competitive peer review, based on scientific and strategic significance, and that the most important recommendation is that a responsive, competitive and recurrent funding scheme be established that could support such projects over a decade.

The number of projects that we envision would be supported would be ~3-4 medium scale, ~5-10 small scale in astronomy over a decade. This would cost ~$30M over the decade (but some of this could be taken from existing schemes).

These include facilities located on Australian soil. Table 4 shows some examples and indicative costs of various mid-scale opportunities.

Table 4: Estimated minimum investments and investments based on the fractional Australian anticipated use multiplied by facility cost.

Named Facility (as a placeholder for an equivalent capability)	Lowest Investment for Partner Status	Investment if paying for full use share
Within decade, mostly offshore		
Advanced LIGO	$5M	$15M*
MaunaKea Spectroscopic Explorer	$5M	$20M
4MOST Instrument	$2M	$20M
Cherenkov Telescope Array	$3M	$6M
KDUST	$10M	$25M
DATE5	$10M	$25M
Within decade, onshore as part of international collaboration		
SONG Node	$3.5M	$3.5M
MINERVA Node	$0.3M	$3M
AuScope VLBI Broadband Upgrade	$2.2M	$2.2M
MWA upgrade	$7M	$10M
Likely Beyond Decade		
Planet Formation Imager	$5M	$50M

- includes Partnership in US Advanced LIGO and Japanese KAGRA.

For some of these mid-scale facilities, a relatively small investment can leverage a large international investment where Australian astronomers are likely to lead more than their "fair share" of the research output. For others, e.g. SONG, research leadership is likely to be proportional to investment, but longitudinal coverage in the Australian time-zone adds a disproportionately large value to the international network.

In addition to these international facilities, there are a number of similar scale national facilities that would likely compete for a similar scale of funding. These include VELOCE (a precision high-resolution spectrograph for the AAT) at the $3-5M level, HECTOR (a highly multiplexed multi-IFU instrument for the AAT) at the $10-12M level, and a wideband facility for Parkes (a pulsar upgrade) at the $2M level. Assuming that investments towards the lower limit of that likely required for partner status are made, the minimum total investment over the decade is at the $35M level for international facilities only, or more than $50M when national facilities are also counted.

<u>Notes on Individual Facilities</u>
4MOST: A 25% share of Australian-lead papers (most of the WAVES survey plus papers for other investigators) for a ~$80M facility.
KDUST/DATE5: It may not be possible to invest in one without investing in both, as the Chinese see both of these telescopes as a single observatory.

MINERVA: The minimum buy-in is based on a single telescope purchase within a multi-telescope Australian node. Such a low investment requires a large unidentified source of foreign funds.

MWA upgrade: additional collecting area (tiles) to improve sensitivity together with increased baseline to improve angular resolution and improved signal path. Overseas share of 30% is probably the realistic limit.