SKA and Pathfinders

A white paper prepared for the Mid-Term Review of the Australian astronomy Decadal Plan
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This paper has been informed by presentations and moderated discussion sessions at two community consultation workshops held in Perth and Sydney on 11 and 13 September 2019, respectively. The program of each workshop, and the slide decks that were presented, are available at this webpage: https://confluence.csiro.au/display/MTR2019/
Throughout, "this decade" refers to the period covered by the Decadal Plan: 2016-2025.

Executive Summary and Recommendations

This white paper provides a snapshot of the progress that the Australian radio astronomy community is making toward meeting the priorities identified in the Decadal Plan (DP), highlights the most impactful developments since the beginning of this decade, and discusses associated risks as well as consequences that should be taken into consideration through the remainder of this decade. The following developments are of particular note:

- The past few years have seen excellent progress made with Australia's SKA Precursors MWA and ASKAP, along with the rest of our fleet of radio facilities, collectively leading to significant steps toward answering key DP science questions.
- New, high-impact science themes have emerged, namely the identification of Fast Radio Bursts (FRBs) as unique cosmological probes, and electromagnetic followup of gravitational waves (GWs) detected by laser interferometers.
- Delays in the SKA timeline mean that the telescope will not be fully operational until after the end of this decade (at least 2027-2028).

The following key recommendations derive from these developments:

- Existing radio astronomy facilities, including Parkes and ATCA, should be supported for continued operation through the end of this decade. This includes support of essential upgrades. Australia's unique radio capabilities continue to be required in order to serve (inter)national community needs and enable followup of MWA and ASKAP discoveries.
- The Australian astronomy community requires access to large optical facilities in order to maximise the scientific impact of discoveries made with our radio telescopes. Australian membership in ESO would broadly serve community needs.
- Radio instrumentation programs must continue in order to retain world-class capability to open and pursue new science areas. This will require enhanced funding support.
- Data and processing centres will be required to realise the full promise of Australia's radio telescopes, and to develop computing capability to support SKA data.
- The Australian astronomy community needs to foster stable career pathways to retain top talent in technical and scientific research domains in preparation for the SKA era.

Science overview

In the leadup to the era of the Square Kilometre Array (SKA), the Australian radio astronomy community is engaged in a broad program of research and capability development with three primary themes: broadband, widefield galaxy surveys; cosmology; and the transient radio sky. These themes provide significant impact toward addressing the six fundamental science questions described in the Decadal Plan. Additionally, new and prominent developments in the science domain are leading to adjustments in the priorities of the community, such as the recognition of Fast Radio Bursts (FRBs) as uniquely powerful cosmological probes, and the follow-up of Gravitational Wave (GW) sources detected with laser interferometry.

At the same time, the SKA timeline has expanded beyond what was anticipated at the time that the current Decadal Plan was published. At present, the SKA timeline *optimistically* anticipates a start to construction in mid-2021 and completion in 2027-2028. Commissioning and early science would likely extend over a longer period. This revised timeline demands a renewed focus through this decade on stabilising and maximizing the capability of our national radio astronomy infrastructure. It is important to recognise that smaller-scale domestic facilities will not start to become broadly obsolete (and thus become susceptible to phase-out) during the current decade. It is clear that despite delays, the overall SKA effort has nevertheless already borne tremendous fruit by strengthening and empowering the Australian radio astronomy community. (It is also interesting to ask how much initially-planned SKA science will be done by the time that the SKA is built!)

Australian radio astronomy has made substantial impact toward the fundamental science questions described in the Decadal Plan.

1) *How did the first stars and galaxies transform the Universe?*

At the time of writing, the Murchison Widefield Array (MWA) has established the best published upper limits on the Epoch of Reionization (EoR) power spectrum at redshift z=7 (Barry et al., 2019) and in the redshift range z=10-20 (Ewall-Wice et al., 2016), and competitive limits at other redshifts. The published results have been achieved on the basis of Phase I capability, but during the first half of this decade the MWA has been upgraded to permit the application of new techniques for EoR analysis, making the telescope even more competitive in this field. The Murchison Radio-astronomy Observatory (MRO) has also been demonstrated as an excellent site for radio astronomy through the EDGES announcement of a detection of the Cosmic Dawn (Bowman et al., 2018) - a high-profile result which is subject to scrutiny but does demonstrate the MRO's excellent radio environment and its key role in facilitating cutting-edge science results.

2) *What is the nature of dark matter and dark energy?*

During the first half of this decade, ASKAP's survey capacity has advanced dramatically. At this point, spectral line survey capability has been demonstrated with the fully-equipped ASKAP array, allowing detailed mapping of the internal structure and kinematics of galaxies, as well as their distribution throughout the large scale structure of the Universe. Pilot surveys for the two primary survey projects, WALLABY (an all-sky neutral hydrogen survey) and EMU (an all-sky radio continuum survey) have already commenced, and are poised to make new progress during the remainder of this decade in characterising the large-scale structure of the Universe.

3) *How do galaxies form and evolve across cosmic time?*

Highly efficient sky survey capability has been demonstrated with the fully-equipped ASKAP array via the ongoing shallow, all-sky Rapid ASKAP Continuum Survey (RACS). Future epochs of this rapid survey will provide an increasingly comprehensive sky model below declination +40° that can be used for advanced calibration methods and studies of slow (incoherent) radio transients with unprecedented cadence. The faintest sources detected by the EMU survey will be dominated by star-forming galaxies due to its groundbreaking depth, which marks a change in the scope of radio continuum surveys. Followup of ASKAP detections at higher frequencies (5-20 GHz) will provide crucial complementary information and is uniquely enabled in the Southern hemisphere by ATCA. This mid-frequency activity is highly complementary to the strengths of the upgraded MWA, which has already demonstrated rapid widefield survey ability during Phase I (GLEAM; Hurley-Walker et al., 2017) and has now gained the capacity for deeper and higher resolution imaging surveys, while retaining the same powerful widefield capability. Together ASKAP and MWA uniquely equip Australia to probe the co-evolution of AGN and star formation across cosmic time during the current decade.

4) *How do stars and planets form?*

ATCA, Parkes, and the Long Baseline Array (LBA) provide complementary capability for the study of gas in star forming regions within our Galaxy, crucial for understanding the conditions under which stars and stellar systems form. The MWA and ASKAP will together provide unique probes of the magnetized, turbulent interstellar medium (ISM). Additionally, Parkes and the MWA are being used as part of a broad campaign searching for extraterrestrial intelligent life.

6) *What is the nature of matter and gravity at extreme densities?*

Followup of GWs has been a high priority with Australian radio facilities since the first detection of a binary black hole merger in late 2015. Australia's radio telescopes are uniquely equipped to play an important role in this field, particularly for sources in the southern sky. The large fields of view of ASKAP and MWA are well matched to the uncertainty regions provided by gravitational wave detections, and the rapid follow-up capacity of MWA and ATCA means that electromagnetic signatures associated with GW events can be sought on short timescales. The

LBA provides unique capacity to measure sizes and proper motions of GW afterglows in the south. Parkes has long been a leading player in pulsar timing arrays, and this technique holds great promise for detections of gravitational waves in a very different mass range. Connecting this activity through to the era of the SKA in an uninterrupted way is crucial for realising the rewards of the investment to date in this long-term observational program.

A prominent addition to the science priorities of essentially all Australian radio telescopes is the detection, localisation, and follow-up monitoring of FRBs. These sources have been established as cosmological probes of the Universe (Prochaska et al., 2019). The first FRB was detected using Parkes data. Since then, major efforts to detect FRBs with ASKAP and UTMOST have been highly productive (Shannon et al., 2018; Farah et al., 2019), and ASKAP has led the field in localising non-repeating FRBs (Bannister et al., 2019). Both the nature of FRBs themselves, and their use for studying the intergalactic and circumgalactic media (IGM and CGM), are hot topics internationally that are presently being dominated by Australian work. To continue to build on this position of strength, the ongoing development and improvement of instrumentation that enables FRB science must be factored in during the remainder of this decade.

As Australia's radio survey capabilities grow, the need for complementary multiwavelength data products becomes increasingly pressing - particularly in the optical/infrared bands. The radio community will increasingly require access to excellent optical/IR imaging and spectroscopy, as well as access to large-aperture facilities for followup of FRBs, GW counterparts, and interesting new objects (either transient or persistent) that will be discovered in radio survey projects. As such, Australian membership in European Southern Observatory (ESO) would service a broad range of Australian astronomers.

Connections to Decadal Plan priorities

The radio astronomy community has achieved excellent progress toward key recommendations of the Decadal Plan. The SKA Precursors MWA and ASKAP are both operational, and providing Australian (and worldwide) astronomers with high-quality data relevant to the fundamental science questions as described above. The Australian Government has signed the SKA Convention and commenced the ratification process, marking a commitment to join the SKA Observatory as a co-host. Australia remains active in many of the SKA design teams and Science Working Groups, and is a leader in the establishment of SKA Regional Centres (SRCs). The MRO is a world-class observatory site, with excellent RFI characteristics (despite ubiquitous satellite RFI) as demonstrated by MWA and EDGES. ATNF continues to operate ATCA, LBA, and Parkes, and to develop new instrumentation that drives Australian capability in the pre-SKA era.

A crucial aspect of Australian radio astronomy is multiwavelength coverage, not just within the radio window but also including access to large-aperture optical facilities to support the identification of FRB hosts, for example. Our geographical advantage places us in a prime position to uniquely identify southern transient sources, and to answer key questions about the magnetised, multiphase ISM and star formation processes within the Milky Way.

The strength of the Australian radio astronomy community has long been grounded in a world-class and accessible national facility system incorporating ATCA and Parkes, and University-led facilities that “punch above their weight”. The Decadal Plan foresaw a transition away from this traditional structure, but particularly given the projected changes to the SKA timeline we should re-emphasise the core role that these small- to mid-scale facilities play in making new scientific discoveries, as well as motivating, and in some cases achieving, SKA science aims.

Data and processing centres are crucial to effectively translate observational capability into the hands of astronomers. The development of an Australian SKA Regional Centre (AusSRC) will be crucial for supporting existing SKA Precursor activities (MWA and ASKAP), as well as preparing for the SKA era itself. Efforts such as the CSIRO ASKAP Science Data Archive (CASDA) for ASKAP, and the All-Sky Virtual Observatory (ASVO) for MWA, are key prototypes for this activity. In the current review period, ASKAP data have been released publicly through CASDA, and the MWA has started providing calibrated visibility data through ASVO which has increased the accessibility of the telescope for a far wider user base. Development of this capacity through the remainder of this decade is supported by the Pawsey Supercomputing Centre and national research infrastructure (AARNet, NCI).

High angular resolution followup to determine morphology of detected radio sources, precise localisations of transient events, and astrometry of compact sources are all key capabilities that are provided by VLBI in Australia. Although not mentioned in the Decadal Plan it is crucial to retain this capability during the era of ASKAP and MWA, and especially into the operational period of the SKA. Australia operates the only long-baseline array in the Southern hemisphere and this will be crucial for maximising the impact of SKA discoveries. An increase of correlated bandwidth in the LBA network, matching upgrades to the telescopes forming the array, would be an important step to retain competitive sensitivity at mid frequencies. It may also prove desirable to expand LBA capability into lower frequencies, should resources permit.

The Australian radio community has a key role to play in training the next generation of astronomers who will use the SKA to achieve new science outcomes. It is important to continue the tradition of ATNF radio schools and engaging the Universities, fostering the fundamental and practical skill sets of the upcoming generations of Australian SKA users. The Australian radio astronomy community values the educational benefit of hands-on observing with ATCA, Parkes, and UTMOST. At the same time, it is crucial to train our radio astronomers to do science with ASKAP and MWA data, as a prototype of the model for how we will interact with the SKA and utilise its data products. UTMOST also provides students with opportunities to develop and implement technical upgrades associated with the UTMOST-2D project.

Current issues and key risks

A key risk in the current period is that SKA timeline delays will lead to a capability gap in Australian radio astronomy infrastructure. We must ensure that the ability to maintain our world-leading strengths is not compromised by such external factors. This is particularly acute for programs such as searches for gravitational waves through pulsar timing, which demands an uninterrupted and consistent observational platform that is currently uniquely provided by Parkes. A reliable and stable observational capacity is also crucial for maintaining career pipelines, technology development programs, and high quality science outcomes. Coupled with this risk is the compounding factor that our existing facilities are all in need of upgrades (described below) to reinvigorate aging infrastructure. Traditional core national facility telescopes, ATCA and Parkes, are supported by a lean and aging workforce, which needs to be taken into consideration as the timeline to transition our observational capacity into the SKA era extends beyond the current decade. The availability of steady and reliable operating funds is a key risk for all of our radio astronomy facilities, especially as we diversify our income streams through the sale of telescope time, and should be prioritised despite the challenge of doing so in the leadup to the SKA with its uncertain timelines.

Instrumentation development is a top priority of the Decadal Plan and has generated exciting new upgrade opportunities for Australian facilities as is described below, but is not currently adequately funded. This requires substantial support from national funding streams e.g. LIEF.

Computing remains a major challenge for radio astronomy and this will only become more of an issue as existing telescopes look toward upgrades that will increase data rates and the scale of end-user data volumes. Moreover, our radio telescope facilities increasingly require the use of computationally expensive algorithms to get the most value from the recorded data products. Particularly as we develop these algorithms, our data flows often rely on multi-pass data processing which fundamentally cannot operate in real time.

An issue that has already been addressed above is the risk that Australia’s access to world-class optical followup capability is not sufficient to appropriately supplement outcomes in the radio domain. The radio astronomy community should support the ambitions of the optical community to gain access to large-aperture facilities that will maximise the complementarity with our radio astronomy portfolio, possibly through ESO membership.

The radio astronomy community has highlighted career pathways as an area that needs attention, both in the domains of scientific research and technical (hardware and software) development.

Synergy with other Decadal Plan priorities

This section highlights some key synergies with science and capability areas that are the focus of other white papers provided to the Mid Term Review committee.

ESO and ELTs: As noted above, access to large-aperture optical facilities is crucial for followup and identification of FRB and GW hosts, as well as detailed investigation of the plethora of high-priority targets discovered by surveys with the SKA Precursors. The radio astronomy community would benefit from, for example, Australian membership in ESO.

Gravitational Waves: As also noted above, there are two complementary aspects of this exciting science area from the perspective of radio astronomy. First, our radio facilities play a key role in identifying and characterising the hosts of GW events detected by laser interferometers, as well as studying GW afterglows. Second, efforts continue to detect much higher-mass merger events with pulsar timing arrays. When this activity pays off with, for example, Parkes (possibly as part of the International Pulsar Timing Array), the two complementary approaches will open the new field of GW astronomy over a much wider binary black hole mass range.

Data and HPC: As is highlighted in the section on risks, data management and HPC resources are essential for maximising the science return from our SKA Precursors, and increasingly for our other existing radio facilities. Additionally, there is a key role for computer simulations to supplement observational developments in areas including cosmology and the structure and kinematics of galaxies. Increasingly, GPU resources are required in addition to CPU capability. The AusSRC will be crucial for enabling science outcomes from Australia's SKA Precursors, as well as the SKA itself after this decade.

Space: Ground-based radio astronomy shares a high degree of complementarity with space activity and research as described in the Space white paper. Australia has a strong history in this domain thanks to our unique geographical location, excellent radio observatory sites, and strength in relevant technology development. In addition to facilitating deep space communications, radio astronomy provides the capability to study the ionosphere and monitor space weather, as well as to detect and track objects in Earth orbit.

Multi-messenger / high energy: There is a high degree of synergy with this science area; a few key common priorities are listed here. ASKAP will build on Australia's existing capacity to understand Galactic TeV sources. High-resolution radio imaging provided by the LBA is crucial for monitoring blazars, which are the first known source of high-energy neutrinos. The MWA has the capacity to study cosmic ray cascades in the atmosphere and to understand the composition and energetics of the parent particles, and the SKA will increase our scientific capability in this domain after this decade. Australian radio facilities provide important essential contributions to multimessenger transient networks, which are enabled by explicit MoUs.

Engagement model

Australia is engaged in the SKA project as described above. Our leading role in the decentralised data and processing centre model, through the development of the AusSRC, is a key aspect of how our astronomy community will engage with the SKA effort. We must continue to engage with the SKA during the present decade in order to share our experiences with the operation of SKA Pathfinder facilities, and the same will hold true for our experience with developing and ultimately using the AusSRC when it comes online.

Costs

This section provides a top-level summary of the upgrade investment required to support our radio astronomy facilities in maintaining world-leading research capacity leading into the SKA era. This upgrade pathway is particularly important for Australian astronomy since the SKA will not begin science operations until after the present decade has completed. Facilities are listed and discussed in alphabetical order.

ASKAP: The addition of a coherent FRB search mode would bolster ASKAP's already world-leading FRB observational leverage, increasing the detection rate by up to a factor of 20. This upgrade would ensure that ASKAP remains competitive in the regime of FRB localisations for the remainder of this decade. On a 5-year timescale, possible upgrades would include increased capacity such as tied-array beamforming for pulsar research and VLBI, as well as sensitivity enhancements through (for example) dish surface extensions. On a longer 10-year outlook, upgrades would conceivably take the form of new PAFs, possibly at higher frequencies than the current system.

ATCA: The primary upgrade program for this decade is a new correlator (BIGCAT), replacing the existing CABB which has reached end-of-life and represents a high risk for disruptive hardware failures. CABB has proven that a flexible and broadband correlator can provide high scientific impact even from a telescope of modest scale, and BIGCAT is being designed with even greater flexibility. There are two options for this upgrade path depending on funding resources: either building on the existing RF system and retaining 4 GHz bandwidth, or upgrading the RF system to permit an increase to 8 GHz bandwidth. At a later stage, a high-frequency PAF in the 7-15 mm range could offer a good opportunity to complement ALMA.

LBA: Upgrades to ATCA and Parkes through their respective BIGCAT and UWH programs would also serve to increase the available bandwidth for VLBI, which is key to retaining competitive sensitivity for high angular resolution science. Both of these programs are being designed to include VLBI capacity, and negligible additional expense would be required to begin to transition the LBA to a more competitive 8 Gbps (1 GHz bandwidth). Further investment would permit an upgrade across the entire network. The five University of Tasmania antennas play a key role in LBA and are either already capable of broad bandwidth, or will be upgraded during the current decade. A tied-array mode for ASKAP would also provide substantial extra sensitivity and much improved *uv* coverage for the LBA, albeit with reduced bandwidth. A low-frequency counterpart to the LBA would provide increased capability for high-resolution followup to ASKAP and MWA detections, pulsar astrometry, and scintillometry, as well as establishing a key national role for Australian radio astronomy that will remain relevant and important for the era of SKA1-LOW.

MWA: The highest priority for the MWA is to replace and upgrade the existing, aging correlator. This will increase the instantaneous bandwidth and provide greater spectral resolution, as well as increase the number of inputs and formed tied array beams. An increase in the number of inputs is essential in order to allow the use of all 256 tiles, beyond the current 128-tile correlator capacity, enabling imaging surveys with excellent surface brightness sensitivity and high angular resolution. It is also important to replace the existing receivers with an upgraded system, removing the coarse channel edges and enhancing the quality of the data for EoR and spectral line work. Additional receivers are also required to build on new correlator input capacity and enable the use of the full 256-tile array.

Parkes: There are two key planned upgrades for Parkes following on the successful integration of the Ultrawideband Low (UWL) system. First, the counterpart Ultrawideband High (UWH) broadband receiver would cover the range from 4 to ~25 GHz, with a system temperature of ~20K. The UWL and UWH packages fit together in the prime focus cabin, and would cover the uninterrupted frequency range 0.7-25 GHz with a high degree of flexibility. UWH would enable broadband VLBI, space tracking and asteroid radar capability, and broad access to spectral lines. Second, a cryogenic phased array feed (cryoPAF) would cover 700-1800 MHz with a system temperature of ~20K, enabling mapping of cosmic HI, enhanced study of FRBs (accurate fluences and ASKAP triggering), along with a substantial (>10x) increase in survey speed.

UTMOST: An ongoing project is focused on retrofitting the north-south arm of the Molonglo Synthesis Telescope, supplementing the east-west UTMOST to create a two-dimensional array with far greater capacity for instantaneous localisation. Dubbed UTMOST-2D, the project is intended to detect and localise FRBs, as well as enable high-cadence pulsar search and timing programs. The upgrade project is currently funded at the 10% level; a full retrofit of the 2D array would increase the sensitivity and thus provide world-class FRB detectability, competitive with and filling a niche between CHIME and MeerKAT. UTMOST-2D would be complementary to ASKAP by localising fainter FRBs over a smaller field of view.

Table 1 provides estimated costs for the upgrade plans described above, as well as a summary of operating costs per annum for each of the Australian radio astronomy facilities covered here.

Telescope / facility	Upgrade investment (M$) †	Operating cost p.a. (M$)
ASKAP	1.7 (Coherent FRB search)	7.5 (5.7) * + 3.5 (MRO)
ATCA	1.6 (BIGCAT 4 GHz) 2.8 (BIGCAT 8 GHz)	4.7 (3.0) *
LBA	-	0.35
MWA	0.96 (Correlator) 7.0 (Receiver upgrade and expansion)	1.8 ‡
Parkes	1.7 (UWH) 3.5 (CryoPAF)	3.8 (2.4) *
UTMOST	3.0 (100% UTMOST-2D)	0.4 (UTMOST) 0.45 (100% UTMOST-2D)
Total	22.26	22.1

Table 1. *Expected radio telescope upgrade investments and operating costs per annum.*

† *Upgrade investment costs include FTE contributions where appropriate.*

* *ATNF operations costs are provided both as total costs, as well as direct costs without overheads (in brackets).*

‡ *MWA operations costs are provided as the desired Australian contribution from NCRIS funding (55%); the remainder of the operations costs are funded by international partners.*

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