ATCA Future Science Case: 2020 onwards

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1 Executive summary

The Australia Telescope Compact Array (ATCA) is a radio interferometer with six 22 m dishes operating across a wide frequency range from 1–105 GHz and located near Narrabri, NSW. The ATCA has undergone regular upgrades since it began operation in 1988. Its broad frequency coverage is unique in the southern hemisphere, and several of its other capabilities are unmatched anywhere in the world.

This document examines the science case for continued operation of the Australia Telescope Compact Array (ATCA) in the era after 2020 when the SKA precursor telescopes ASKAP and MeerKAT will be in full operation. SKA1-MID is not expected to start science operations until 2029-30. The key ATCA science areas from 2020 onwards are identified as:

- **Studies of transient and variable radio sources**, mainly through 1–50 GHz follow-up of objects discovered at lower radio frequencies (ASKAP, MWA, MeerKAT), at other wavelengths (optical, X-ray, gamma-ray) or by multi-messenger facilities (e.g. Gravitational Wave events detected with LIGO/VIRGO, or high energy neutrinos detected with IceCube or KM3Net).
- **Essential astrophysical studies of objects discovered in ASKAP surveys,** including measurements of the radio spectra of active and star-forming galaxies, high-resolution spectral-line and polarisation studies of the Milky Way and other galaxies, characterisation of the host galaxies of Fast Radio Bursts, and VLBI studies of a range of Galactic and extragalactic radio sources.
- **VLBI science observations and technical development** in specific areas where southern-hemisphere observations offer unique advantages (e.g. studies of southern LIGO/Virgo detections, objects in the Magellanic Clouds and the southern Galactic plane), including pathfinder science for a future VLBI array with SKA1-MID.

The northern-hemisphere JVLA is currently the only other major radio interferometer with a wide-band capability at 1–50 GHz. However, the JVLA has only limited coverage of the southern sky and also lacks some of the ATCA's unique technical capabilities, including compact array configurations for low surface-brightness imaging, on-axis linear polarisation feeds for sensitive observations of circular polarisation, and an automated rapid response mode enabling the ATCA to slew to a flaring source within minutes of an alert being triggered by other telescopes. If the ATCA were no longer available, the main consequences for the astronomy community would include:

1. Loss of a unique fast-response capability for detection and monitoring of radio transients at frequencies above 1 GHz, with the likely loss of Australian science leadership in several high-profile and fast-moving research areas.
2. Loss of the only southern-hemisphere VLBI array operating at GHz frequencies, along with the likely loss of any future southern VLBI capability for SKA1-MID.
3. Loss of an important training facility that provides 'hands-on experience' in radio interferometry for Australian (and overseas) astronomers and students.

The Australian astronomy community would also lose the ability to conduct many of the large and ambitious follow-up programs that are planned for objects identified in the ASKAP wide-field surveys, as well as the ability to conduct high-frequency follow-up studies of objects found by major new southern-hemisphere facilities like LSST (Legacy Survey of Space and Time) and CTA (Cerenkov Telescope Array) that are coming online in the next few years.

2 Background

This document builds on some of the material from two earlier ATNF documents, *ATNF Science Priorities 2010 - 2015* (Nov 2008) [5] and *Science with the ATCA in the next 5-10 years* (May 2016) [22]. Some of the most significant changes in the scientific and technical landscape since 2016 include:

2017: The LIGO detection of gravitational waves from a merging neutron-star binary, with the ATCA playing a key role in radio follow-up of this and other LIGO and LIGO/VIRGO events. [1, 14, 19]

2019: ASKAP entering science operations in its full 36-dish mode, with a 30 deg^2 field of view at frequencies between 700 MHz and 1.8 GHz. This opens up exciting new scientific synergies between ASKAP and the ATCA, but also places increasing stress on the overall ATNF operations budget.

2019: ASKAP localisation (with ATCA assistance) of Fast Radio Bursts (FRBs) to their host galaxies [7], placing Australia in a leading position in a new and fast-moving research field.

2019: The award of 2020 ARC LIEF funding for a new ATCA correlator (BIGCAT).

The period from 2016–20 has also seen the commissioning of new radio interferometers (MeerKAT) and upgrades to existing ones (uGMRT, Apertif, JVLA, ALMA), so that the international landscape in which the ATCA operates has changed significantly over the past five years.

The current operating cost for the ATCA is around $3M per year ($2.1M labour and $0.9M operations), and this is not expected to change significantly over the rest of the decade. With the ATNF Operations budget now over-stretched by the additional running costs of ASKAP, CSIRO has put out calls for partners willing to provide external revenue in return for access to telescope time on the ATCA, LBA, Parkes or ASKAP.

Parkes has been successful in attracting several such projects (Breakthrough Listen, NASA tracking of Voyager 2, Chinese Academy of Sciences), but there so far been only a limited uptake in funded projects with the ATCA. This may be partly because outside users are attracted by the simplicity of using a single dish, rather than the additional complexity of an interferometer array. Efforts are continuing to explore options for non-astronomy applications of the ATCA, including satellite tracking and Space Situational Awareness (SSA).

Given the pressure on the operating budget for ATNF telescopes, it is timely to examine the scientific case for keeping the ATCA in operation over the next decade before SKA1-MID becomes available in 2029-30.

3 The ATCA and LBA

3.1 The Australia Telescope Compact Array (ATCA)

The ATCA is an array of six 22 m antennas, connected as a radio interferometer and located on a site outside Narrabri in north-west New South Wales, about 500 kilometres from Sydney. A suite of sensitive, cryogenically-cooled receivers gives the ATCA near-continuous frequency coverage between 1 and 105 GHz. Five of the antennas can be moved to different positions along a railway track, to change the spatial resolution (and sensitivity to diffuse radio structures) at each observing frequency. The ATCA reconfiguration system allows each of the five track antennas to be driven along the long east-west and short north-south railway tracks. This allows a full reconfiguration of the array to be completed in a day, making the telescope configuration-agile.

The ATCA can also be linked with other telescopes, including the 64 m Parkes telescope, the Hobart and Ceduna antennas operated by the University of Tasmania, telescopes in New Zealand operated by Auckland University of Technology and the South African Hartebeesthoek telescopes, to form the southern hemisphere Long Baseline Array (LBA). The long baselines of the LBA, up to ∼10,000 km, allow it to image compact radio sources with angular resolutions ∼1500 times higher than is possible with the ATCA alone.

Observing time on the ATCA is allocated competitively every six months on an 'open access' basis to astronomers within Australia and around the world. Currently, 40–50% of ATCA time is used by overseas astronomers [12], many of whom collaborate with Australian groups in this work.

Figure 1: The ATCA in one of its compact configurations (Image: CSIRO)

Over the past decade, the ATCA has consistently been the most scientifically productive of the ATNF telescopes in terms of the number of journal articles published by users of the telescope (see Figure 2). The number of ASKAP publications is expected to ramp up in future years as the main ASKAP surveys begin, but the ATCA should still retain its scientific productivity since its capabilities (such as its high-frequency receivers) are complementary to those of ASKAP.

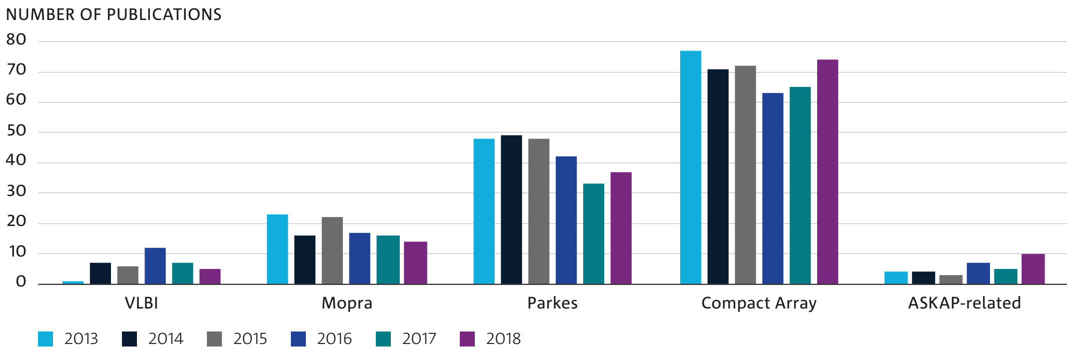

Figure 2: Publications in refereed journals (from 2013-18) that include data from ATNF facilities, grouped by telescope [12].

3.2 Upgrades and technical innovations

Since its opening in 1988, the ATCA has been regularly enhanced and upgraded. For example:

- The ATCA pioneered the use of mosaicking in the 1990s [32], making it possible to image large areas of sky in a highly-efficient way.
- In 1998, a north-south spur was added to the original east-west antenna track, providing improved (u, v) coverage for snapshot observations in the most compact configurations.
- The array was upgraded with new 15 mm and 3 mm receivers in the early 2000s, and 7 mm receivers in 2007.
- A new Compact Array Broadband Backend correlator (CABB) [33] was installed in 2009 to replace the original correlator, increasing the instantaneous bandwidth by a factor of 16;
- The 2009 CABB upgrade also provided new Zoom bands that enabled simultaneous wide-band continuum and narrow-band spectral line studies;

- In the early 2010s the 16 cm and 4 cm bands were upgraded, providing increased bandwidth and improved sensitivity.

In addition to these hardware upgrades, a novel on-the-fly mosaicking mode has been implemented, and CABB auto-correlations have been used for a 'fly's eye' mode. The telescope now has the ability to respond automatically to external triggers within seconds, a very powerful feature for work on transient and variable radio sources.

3.3 The BIGCAT correlator

The CABB upgrade [33] greatly enhanced the ATCA's performance, but its underlying technology is now almost 20 years old. While CABB's key modes were implemented, some planned spectral modes were not completed, and the number of spare CABB boards is dwindling. An ARC LIEF proposal, led by Western Sydney University in collaboration with CSIRO and seven other university partners, was awarded funding in late 2019 for a GPU-based replacement of CABB that will have greater flexibility and also double the bandwidth able to be processed. BIGCAT will also enhance the ATCA's VLBI capabilities.

The BIGCAT upgrade will entirely replace all digital processing on the telescope, including samplers, using the same overall approach that was successfully used for the digital stage of the Parkes UWL receiver. The digitization stage will sample 2 GHz wide IFs in each telescope using the Xilinx RFSoC chips, on a CASS custom designed board. The RFSoC (Radio Frequency System-on-Chip) has multiple analogue to digital converters and FPGA fabric for initial digital processing. As well as a digitizing the astronomy signal, this board will create a coarse filterbank (of $\sim$128 MHz) and transport the voltage data to the control room using 100 Gbps Ethernet, utilizing existing optical fibre. The same RFSoC board will be used for the Parkes cryogenically cooled PAF, significantly reducing the cost of development. Further digital processing, including fine channelisation and cross correlation, will be performed by a small cluster of GPU equipped servers.

The BIGCAT upgrade is currently planned in two stages. The first stage will replace the existing CABB system, with no significant changes to the RF system. This will not change the processed bandwidth of the array, but will mitigate against hardware failure of CABB and allow new astronomy modes to be trivially implemented (the planned GPU architecture will allow different astronomy modes to be used with changes to simple configuration files, plus verification by an expert). The planned date for CABB replacement is the end of 2021.

The second stage of the BIGCAT upgrade will involve replacement of the last stage of the CABB IF to double the processed bandwidth, from 4 to 8 GHz per polarisation. The design of this RF replacement is ongoing and may be involved a series of fixed bands covering the existing 8 GHz band available for all receivers other than the 1–3 GHz receiver. More flexible options are being investigated, if cost effective, including the option to cover the 12.2 GHz methanol maser transition, which is currently not accessible by CABB due to tuning limitations (even though the receivers will operate at 12.2 GHz).

With fully software-based processing on CABB, there will be a lot more flexibility for innovative new observing modes to be developed. The software design of the core processing will be designed such that external users can explore different and novel experiments. Potential experiments would be nanosecond transient experiments using wide bandwidths (> 1 GHz) or investigating RFI mitigation techniques.

3.4 The Long Baseline Array (LBA)

The ATCA and Parkes are the most sensitive elements of the LBA (the occasional availability of the Tidbinbilla 70 m notwithstanding) and enable the array to make use of a number of 12 m class telescopes. The ATCA is currently limited (by CABB and the tied-array hardware) to a single 64 MHz bandwidth in each of the two IF bands, and hence a total recording rate of 1 giga-bit per second (64 MHz x 2 IFs x 2 polarisations x 2-bit sampling x 2 Nyquist sampling) which is now lagging behind the rest of the world's VLBI arrays. While upgrading the ATCA is only one step towards upgrading the LBA, the fact it is an interferometer makes it the hardest instrument to upgrade. The standard LBA bands cover the frequency range from 1 to 26 GHz, which is the highest frequency Parkes can observe at. The ATCA's ability to observe in the 7 mm and 3 mm bands means it has also been able to participate in VLBI observations with other telescopes in these bands (such as the Korean VLBI Network).

4 The international landscape

4.1 Radio interferometers operating at frequencies above 1 GHz

Table 1 compares the ATCA with other major interferometers around the world that operate at frequencies above 1 GHz, including the SKA precursor telescopes ASKAP and MeerKAT. Interferometers that operate exclusively below 1 GHz, such as the Australian MWA and UTMOST, Canadian CHIME and international SKA1-LOW are excluded from this table.

Facility	Array	Freq. (GHz)	Beams	Bmax (km)	Bandwidth (GHz)	Location
Southern hemisphere						
ATCA	6×22 m	$1.1 - 105$	1	6	4–8	Australia
LBA (VLBI)	ATCA+other	$1 - 26^a$	1	10,000	0.1	Australia
ASKAP	36×12 m	$0.7 - 1.8$	36	6	0.3	Australia
MeerKAT	64×13.5 m	$0.6 - 1.7^b$	1	8	0.75^c	S. Africa
ALMA	54×12 m	$84 - 950^d$	1	16	8	Chile
Future (from 2029?)						
SKA1-MID	130×15 m plus MeerKAT^e	$0.35 - 14$	1	150	1–5	S. Africa
Northern hemisphere						
JVLA	27×25 m	$1 - 50^e$	1	36	1–8	USA
VLBA (VLBI)	12×25 m	$0.3 - 90$	1	8600	0.5	USA
uGMRT	30×45 m	$0.05 - 1.5$	1	25	0.4	India
Apertif	12×25 m	$1 - 1.7$	37	2.7	0.3	Netherlands
EVN (VLBI)	∼20 telescopes	$0.3 - 50$	1	10,000		International

Table 1: Major radio interferometers operating at frequencies above 1 GHz range. **Notes:** ^{a} The ATCA can observe at higher frequencies than 22 GHz, but the current LBA observing band is limited by the capabilities of other telescopes in the array. ^{b} MeerKAT will be extended to 3.5 GHz in the near future. ^{c} Future upgrades to MeerKAT are expected to increase the bandwidth to at least 2 GHz. ^{d} New 35–50 and 65–90 GHz band receivers are currently planned for ALMA. ^{e} SKA1-MID will have ∼200 dishes in total, including those from MeerKAT. ^{e} The JVLA also has receivers working at 0.23–0.47 GHz.

4.2 ATCA–JVLA comparison

Only two radio interferometers in the world have broad frequency coverage from 1–50 GHz, the ATCA and the US Jansky Very Large Array (JVLA). The ATCA has an additional set of 3 mm receivers operating from 83–105 GHz, and ALMA is expected to install new receivers covering the 35-50 GHz range in the years to come.

The long-term scientific value of a radio interferometer operating across the full 1–100 GHz range is recognised in the science case for the proposed US Next-Generation VLA (ngVLA) telescope [30], which is currently seeking funding on the path to full operation in the mid 2030s. The proposed ngVLA frequency range, 1.2–116 GHz, is almost identical to that covered by the ATCA. The future science case for the ATCA from 2020 is discussed in section 6 of this document. Here, we expand on the information in Table 1 to present a more detailed comparison of the technical capabilities of the ATCA and JVLA across the 1–50 GHz range that is unique to these two telescopes.

The **JVLA's advantages** include:

- *Better sensitivity* than the ATCA, since it has four times as many dishes (and individual dishes have 1.3 times the collecting area)
- *Higher spatial resolution* than the ATCA at the same observing frequency, and a *more circular synthesised beam response* for sources near the celestial equator, due to the JVLA's longer baselines and Y-shaped array configuration.

- The ability to form *independent sub-arrays* while retaining good (u, v) coverage.
- *Dynamical scheduling* to optimise observing conditions. This capability is only available in a limited capacity at the ATCA, though it could be more fully implemented.

While these are significant advantages for the JVLA, the ATCA also has a range of features that are not available at the JVLA, and which give the ATCA an advantage for some science programs.

The **ATCA's advantages** include:

- *Unique sky coverage*, since the ATCA can observe the whole southern hemisphere, including the southern Galactic Plane and Magellanic Clouds which are below the horizon at the JVLA site. JVLA observations of targets south of declination $-30°$ have low elevation and high airmass, resulting in poorer high-frequency phase stability. Sources south of declination $-45°$ are below the horizon at the JVLA and cannot be observed.
- The ATCA has a *fast automatic transient response* that allows it to interrupt the scheduled observation and move start moving to a new target within seconds of receiving an external trigger.
- The ATCA's symmetric on-axis design provides *superior polarisation performance* compared to the JVLA, and the ATCA's circular polarisation properties in particular are far superior to the JVLA.
- The ATCA's *mosaic mode* allows it to cover the sky rapidly and make multi-frequency observations of large numbers of different pointings with minimal time overheads. As an example, the ATCA has carried out a radio continuum survey of the whole southern sky at 20 GHz [31], but it would not be feasible to carry out a similar survey in the north with the JVLA because of the high overheads involved in moving between the many pointing centres required at high frequencies.
- The ATCA can be *quickly reconfigured*, and its array is reconfigured on average about 16 times a year while the JVLA has only 3 or 4 reconfigurations per year. The chance for an array suitable for a particular experiment in a given month is therefore higher for the ATCA, and this is especially beneficial for transient studies.

5 Science with the ATCA

5.1 Current ATCA science projects

The ATCA is an extremely versatile general-purpose telescope that currently supports around 70 different observing projects a year, across a wide range of science areas (see Figure 3).

One of the most notable changes over the past five years has been the growth of studies of transient and variable radio sources, which now account for 40% of all ATCA proposals and over 20% of total observing time. These projects in 'time-domain' radio astronomy cover a wide range of topics, from studies of the stellar-mass black holes in Galactic X-ray binaries [13] to follow-up of gravitational-wave signals from nearby galaxies [1] and gamma-ray bursts from the distant Universe [18].

The wide (1–105 GHz) frequency range of the ATCA allows it to observe a broad range of radio spectral lines in Galactic and extragalactic sources (see Table 2), while the telescope's fast-scanning capability has allowed it to carry out high-frequency radio surveys of large numbers of sources and large areas of sky [9, 20, 27, 26, 31].

5.2 ATCA Legacy Surveys 2016-20

In 2016, CASS began a new program of ATCA Legacy Projects. These Legacy Projects are large, coherent science investigations, not reproducible by any combination of smaller projects, that generate data of general and lasting importance to the broad astronomy community. These Legacy Projects required more than 2000 hours of observing time over the lifetime of the project, with the expectation of at least 300 hours to be allocated each semester.

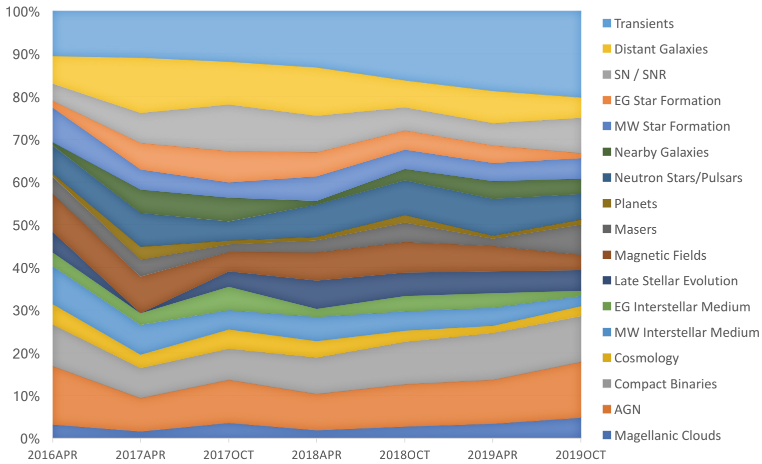

Figure 3: Science areas of successful ATCA proposals since 2016 (excluding the time allocated to Legacy Surveys). Data provided by Jamie Stevens.

Band	Frequency range (GHz)	Main spectral lines
16 cm	1.1 – 3.1	HI, OH, radio recombination lines
4 cm	4.0 – 12	Formaldehyde, methanol, excited OH, radio recombination lines
15 mm	16 – 25	Water vapour (H_2O), ammonia (NH_3)
7 mm	30 – 50	Silicon monoxide, carbon monosulphide, methanol, redshifted CO
3 mm	83 – 105	SiO, C_2H, HCN, HCO+, HNC, N_2H, CS, redshifted CO

Table 2: The ATCA frequency bands, and main spectral lines observable in each band.

Since 2016, up to 35% of the observing time has been allocated to four Legacy Projects, which are now nearing completion. From a list of 15 Expressions of Interest, two projects were selected by an international assessment committee as the top-priority Legacy Surveys. These two programs began observations in late 2016:

- **The GAMA Legacy ATCA Southern Survey (GLASS)**, a deep 4 cm radio continuum survey of the GAMA G23 Field, see `https://research.csiro.au/glass`, and
- **Deep Imaging of the Circum-galactic Medium with ATCA (IMAGINE)**, a search for neutral hydrogen gas at extremely-low column densities in the 'cosmic web' around nearby galaxies.

Two other projects were also selected at lower priority, and began observations in 2017:

- **Dense Gas Across the Milky Way - The 'Full-Strength' MALT45**, a survey using the 7 mm band of clumpy sub-structure on sub-parsec scales in a sample of Galactic molecular clouds, and
- **A Comprehensive ATCA Census of High-Mass Cores**, a study of the dense gas structure of our Galaxy through sensitive observations of the carbon monosulphide (CS) and ammonia (NH_3) spectral lines in the 15 mm band.

All four of these Legacy Survey projects are now nearing the end of their planned ATCA observing programs, and CASS will carry out a review of the results before deciding whether to issue a new call for a second round of ATCA Legacy Surveys.

5.3 Current LBA science projects

In recent years the LBA has undertaken a variety of projects, including studying the parsec-scale structure and evolution of the relativistic jets in gamma-ray emitting galaxies; astrometric observations of pulsars, methanol masers, and a water fountain planetary nebula to determine their distances; observations of flaring X-ray binary sources in our Galaxy; and space VLBI observations withe the RadioAstron satellite probing the most compact structures in masers and active galaxies on baselines up to 30 Earth diameters.

The high angular resolution provided by VLBI observations enables distances to be determined by measuring the parallax of the foreground source compared to background galaxies over the course of a year, due to the Earth's motion around the sun. A VLBI capability for the ATCA is also vital for projects such as bistatic radar observations of asteroids and satellite tracking.

6 Future science with the ATCA

Here, we focus on the science areas where the ATCA appears most likely to make important contributions over the next few years.

6.1 Transient and variable radio sources

This is a diverse and fast-growing field of research for the ATCA, and can provide new insights into the physics of extreme objects such as black holes and merging neutron stars.

The key ATCA science projects over the next few years include follow-up of LIGO gravitational-wave events and Fermi gamma-ray bursts (GRBs); searches for 'orphan' GRBs; radio supernovae; tidal disruption events; studies of Galactic stellar-mass black-hole outbursts and flaring radio stars; high-frequency follow-up of transient and variable radio sources detected by ASKAP, and characterisation of the host galaxies of FRBs. In the next few years, the ATCA is also expected to play a key role in the follow-up of optical transients from the Vera Rubin LSST survey, which will image the entire southern (night) sky at optical wavelengths every few days.

Figure 4 shows two examples from recent studies. In the left-hand plot, data from the ATCA was crucial in determining the peak of the radio light curve from the aftermath of a gravitational wave event observed by LIGO. This made it possible to constrain the total energy of the outflow triggered by the neutron-star merger [15]. In the right-hand plot, ATCA observations of an accreting binary system showed that this system contains a stellar-mass black hole and is one of the most compact systems of its kind in our Galaxy[4].

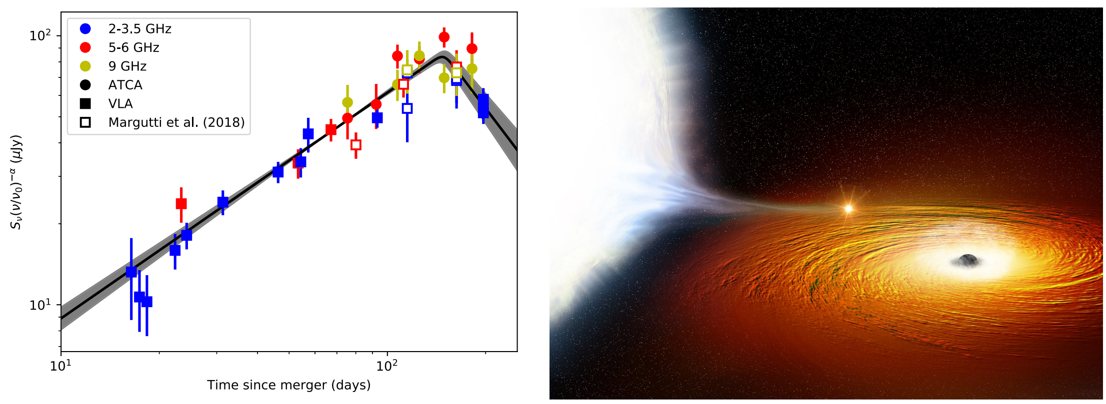

Figure 4: Two examples of recent ATCA results in time-domain astronomy: (left) Radio light curve of the neutron-star merger GW170817 in the galaxy NGC 4993, from ATCA (circles) and VLA (squares) observations grouped by frequency band, with 2–3.5 GHz (blue), 5–6 GHz (red), and 9 GHz (yellow), from [15]; (right) An artist's impression of a white dwarf star (left) in orbit around a black hole, based on a system identified in the globular cluster 47 Tucanae through simultaneous observations with the ATCA and two X-ray telescopes [4]. Illustration: NASA/CXC/M.Weiss.

6.2 Studies of molecular gas reservoirs in distant galaxies and protoclusters

This is a field where the ATCA has a niche advantage, since its compact configuration and sensitive 7 mm receivers make it possible to identify and study extended reservoirs of cold molecular gas in and around very distant galaxies. This cold gas, traced by the CO 1–0 molecular line at a rest frequency of 115 GHz. At redshift $z > 2$, this line shifts out of the frequency range observable with ALMA, and into the range observable with the ATCA 7 mm receivers.

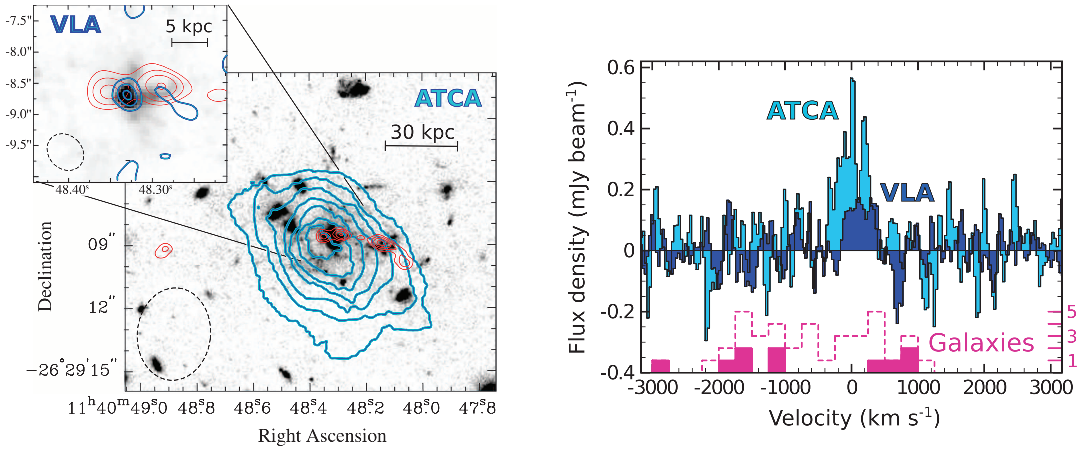

Figure 5: ATCA and JVLA observations of cold molecular gas (traced by the redshifted CO 1–0 line) in and around a distant radio galaxy at $z = 2.2$, from a recent *Science* paper [16]. (left) The spatial distribution of the gas, showing that the ATCA's compact configuration is able to detect very extended emission, (right) Velocity profile of the molecular emission, again showing the high sensitivity of the ATCA to extended molecular gas reservoirs in the distant Universe.

Figure 5 shows the recent ATCA detection of a large reservoir of cold molecular gas in and around a distant galaxy [16]. In this case, the short baselines in the ATCA's most compact configuration allows it to detect extended gas that is resolved out by the VLA (which lacks these short baselines even in its most compact configuration).

6.3 Essential astrophysical studies of objects from the ASKAP surveys

The Australian SKA Pathfinder (ASKAP) telescope is about to begin its long-planned program of radio continuum and spectral-line surveys of the entire southern sky at frequencies of 0.7–1.8 GHz. The ASKAP survey science teams[1] bring together over 350 scientists from more than 130 institutions worldwide, and most of these teams have been working together since 2009 to plan and prepare for the full ASKAP surveys and analyse data from the commissioning and Early Science observations already carried out.

Several of the ATCA's capabilities will be vital to unlock the full scientific value of the large surveys that ASKAP will carry out over the next five years. These capabilities include common sky coverage, wide frequency coverage, excellent polarisation qualities, a fast-response mode for transient studies, the ability to observe large samples of objects efficiently with minimal overheads for moving between positions on the sky. Some of the essential 2–50 GHz follow-up programs identified by the ASKAP survey science teams are outlined below. Many of these are expected to be large programs requiring hundreds of hours of observing time on the ATCA.

6.3.1 High-resolution HI imaging of nearby galaxies

Nearby, HI-detected galaxies from the ASKAP WALLABY survey will be imaged at higher spatial resolution in HI with the ATCA for detailed kinematic and dynamical studies, possibly also in combination with higher-frequency polarisation and continuum measurements to study the interplay between HI and star formation. The WALLABY survey can only use ASKAP baselines out to 3 km (due on insurmountable processing limits) so the ATCA, with its 6 km maximum baseline, provides an improvement of a factor of two in spatial resolution for HI imaging.

[1] See `https://www.atnf.csiro.au/projects/askap/ssps.html` for an outline of the ASKAP survey science projects.

6.3.2 Astrometric measurements of the host galaxies of Fast Radio Bursts (FRBs)

High-frequency observations with the ATCA have higher spatial resolution than ASKAP images, and are an essential component of the highly-successful FRB localisation program carried out by the ASKAP CRAFT team. The ATCA can help localise FRBs found by ASKAP not just to a host galaxy, but to an individual region within that galaxy. Figure 6, published in *Science* [7], shows the localisation of a single millisecond burst, FRB 180924, to sub-arcsec accuracy using ATCA astrometry to refine the ASKAP position.

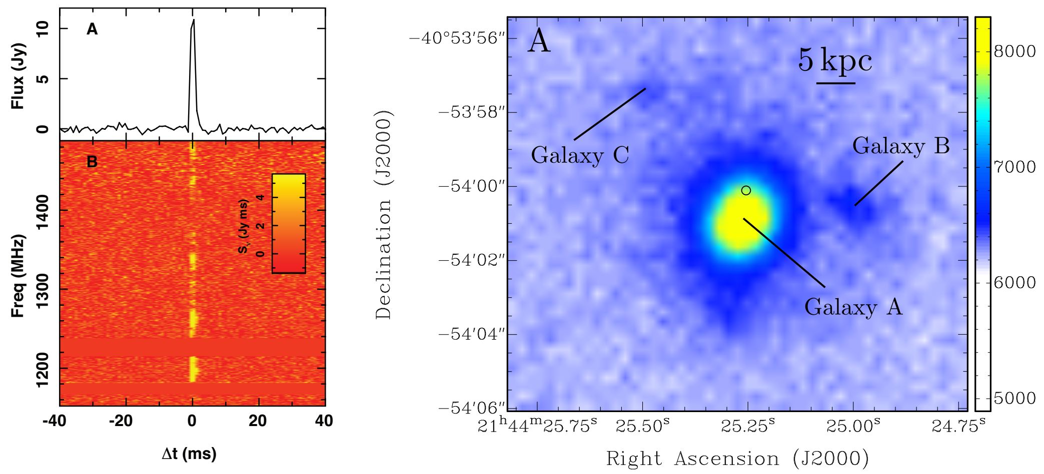

Figure 6: (left) ASKAP pulse profile of the Fast Radio Burst FRB 180924, the first single FRB to be localised to sub-arcsec precision, (right) The burst position (black circle), in the outskirts of a distant galaxy ∼4 billion light-years away. Both images from [7].

6.3.3 High-frequency polarisation studies of distant radio sources

The study of cosmic magnetism, as traced by observations of polarised radio continuum emission, is a fast-moving research field that will be transformed by the study of the large numbers of polarised sources detected in the ASKAP POSSUM survey. The ATCA's superb polarisation properties and broad frequency coverage make it an ideal complement to ASKAP for polarisation studies. ATCA observations at frequencies of 2-8 GHz will be critical for understanding the inner structure of the most complex ('Faraday-thick') polarised sources from the ASKAP survey, since high frequencies are needed to disentangle the contributions from the core and lobes of these sources.

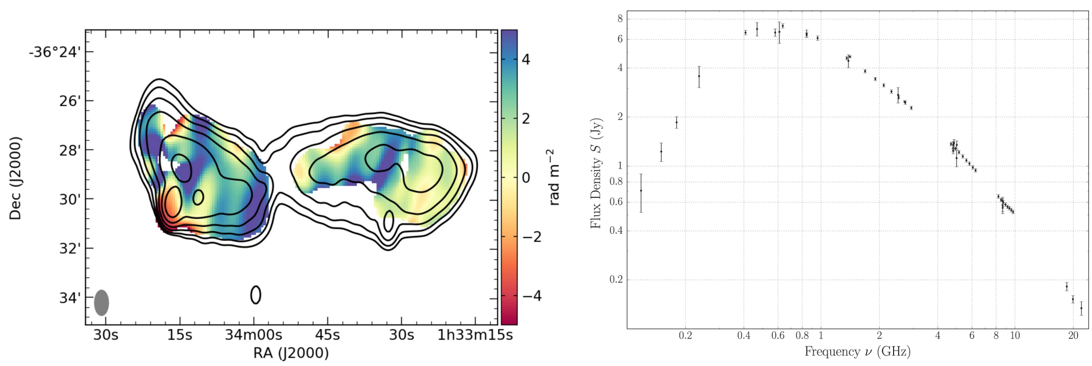

Figure 7: (left) A Faraday rotation image of the hybrid morphology radio galaxy NGC 612 (PKS 0131-36), based on ATCA polarisation observations in the 1–3 GHz band. Solid black contours show the total intensity (Stokes I) emission [6]. (right) The radio continuum spectrum of the extragalactic peaked-spectrum source PKS B0008-421, showing the ATCA measurements at 1-22 GHz. These measurements place important physical constraints on the radio emission mechanism [10].

6.3.4 Wide-band studies of radio continuum sources

Wide-band ATCA continuum imaging at 4–12 GHz will allow detailed study of thousands of the rarest and most interesting radio sources identified in the ASKAP EMU survey - including peaked-spectrum sources, high-redshift radio galaxies and distant starbursts. The left-hand plot in Figure 7 shows one example of a peaked-spectum radio source, where the shape of the high-frequency spectral slope provides a strong discriminant between competing radio-source models [10]. ATCA observations at 4-20 GHz also have the potential to separate the thermal and non-thermal emission from star-forming galaxies at both low and high redshift.

6.3.5 Characterising radio sources used for 21 cm HI absorption studies

ATCA follow-up observations planned by the ASKAP FLASH survey include high-frequency continuum measurements for several thousand of the brightest radio sources used in their ASKAP search for redshifted 21 cm HI absorption lines. These high-frequency measurements make it possible to separate the core and (extended) radio lobe components of these sources, allowing the team to carry out a more detailed statistical analysis of the very large HI absorption dataset that ASKAP will provide. The FLASH team will also use the ATCA in spectral-line mode to search for redshifted H_20 megamaser emission in distant radio galaxies where HI absorption has been detected by ASKAP.

6.3.6 Studies of the Milky Way Galaxy and the Magellanic Clouds

HI: The ATCA will be indispensable to supplement and follow-up on the discoveries made by the GASKAP 21-cm survey of the HI line in the Milky Way and Magellanic Clouds and Stream. The ATCA can add value and deeper astrophysical understanding to the GASKAP data in several ways. First, the ATCA will allow high sensitivity, high spectral resolution follow-up with full polarisation for Zeeman magnetic field measurements of HI absorption through the Milky Way and Magellanic Clouds. Second, the ATCA will provide the the ability to search for molecular lines from interstellar clouds with densities and temperatures in the range where molecules can form. The ATCA bands at 18-25 GHz and 40-50 GHz contain many molecular species that trace the molecular hydrogen phase at steps of increasing density on the path from atomic clouds to star formation (see Table 2). These bands are currently not accessible with ALMA. Finally, the ATCA used together with the Australian LBA can achieve much higher resolution than ASKAP at 21-cm. This is very important for studies of the small scale density and temperature structure in the ISM, particularly as seen in absorption toward background sources that have multiple continuum components separated by 10 arc sec down to 10 milli-arcsec. This allows study of variations in temperature and density on "tiny" scales of a few to a few hundred AU in diffuse interstellar clouds.

OH: ATCA full polarisation observations of OH masers detected with ASKAP will allow for detailed studies of the local magnetic field in star-forming regions and a comparison with large-scale magnetic fields in the Milky Way as traced by POSSUM. The preservation of large-scale magnetism into small-scale fields during star formation is a topic of current interest and study. In addition, ASKAP OH observations are currently limited to only 3 of the 4 OH lines, which places limitations on the thermal modelling of OH detections. The four ground-state OH lines are a sensitive barometer of physical conditions in the molecular ISM, whose line ratios can be modelled to provide information on the physical state OH-bearing gas. GASKAP will identify many new absorption detections in the 1612 MHz and/or main lines, which can be followed up in all four transitions with the ATCA to provide the largest ever sample of optical depth measurements for the full set of four lines. Crucially, this includes diffuse, CO-dark molecular gas, which plays an important role in the ISM life-cycle, but whose properties are still poorly constrained.

6.3.7 Transient and variable sources discovered by ASKAP

In addition to the time-domain radio research discussed above in section 6.1, there are several specific areas where the ATCA will be needed to study transient and variable radio sources identified in the ASKAP VAST survey.

ASKAP's wide field-of-view makes it competitive for detection of gravitational-wave radio afterglows [14, 15], and the high sensitivity and broad wavelength coverage of ATCA can set important constraints on the geometry and energetics of ejecta. LIGO/Virgo are continually improving sensitivity and adding detectors (Kagra), so upcoming future runs with these gravitational-wave detectors are expected to yield a higher rate of well-localised binary neutron stars. ASKAP is likely to detect more members of an intriguing population of slow transients [24], which may relate to orphan GRBs or other events without high-energy/optical detections. All of these will need multi-wavelength radio follow-up for localization, evolution studies to get constraints on environments, energetics. Very recent work by the VAST team has highlighted the time-domain potential of ASKAP to study energetic stellar phenomena such as flares and coronal mass ejections, and additional radio frequency coverage from the ATCA will help constrain the flare mechanism and magnetic field.

6.4 VLBI science observations and technical development for VLBI with SKA1-MID

6.4.1 Multi-View Observing for Ultra-precise Astrometry

With the advent of the BIGCAT correlator, a cryogenically cooled Phased Array Feed at Parkes, and a new phased array capability at ASKAP, the LBA will be uniquely placed to demonstrate the potential of multi-view calibration for ultra-precise astrometry – a goal of great relevance to the SKA (see below). Multi-view calibration is a technique that requires observing multiple sources such that the separation between them can be very precisely measured. Ideally the sources are observed simultaneously, but this is in general difficult to achieve with current VLBI arrays due to the intrinsically small field of view of the elements of the array, particularly the phased elements such as the ATCA. However, with the multiple observing beams in the BIGCAT design this field of view limitation can be overcome and precise astrometry provided for a much larger number of sources than is currently possible. BIGCAT will also be designed with a subarray option for VLBI, allowing multiple targets to be observed simultaneously. This has application across a wide range of science goals including Galactic and local group dynamics [23], black hole physics [2] and probing fundamental physics with observations of pulsars [25].

6.4.2 High Resolution Follow-up of ASKAP Detections – EMU

The ASKAP EMU Survey Science Project has identified VLBI follow-up of a large number of EMU detections as an important means of adding value to the EMU survey. In particular, a quick, sensitive, single-baseline snapshot, such as could be provided by the ATCA–Parkes baseline will provide a powerful discriminant between an AGN and a starburst origin for the emission in detected radio galaxies. Such a snapshot survey should provide statistics on many thousands of sources, which will be feasible using the multi-beam capability of the BIGCAT correlator to compensate for the small field of view provided by a single ATCA phased array beam. For brighter sources, an even more ambitious multi-beam capability with the individual ATCA telescopes sub-arrayed to point in independent directions, coupled with a Phased Array Feed at Parkes, could further increase the survey speed by up to a factor of six.

6.4.3 High Resolution Follow-up of ASKAP Detections – FLASH and GASKAP

HI absorption studies using extragalactic radio sources as probes require knowledge of the morphology of the background continuum source to determine the covering factor of the absorption feature. This information provides an important input to the statistical analysis of the HI sources detected in the FLASH survey, and also assist with the interpretation of Galactic HI absorption lines detected in the GASKAP survey (as detailed in section 6.3.6 above). As with the EMU case above, a single-baseline VLBI survey of several hundred sources on an ATCA-Parkes or (if feasible) a longer baseline would be a very effective way to provide the information needed.

6.4.4 High Resolution Follow-up of ASKAP Detections – VAST

The VAST survey aims to detect a variety of transient and variable sources, which by virtue of their rapid evolution are sure to be of small spatial extent. VLBI observations will form an important part of their investigation, as exemplified by a host of previous studies. Such sources will include Gravitational Wave events [17], X-ray binaries [3], extreme scattering events [8], and pulsars [29].

6.4.5 Importance of the ATCA to SKA1-MID

SKA1-MID will lack the long baselines (1,000 to 10,000 km) needed to produce the high spatial resolution required by many of its science goals. This has led to an interest in creating an intercontinental VLBI array with the phased-up SKA1 operating as a central, extremely sensitive, element observing in conjunction with existing telescopes distributed across the globe (see Figure 8). This SKA-VLBI concept is now part of the baseline design for SKA1.

The southern hemisphere location of SKA1-MID means that sensitive telescopes in Australia will be of paramount importance to realising the potential of SKA-VLBI for both astrometric and imaging goals. Figure 9 shows an example *(u,v)* coverage for potential SKA-VLBI arrays using the LBA (of which ATCA and Parkes are the primary elements) and the EVN. Other arrays such as the VLBA and EAVN are less useful because their longitude severely limits any mutual sky visibility with SKA1-MID. The (u, v) coverage for any VLBI array depends strongly on the declination of the source being observed, but for sources below a declination of 10°, an SKA-VLBI array including the LBA is vastly superior to one without, and **for sources south of $-40°$ declination, meaningful SKA-VLBI observations without the LBA are essentially impossible**.

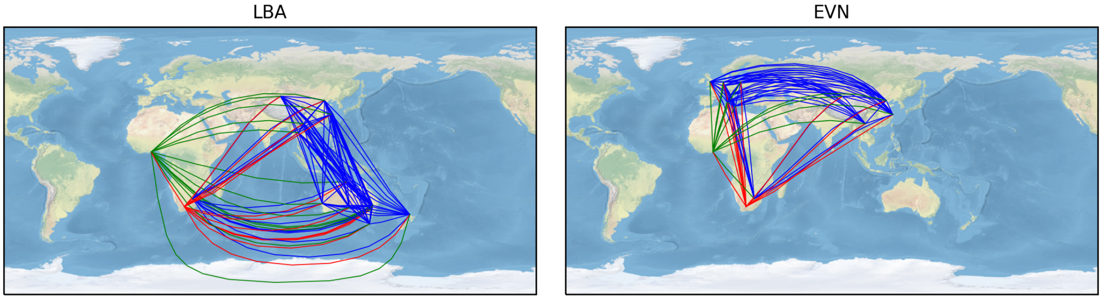

Figure 8: Geographic locations of radio telescopes that could be used to form a VLBI array with SKA1-MID. (left) **LBA:** Baselines to MeerKAT (red), an African VLBI station in Ghana (green), and an extended LBA array with some Asian telescopes (blue); (right) **EVN:** Baselines between MeerKAT (red), Ghana (green) and the northern-hemsiphere EVN.

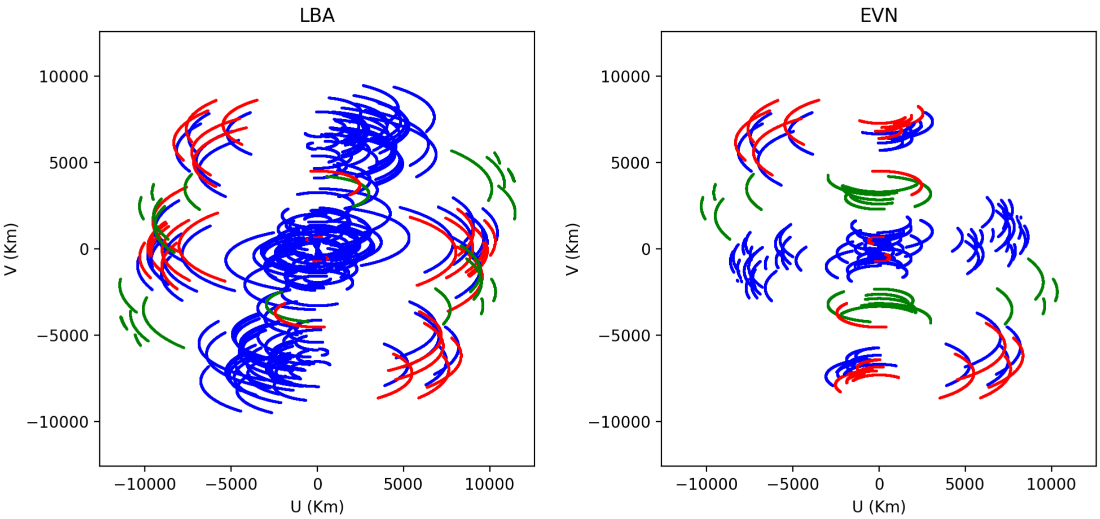

Figure 9: (u, v) coverage at a declination of $-20°$ for the two potential SKA VLBI arrays shown in Figure 8. Coverage that is better filled, and with fewer gaps, will provide better image fidelity. (left) **LBA:** Baselines to MeerKAT (red), an African VLBI station in Ghana (green), and an extended LBA with some Asian telescopes (blue); (right) **EVN:** Baselines between MeerKAT (red), Ghana (green) and the EVN. Note the greatly-improved coverage of a source at $-20°$ when the LBA is used. This advantage in (u, v) coverage is even greater for the LBA for objects south of $-20°$.

SKA-VLBI usage is expected to be dominated by projects requiring ultra-precise ($\sim$ microarcsecond) astrometry, beyond what is routinely possible with existing lower-sensitivity VLBI arrays. One of the cornerstone advances that will permit this new level of ultra-precise astrometry is the application of routine multi-view calibration (described above). The long, sensitive, baseline between SKA1-MID and ATCA, coupled with their complementary multi-beam capabilities, will be vital for meeting these ambitious astrometric goals over the entire southern sky.

6.5 Synergies with other southern-hemisphere facilities

6.5.1 ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA) consists of 66 radio telescopes in the Atacama Desert of northern Chile. The array is located at an altitude of 5,000 m above sea level which, together with the site's low low humidity, decrease signal attenuation due to Earth's atmosphere. ALMA observes in bands between 84 and 950 GHz, and is vastly superior to the ATCA in the 3 mm band. ALMA's scientific focus includes molecular clouds, and star and planet formation, as well as studies of extragalactic objects.

The 2016 ATCA science case [22] noted the strong synergies between the ATCA and ALMA for studies of Galactic star formation. In particular, the ATCA has a niche in the 16-25 GHz window covered by the 15 mm receivers, where key diagnostic tracers of dense gas and star-formation regions, including the ammonia spectral-line and H_2O maser emission, are observable (see Table 2). Two of the current ATCA Legacy Surveys discussed in section 5.2 focus on this area.

6.5.2 eROSITA

eROSITA is the primary instrument on-board the Russian-German Spektr-RG satellite, launched in 2019 and operating in a halo orbit around the Lagrangian L2 point. eROSITA is performing the first imaging all-sky survey in the medium energy X-ray range up to 10 keV, with unprecedented spectral and angular resolution. The scientific goals for eROSITA include detection of the hot intergalactic medium in galaxy clusters and groups (and hot gas in filaments between clusters) for studies of cosmic structure ans its evolution; the detection of obscured accreting Black Holes in nearby galaxies; identification and study of active galactic nuclei; and detailed studies of the physics of galactic X-ray source populations, including pre-main sequence stars, supernova remnants and X-ray binaries.

The all-sky X-ray data from eROSITA will be proprietary for the eROSITA team for up to two years, and will be split into two equal, non-overlapping sky parts for the German and Russian eROSITA Consortia respectively. The division line cuts the Galactic plane in two halves, through the Galactic Center and the north and south Galactic poles [28].

The 'German' eROSITA sky falls mainly in the southern hemisphere, and a Memorandum of Understanding designed to promote collaborations between Australian scientists and members of the German eROSITA consortium has been in place since 2013.[2] This allows Australian astronomers to obtain early access to eROSITA data through collaborative projects with members of the eROSITA_DE team. Several of the projects already approved involve ATCA follow-up of objects detected by eROSITA (including X-ray transients, supernova remnants and galaxy clusters), and the number of such projects is expected to increase rapidly over the next couple of years as eROSITA data start to flow.

6.5.3 Rubin Observatory (LSST)

The Vera C. Rubin Observatory, previously referred to as the Large Synoptic Survey Telescope, is currently under construction in Chile. Its main task will be an astronomical survey, the Legacy Survey of Space and Time (LSST).

The LSST will take more than 800 panoramic images each night with its 3.2 billion-pixel camera, recording the entire visible sky twice each week. Comparison with previous images will allow changes in the brightness and position of objects to be detected. It is anticipated the Observatory will issue up to 10 million alerts each night, reporting such changes between epochs.

[2] see `www.astronomyaustralia.org.au/erosita.html`

The Rubin Observatory is a partnership between public and private organisations. The mechanism for Australian participation in the LSST project is currently under discussion, but appears likely to be based around the provision of follow-up observing time on Australia facilities.

6.5.4 The Cherenkov Telescope Array

The Cherenkov Telescope Array (CTA) is the next-generation TeV gamma-ray observatory now under construction at two sites (South — Paranal, Chile, and North — La Palma, Canary Islands, Spain;). The CTA-Australia group (presently University of Adelaide, Western Sydney University, University of Sydney, UNSW, ANU and Monash) are active in CTA's construction phase and many of its Key Science Projects (KSPs). The CTA Consortium recently outlined the observations in optical, radio, X-ray and other bands that will be needed to achieve the KSP goals [11].

Radio coverage is a major component of these requirements, with >1000 hrs per year of observing time needed across the cm to mm radio bands. As the most sensitive instrument in the southern hemisphere operating at GHz frequencies, the ATCA will be a crucial asset here.

Radio follow-up of CTA sources is largely focused on the study of transient and variable sources such as active galactic nuclei (AGN), X-ray binaries, GRBs, FRBs, and Galactic objects. Initial steps have already been taken in this area with a current ATCA project that aims to trigger ATCA on GRBs detected at TeV energies with HESS. CTA will effectively expand on the long-running TANAMI project which has so far concentrated on GeV flares from AGN. As CTA is expected to detect hundreds of TeV AGN, we can anticipate a significant increase in opportunity for TeV flare studies. Such studies also extend to long baseline interferometry and ATCA's role in this as discussed above.

CTA will be constructed over the 2021–26 timeframe (the first CTA-North telescope is currently being commissioned) and we can expect a significant ramp-up in requests for ATCA time over this time scale, either in monitoring or ToO observations triggered by CTA results.

7 Competitiveness and uniqueness of future ATCA science

In this section, we consider three specific questions posed by the ATNF Steering Committee (ATSC) chair Dr David Skellern with regard to the future ATCA science program:

- Is this going to be breaking new ground, or consolidating old work?
- Can the work be done elsewhere, and how practical is that?
- What (explicitly) are the expected outcomes?

7.1 Research that breaks new ground

Several of the research areas described in section 6 above are genuinely ground-breaking. In particular:

- **Time-domain radio astronomy** is a new and fast-moving field. The ATCA is ideally-equipped to carrying out studies of transient and variable radio sources, and the work of Australian-led research teams already has a high international profile in this area. Recent ATCA observations of gravitational-wave afterglows and Fast Radio Bursts have produced high-impact *Nature* and *Science* papers [7, 19, 21]. This is a field where the complementarity between the ATCA, ASKAP, and new facilities like LSST, CTA and eROSITA will allow current research to be expanded in both scale and scope over the next decade. For example, ASKAP's wide field-of-view is ideally suited to the detection of gravitational-wave radio afterglows [14, 15], while the higher sensitivity and broader wavelength coverage of the ATCA allows physical constraints to be placed on the geometry and energetics of the ejecta.

- **Astrophysical studies of objects discovered in ASKAP surveys** is the second area where ATCA research will be able to break new ground over the next few years. The science areas that will be covered are very broad, but to some extent all this work will capitalise on combining the wide-field survey capabilities of ASKAP with the ATCA's ability to provide multi-frequency, high-resolution imaging in both total and polarised intensity, the versatile spectral-line capabilities provided by the new BIGCAT correlator, and the telescope's ability to observe large numbers of sources quickly and efficiently even if these sources are widely distributed across the sky.

- **VLBI pathfinder science for SKA1-MID** is the third area where the ATCA has potential to break new ground in future. Northern-hemisphere VLBI arrays EVN, VLBA) currently have much larger collecting area, and more versatile (u, v) coverage, than the southern-hemisphere LBA. This is starting to change, with the arrival of new mid-frequency telescopes in the south (ASKAP, MeerKAT and eventually SKA1-MID), and the development of a southern-hemisphere 'pathfinder' VLBI capability for SKA1-MID should be given serious consideration in any planning for the future of the ATCA.

7.2 Can this science be done elsewhere?

Only a relatively small subset of the science discussed in section 6 could be carried out at other telescopes. High frequencies (5-50 GHz) are important for much of this work, and the ATCA is the only southern hemisphere telescope operating at these frequencies (its coverage at 15–35 GHz will be unique in the south even in the era of SKA1).

For objects north of declination $-30°$ some of this work could be done at the JVLA, but the concentration of major new observing facilities (ALMA, LSST, CTA, SKA) in the southern hemisphere means that it is difficult for any northern-hemisphere telescope to substitute for the ATCA.

The fast-response mode of the ATCA, which can rapidly interrupt its regular observing program to respond to a trigger, is an important capability not available at other observatories.

7.3 What are the expected outcomes?

The expected outcomes from the ATCA science case outlined above include:

- High-impact research publications in major international journals.
- Australian leadership in important new areas like time-domain radio astronomy, and strong international collaborations across a wide range of science areas.
- Australian access to data from key international facilities like the LIGO gravitational-wave detector, ALMA, the Hubble Space Telescope and the Chandra and eROSITA X-ray observatories.
- An enhanced scientific return from Australia's investment in ASKAP.
- An additional scientific return from the new capabilities of the recently-funded BIGCAT correlator.
- A full exploration of the possibilities offered by ATCA for future VLBI observations with SKA-MID.
- Outstanding research training opportunities for the next generation of scientists.

8 Other possible uses for the ATCA

8.1 RFI mitigation testbed

Terrestrial radio-frequency interference (RFI) from a wide range of sources (TV transmissions, mobile phone towers, airport radar, etc.) increasingly affects the performance of radio telescopes worldwide (see Figure 10). The effects of RFI can be minimised by building telescopes on protected, radio-quiet sites like the Murchison Radio Observatory (MRO) in Western Australia, but even these remote sites are increasingly affected by transmissions from navigation and communication satellites in Earth orbit.

The development of new and effective interference mitigation techniques is vital for achieving the best performance from sensitive new radio telescopes like the SKA, and this is particularly the case for spectral-line studies, where the presence of RFI cannot be overcome by switching to a different

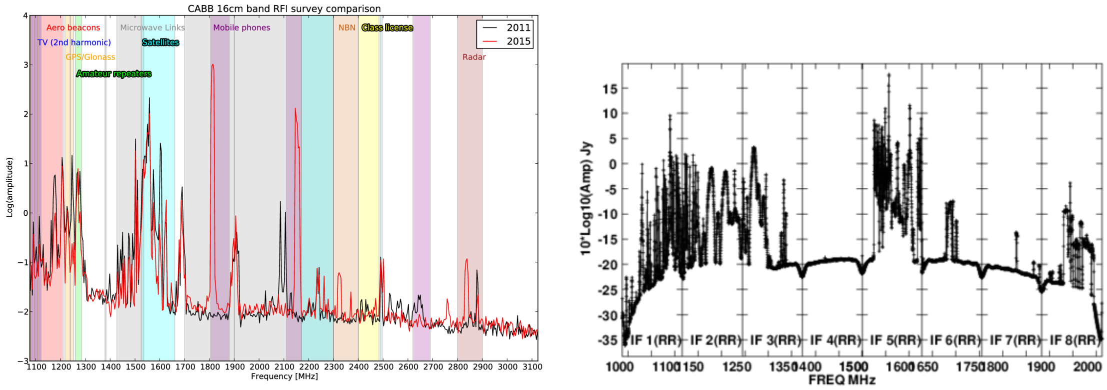

Figure 10: Plots of terrestrial RFI at frequencies of 1–2 GHz at the ATCA site (left) and the VLA site (right). For details and additional plots, see www.narrabri.atnf.csiro.au/observing/users_guide/html/chunked/ch01s03.html and science.nrao.edu/facilities/vla/docs/manuals/obsguide/rfi#section-4

frequency. The high data-rate and wide bandwidth of modern radio telescopes means that RFI mitigation needs to be done automatically and in real-time to be effective. Despite the importance of this problem, only very limited resources worldwide are currently devoted to addressing it and much work still needs to be done.

Current work by the CASS Signal Processing Technologies group offers the possibility of building interference mitigation features into the upcoming (RFSoC) generation of hardware. With modest additional resources, this would allow the ATCA, with the new BIGCAT correlator, to be used as a unique testbed for the development and demonstration of a range of real-time RFI mitigation techniques and algorithms. The most successful of these techniques could then be deployed on the SKA and other telescopes.

Opportunities for real-time RFI mitigation enhancements on the ATCA include:

1. Estimation and removal of RFI in the time domain;
2. Spatial filtering of moving RFI sources (creating nulls in the array beam towards RFI);
3. Blanking over-range signals; and
4. Online calculation of statistics to make flagging autonomous and efficient

Real-time RFI removal or blanking in the time domain can be an effective way to mitigate signals limited in time and frequency, such as aircraft beacons, satellite transmissions, and navigation aids. Removal or replacement of the unwanted signal, early in the signal chain, minimises the amount of data that needs to be flagged as a result. In the case of aircraft radar/beacons, that are often low duty cycle but high power, large fractions of currently discarded data could be made useful.

Spatial filtering (nulling) is more effective with reference antennas tracking RFI sources to better estimate the telescope's response in the direction of the RFI. This can be challenging when RFI enters the telescope from multiple directions at the same frequency. Rather than build many reference antennas, there is an opportunity to build a single 'reference' aperture array that could create many agile 'reference' beams on the sky. This would enable simultaneous tracking of multiple RFI sources and provide reference copies of them to mitigation algorithms running on the ATCA.

8.2 Searches for Extraterrestrial Intelligence (SETI)

Much of the development work for RFI mitigation also has direct application to SETI (Searches for Extra-Terrestrial Intelligence), a key activity of the Breakthrough Foundation who currently fund the 'Breakthrough Listen' project at Parkes.

The ATCA has some strong inherent advantages for SETI experiments, including:

- High instantaneous bandwidth;
- High time resolution; and

- Wide frequency range.

The ability to automatically reject signals that are clearly RFI will spare signal capture and processing resources for signals that are more likely to be SETI, and therefore make SETI searches significantly more efficient. Developments towards RFI mitigation algorithms can also be used to discriminate between RFI and candidate technosignatures of ETI. Mitigation algorithms generate a wealth of additional data that can be used for signal discrimination between natural, human and SETI sources. These include direction of arrival (via array correlations), modulation waveform (via cyclic spectrum), gaussianity (via kurtosis). All of these can be used to help identify candidate SETI signals and/or to trigger voltage capture for further analysis of SETI candidates.

8.3 Space applications

In recent years the ATCA has been used for bistatic radar observations of Near Earth Asteroids. This entails transmitting a radio tone from one of the Tidbinbilla antennas toward an asteroid during its close approach to Earth, and detecting the reflected radio waves with the ATCA. Parkes has also participated in these observations, however the ATCA has the advantage of being able to observe at 7.1 GHz, one of the Tidbinbilla transmit frequencies, which is currently inaccessible to Parkes. Reception of the CW tone enables properties of the asteroid to be inferred, including its rotation rate, size, and surface roughness (based on polarisation ratio of received signal). A proposed upgrade to enable coded transmissions from Tidbinbilla will allow delay-Doppler 'imaging' of asteroids, as is routinely done in the northern hemisphere. A southern-hemisphere capability is important, because some Near Earth Asteroids will not be visible from the northern hemisphere during their closest approach to Earth.

There is interest in characterising Near Earth Asteroids from as astronomical standpoint (they constitute some of the original building blocks of our Solar System), from a 'planetary defence' perspective (should their orbits bring them on a collision course with the Earth), and as potential mining targets in the future.

This work can be considered as a branch of the growing field of Space Situational Awareness, which is primarily concerned with tracking the rapidly increasing number of satellites in Earth orbit. The ATCA's 7 mm receivers were funded by NASA, as it was interested in developing a tracking capability at 32 GHz as a back-up to Tidbinbilla. The ability to track satellites with the ATCA was demonstrated, but the anticipated increase in NASA satellites using the 32 GHz downlink band did not eventuate and the tracking arrangements were curtailed. There is the potential to further develop the ATCA's capabilities in this area, which may be provide a future source of external revenue.

8.4 Research training

In contrast to most radio interferometers, the ATCA (like Parkes) continues to use the proposer-as-observer model, where the team of astronomers who successfully submitted a proposal for observing time are then responsible for conducting the observations. This 'hands-on' observing mode has the scientific advantage of allowing astronomers to refine their observations in real-time — making adjustments for weather conditions, or RFI, or based on the data they are taking. It also provides a unique training role, allowing students and postdocs to gain an understanding and appreciation of how an interferometer works. Experience of this kind is much more difficult to obtain at other facilities around the world.

The ATNF also conducts a week-long Radio School at the ATCA every two years, combining lectures and tutorials with the opportunity for participants (mostly students and postdocs) to drive the telescope themselves. Each of these schools attracts 30–50 participants, many of whom go on to be ATCA users.

ATNF staff also co-supervise the research projects of students from Australian and overseas Universities. There are currently 40 students in the program, all of whom make use of one or more ATNF telescopes in their PhD project.

The ATNF also runs a vacation student program over the summer months. Around 12–15students, typically second or third year undergraduates, carry out s small self-contained project supervised by an ATNF staff member. These students are also allocated time on the ATCA to carry out observing

Figure 11: Participants at the miost recent CASS Radio School, held at the ATCA in Narrabri, NSW in October 2019 (Image: Chenoa Tremblay).

projects, and travel to Narrabri to conduct their observations on-site. This observing trip is often reported as one of the highlights of their time at ATNF.

The ATCA has a designated Duty Astronomer (DA), rostered each week to provide assistance to observers. These DAs are drawn from ATNF staff, co-supervised students, and experienced users. The DA system provides another opportunity for students and postdocs in particular to become familiar with the operation and capabilities of the telescope, and also to interact with visiting astronomers as they come to observe.

There is potential to expand the use of the ATCA as a training facility in future, for example by running residential or online courses for researchers and students from SKA partner countries who want to improve their knowledge and understanding of radio interferometry.

9 Conclusion and recommendations

The ATCA is a versatile and well-instrumented radio interferometer used by astronomers from all around the world. Its capabilities make it a particularly powerful instrument for studies of transient and variable radio sources, a fast-growing area where Australian-led teams are among the world-leaders. The ATCA also has an essential role in maximising the scientific return from Australia's investment in the new ASKAP survey telescope.

The full set of capabilities provided by the ATCA is not available anywhere else in the world. The northern JVLA almost matches the ATCA's frequency coverage, but has only limited coverage of the southern sky and lacks both ATCA's fast-scanning mode and its rapid-response ability for time-domain observations. ASKAP and MeerKAT have the required sky coverage, but their frequency coverage is too limited to address the key ATCA science.

This report outlines a number of potential non-astronomy uses for the ATCA that might bring in external funding, and we urge that all possible avenues should be explored to secure operational funding for the ATCA over the next decade.

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