Science with the ATCA in the next 5–10 years

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Summary

CSIRO's Australia Telescope Compact Array is a highly versatile, world-class radio interferometer, ready to play a major role in the ASKAP era and beyond. Its cutting-edge, broad-band instrumentation provides high sensitivity for competitive spectral line, continuum and polarisation studies with an exceptionally wide frequency coverage (from 1 to 105 GHz).

The ATCA is vital to the success of the ASKAP surveys by enabling follow-up of selected ASKAP discoveries over a broad frequency range (1 - 50 GHz). At higher frequencies, ATCA has a science niche that should be fully exploited in the next few years. The commencement of ATCA Legacy Projects (from Oct 2016), conducted by expert science teams, will ensure ATCA remains a highly productive telescope.

Following community consultation, the main ATCA science drivers are:

1. **Galaxy Formation and Evolution** (1 – 50 GHz) * Partnership with ASKAP
    - high-resolution mapping of the gas and dark matter in galaxies,
    - characterising black holes, quasars and radio galaxies, and
    - low-surface brightness H I and CO mapping of nearby and distant galaxies, respectively.
2. **Galactic Star Formation** (20 – 25 GHz) * Pathway to ALMA
    - measuring the temperature, density structure and gas kinematics on sub-pc scales within dense star-forming clumps.
3. **Transients and the Unknown** (1 – 20 GHz) * Partnership with ASKAP & Parkes
    - fast multi-frequency follow-up of radio transients of both known and unknown origins, related to some of the most energetic events in the Universe.

Possible upgrades over this period of time include: (1) replacing the FPGA-based CABB correlator with a GPU-based software correlator (instantaneous bandwidth: 8 – 16 GHz); (2) construction of a focal plane array at 20 GHz to vastly improve survey speed and provide a development path to similar arrays at even higher frequencies on ALMA; (3) transition towards unattended and eventually fully automated observing with SMS alerts; and (4) provision of database tools and upgrades to the Australia Telescope On-line Archive (ATOA), necessary to support Large and Legacy Projects.

The unique capabilities of the ATCA, its southern hemisphere location and its importance to the success of the ASKAP surveys herald a rich scientific output from the telescope over the next 5 years and beyond, allowing it to retain its ranking as one of the world's most productive radio instruments.

Preface

The ATCA Future Science Plan will keep evolving over time, taking into account user feedback and budget constraints. The first version of this document was presented to the Australia Telescope Steering Committee (ATSC) and the Australia Telescope User Committee (ATUC) in mid 2015. Here we present an updated plan, report on the expressions of interest received for ATCA Legacy Projects[1], in Mar 2016, and adjust for ASKAP progress towards Early Science.

In Section 1 we highlight ATCA's existing capabilities, in particular the 1 – 105 GHz frequency coverage and broad observing bandwidth (2×2 GHz) in comparison to other current and future telescopes (see Table 1 and Fig. 2). This is followed by an outline of ATCA key science areas for the next 5 to 10 years. In particular, we consider ATCA's role prior to full ASKAP operations (Section 2), during full ASKAP operations, ie. when the top-ranked Survey Science Projects (SSPs) are under way (Section 3) and in the lead up to full SKA Phase 1 operations (Section 4). Future developments and ATCA Operations are discussed in Sections 5 & 6, respectively.

This document builds on the "ATNF Science Priorities: Science in 2010 – 2015" paper (dated 25 Nov 2008), but significantly extends the science case to enhance and complement the top-ranked ASKAP 21-cm surveys. User input shows high demand for the very compact ATCA hybrid arrays to carry out low surface brightness H I and CO mapping of galaxies in the Local Universe and at high redshift, respectively, as well as a detailed studies of star formation in dense molecular clouds within our Galaxy. Furthermore, high-resolution H I spectral line and wide-band, multi-frequency continuum/polarisation surveys (1 – 10 GHz) are required, mostly in partnership with ASKAP, and rapid follow-up of transient sources such as Fast Radio Bursts (FRBs).

Update on ATCA Legacy Projects

Beginning in the Oct 2016 semester, up to a quarter of the observing time will be allocated to ATCA Legacy Projects. This move towards larger science projects, conducted by expert science teams in close collaboration with CASS staff, has been discussed with the ATCA user community and is supported by both ATSC and ATUC. By the Mar 2016 deadline, 15 Expressions of Interest (EoIs) for ATCA Legacy Projects were received, covering the 1 - 50 GHz frequency range. In summary, these are:

- a large-scale Galactic Plane survey coupled with studies of individual clouds in continuum and line transitions (20 – 50 GHz),
- low-surface brightness CO mapping of the cold molecular gas in and around distant starburst galaxies (30 – 50 GHz),
- wide-band continuum/polarisation imaging (1 – 10 GHz) to obtain the spectral energy distributions of large samples of radio sources,
- low-surface brightness H I mapping of the diffuse circumgalactic medium in nearby galaxies and galaxy groups (1 – 3 GHz).

The over-subscription rate of the Legacy proposals testifies to the scientific health of ATCA.

[1] ATCA Legacy Projects: *www.atnf.csiro.au/observers/apply/ATCA-Legacy-Projects.html*

Figure 1: Five dishes of the ATCA (Photo credit: CSIRO)

1 The ATCA — a brand-new telescope

CSIRO's Australia Telescope Compact Array (ATCA) is a mature and highly versatile radio interferometer, currently operating in five broad frequency bands between 1 and 105 GHz. It is a world-class telescope, in high demand by a large international user base, with a demonstrated record of outstanding science (e.g., Trimble & Ceja 2007, 2008, 2010). It is vital to the success of the ASKAP surveys and complements research projects with the Atacama Large Millimeter/submillimeter Array (ALMA). — The ATCA is part of the Australia Telescope National Facility which maintains an open sky policy and a scientific merit time allocation process. Following the Compact Array Broadband Backend (CABB; Wilson et al. 2011) upgrade as well as major improvements in both system temperature and receiver bandwidth, ATCA is effectively a brand-new telescope, faster and more sensitive than ever before.

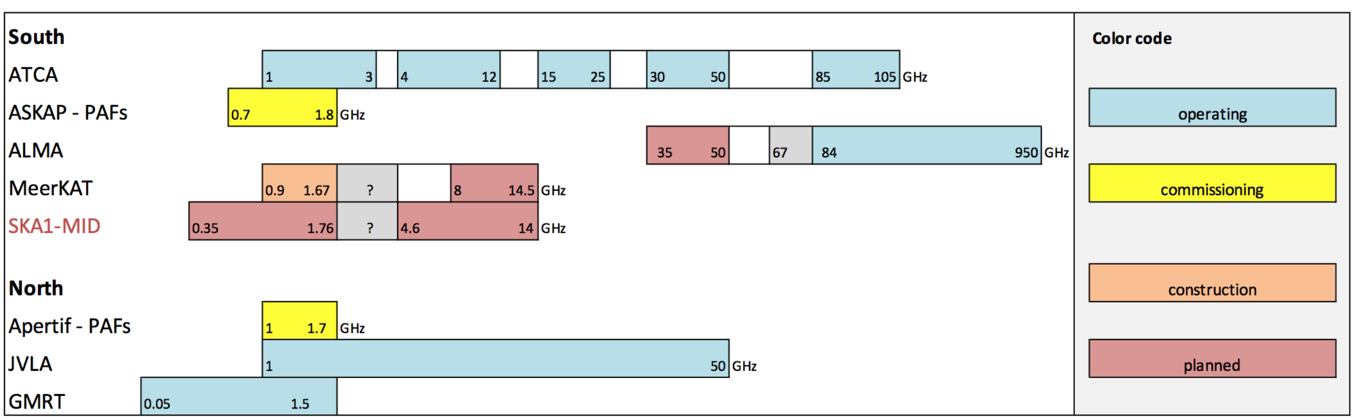

Figure 2: ATCA frequency coverage compared to other radio synthesis arrays (details in Table 1).

For the first decade ATCA operated in four narrow bands within the 1 – 9 GHz frequency range. Major upgrades have not only seen the addition of three wide bands in the 16 – 105 GHz range (known as the 15-, 7- and 3-mm bands; see Fig. 2), upgrades of the antenna surfaces, and construction of a short North-South spur, but also the broadening/combining of existing receiver bands, a factor two better system temperature and a 16-fold increase in correlator bandwidth. The brand-new ATCA is much faster than the original array, with greater frequency agility and previously unfeasible polarisation and spectral line capabilities. The new 9-level CABB correlator means ATCA observing is robust against narrow-band radio frequency interference. The ATCA is currently operated by trained users from around the world, supported by ATNF expert Astrophysics and Operations staff.

Table 1: The ATCA in comparison with other radio interferometers that overlap in frequency coverage

	array	frequency range [GHz]	beams	B_{max} [km]	BW [GHz]	operation	hemisphere
ATCA	6 × 22-m	**1.1 – 105**	1	6	2 – 4	current	**south**
JVLA	27 × 25-m	1 – 50	1	36	1 – 8	current	north
GMRT	30 × 45-m	0.05 – 1.5	1	25	0.032	current	north
APERTIF-6	6 × 25-m	1 – 1.7	37	1	0.3	2016/7	north
APERTIF	12 × 25-m	1 – 1.7	37	2.7	0.3	2018?	”
ASKAP-12	12 × 12-m	0.7 – 1.8	36	6	0.3	2016/7	**south**
ASKAP-30	30 × 12-m	0.7 – 1.8	36	6	0.3	2018?	”
ASKAP-36	36 × 12-m	0.7 – 1.8	36	6	0.3	goal	”
MeerKAT-16	16 × 13.5-m	0.9 – 1.67	1	8	0.75	2016/7	**south**
MeerKAT-32	32 × 13.5-m	0.9 – 1.67	1	8	0.75	2017?	”
MeerKAT	64 × 13.5-m	0.9 – 1.67 + 8 – 14.5	1	20	0.9	2018?	”
SKA1-MID	130 × 15-m + MeerKAT	0.35 – 1.76 + 4.6 – 14	1	150	?	2023*	**south**
SKA1-MID	”	0.35 – 14	1	150	?	?	”
ALMA	54 × 12-m & 12 × 7-m	84 – 950	1	16	8	current	**south**
ALMA	”	+ 35 – 50	1	16	8	2020	”

Notes. ATCA = Australia Telescope Compact Array (5 frequency bands as shown in Fig. 2); JVLA = Jansky Very Large Array; GMRT = Giant Metrewave Radio Telescope; WSRT = Westerbork Synthesis Radio Telescope; APERTIF = Aperture Tiled Feeds on the WSRT (FOV = 8 sq deg); ASKAP = Australian SKA Pathfinder (FOV = 30 sq degr); MeerKAT = Karoo Array Telescope (FOV < 1 sq degr); SKA1-MID = Square Kilometer Array Phase 1 (FOV < 1 sq degr), complementing SKA1-LOW; * current forcast/estimate for full 130 antenna array deployment; ALMA = Atacama Large Millimeter/submillimeter Array.

Figure 3: Aerial view of five ATCA dishes (Photo credit: CSIRO)

2 ATCA Key Science prior to full ASKAP operations

In 2015/6 a relatively small amount of ATCA time was used to complement/enhance science projects carried out with the Boolardy Engineering Test Array (BETA; 6× Mk 1 PAFs; Hotan et al. 2014; McConnell et al. 2016). These include: measuring the radio spectral shapes of 50 bright continuum sources detected in the Tucana field (Heywood et al. 2016), a study of high-velocity OH megamasers in an IRAS galaxy indicative of a supermassive black hole (Harvey-Smith et al. 2016), and H I imaging of the debris detected in the IC 1459 group (Serra et al. 2015).

Several ATCA observing programs that complement ASKAP SSPs have already commenced, eg., the SPT and Scorpio field continuum surveys (O'Brien et al. 2016, Riggi et al. 2016), radio source monitoring for extreme scattering events (Bannister et al. 2016), broadband Faraday rotation and polarisation behaviour of 36 radio sources (Anderson et al. 2016), Galactic and LMC H I absorption surveys (McClure-Griffiths et al.), Fornax H I survey (Serra et al.), the H I dwarf galaxy survey (Johnson et al.). These will help in the target field selection, demonstrate feasibility of semi- or fully automated observing modes, smooth running of dedicated data reduction pipelines and source finding algorithms, database creation and maintainance, and evaluate the proposed residency program.

With the installation and testing of Mk 2 Phased-Array Feeds (PAFs; Chippendale et al. 2015) on 12 ASKAP antennas nearly complete, ASKAP Early Science should get under way soon (2016/7) and will result in an increase of requests for ATCA time (incl. Large and Legacy Projects) to complement and follow-up on discoveries.

2.1 Galaxy Formation and Evolution

Wide-band radio continuum surveys of large, statistically robust source samples over the 1 – 50 GHz range (e.g., Massardi et al. 2016) remain a strength of the ATCA, providing their Spectral Energy Distributions (SEDs) as a function of flux density, redshift, galaxy environment, and galaxy mass. Some ∼10% of these sources will show significant fractional polarization and measuring their SEDs will help in the quest to understand the origin and evolution of magnetic fields and disen-

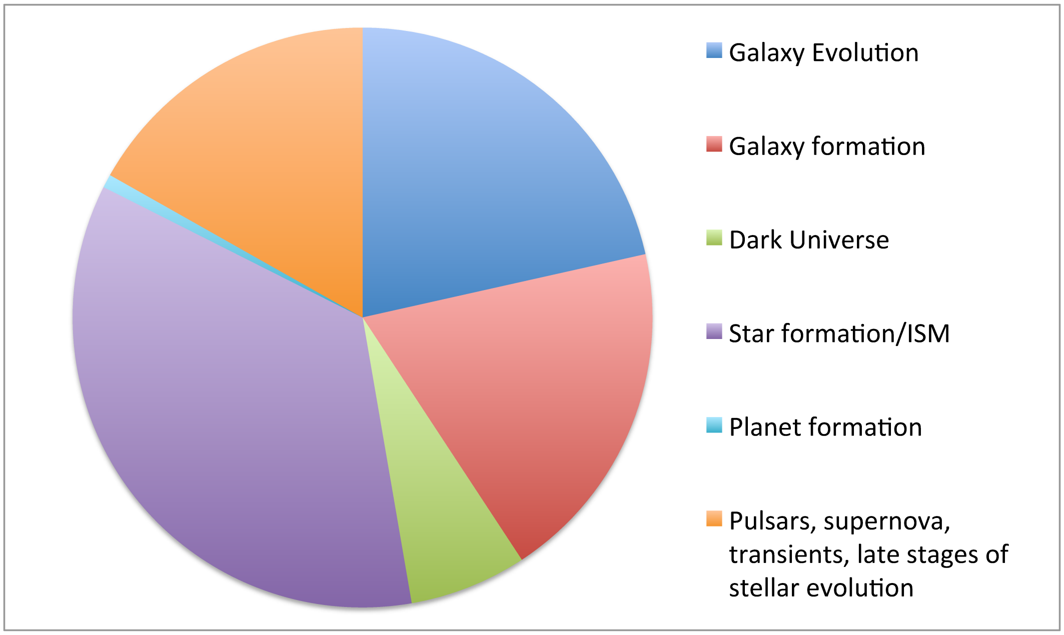

Figure 4: Summary of science areas of proposals that were scheduled time on the ATCA (based on six semesters from 12OCT to 15APR). — Data provided by Phil Edwards.

tangle models of the ISM incorporating depolarisation, synchrotron and layers of Faraday screens.

ATCA also remains excellent for mapping H I emission in low-redshift galaxies and their environments, delivering not only detailed maps of the gas distribution and kinematics in nearby galaxies, but also tracing their interaction history through hydrogen streams, bridges and debris between galaxies. Building on existing ATCA Legacy H I surveys, e.g., of the Magellanic System (Kim et al. 1998, Stanimirovic et al. 1999, For et al. 2014), and galaxies in the Local Volume (LVHIS; Koribalski & López-Sánchez 2009, Kamphuis et al. 2015, Wang et al. 2016) several large H I projects, e.g., surveys of (a) nearby dwarf galaxies to establish their evolutionary sequence, (b) galaxy groups to investigate galaxy properties as a function of environment, and (c) distant galaxies with large star-forming disks to investigate gas accretion in their large-scale environments as demonstrated by Wang et al. (2015) are considered. Until MeerKAT is accessible and faster than ATCA for this type of imaging (see also Section 4), ATCA remains indispensable in this field.

ATCA's hybrid arrays (H75, H168 and H214) are in very high demand to map the low surface brightness H I and CO emission in nearby and distant galaxies, respectively. Ultra-deep H I observations of nearby galaxies at low angular resolution allow us to detect gas accretion and outflows in the far outer disks, search for faint companion galaxies to better understand the missing satellite problem, and trace the densest peaks of the underlying Cosmic Web (e.g., Popping et al. 2015). This provides a unique probe of all environmental processes that matter for the morphological transformation of galaxies. In addition, the low-surface brightness sensitivity of the ATCA can be used to survey star formation and H I in the Magellanic Stream, a still poorly understood reservoir of gas connecting the Large and Small Magellanic Clouds with our Galaxy.

Furthermore, Emonts et al. (2011) have shown that the compact ATCA hybrid arrays together with the capabilities of the new CABB correlator (Wilson et al. 2011) are uniquely suited to detect cold molecular gas in dusty, high redshift galaxies. The hybrid arrays ability to detect low surface brightness emission allows searches for low-J CO transitions in high-redshift galaxies (e.g., Spilker et 2015, Aravena et al. 2016) to accurately measure their overall molecular mass, complementing ALMA high-J CO transitions to determine gas pressure/temperature (eg., Huynh et al. 2014). Three EoIs for high-redshift CO(1–0) surveys in the 30 – 50 GHz range were submitted. Even higher redshift CO studies ($z > 7$) have been proposed for MeerKAT (MESMER project: PI Ian Heywood).

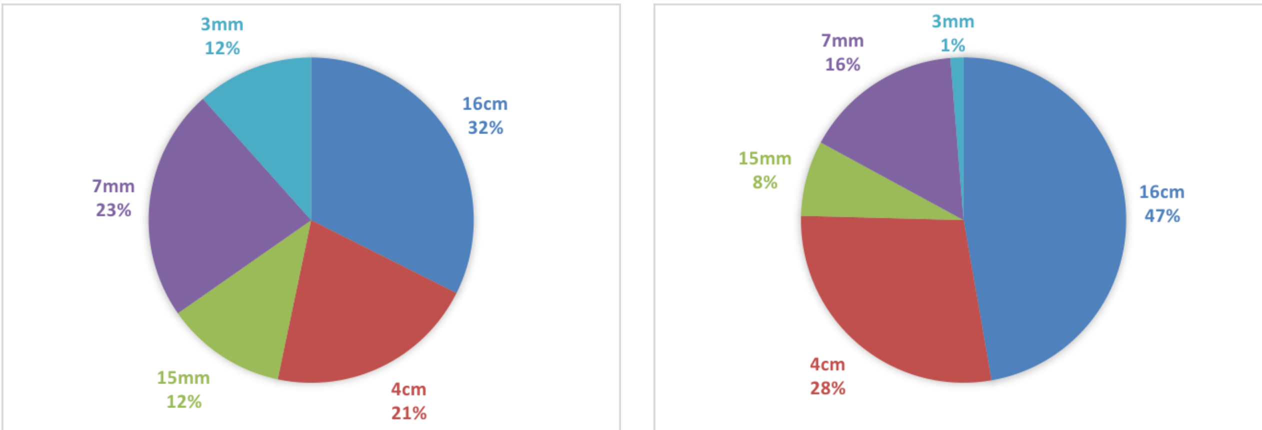

Figure 5: Distribution of ATCA observing time by frequency band for several Apr – Sep semesters (left) and Oct – Mar semesters (right). The Australian summer months are typically much less suitable for 3mm observing than the winter months. — Data provided by Phil Edwards.

2.2 Galactic Star Formation

The ATCA is the only southern hemisphere facility able to provide the wide frequency coverage needed to complement ALMA star formation studies. With CABB, the 4 GHz broadband coverage has transformed the ATCA into a powerful spectral-line instrument. The ATCA will continue to study the spectral energy distributions of star-forming regions at frequencies from 1 to 105 GHz. Such observations are particularly important for studies of dust grains around low-mass stars and understanding the mechanisms producing the ionized gas associated with the earliest stages of high-mass star formation. The 7-mm and 15-mm bands provide very important wavelengths for studying the extreme phenomena associated with the formation of high-mass stars, such as optically thick circumstellar disks, hyper compact H II regions and jets.

The legacy surveys of HOPS and MALT90 undertaken with Mopra have identified and characterised the global properties of the dense gas throughout the Galactic Plane. ALMA will be revolutionary in determining the location, sizes, kinematics and column densities of their embedded pre-stellar cores via sensitive observations of the dust continuum and molecular line emission. However, alone, the ALMA data are insufficient to reliably convert the measured column densities of the individual cores to mass. To do this requires a robust measurement of the gas temperature on small scales. This can only be achieved by the observations of molecular "thermometers": the best "thermometer" is ammonia (NH_3). These observations can be easily undertaken with the ATCA.

Much of the ATCA maser science over the last decade has come from large-scale surveys (e.g., the MMB survey; Breen et al. 2010) which have provided complete samples of maser sources at high resolution and sensitivity, enabling statistical studies of their associations and properties. This will continue to some degree with the completion of the MAGMO and SPLASH OH maser surveys (Green et al. 2012; Dawson et al. 2014). However, much of the new science is likely to come from high resolution observations of individual objects in a suite of maser transitions and utilising their properties to infer the kinematics and physical properties such as magnetic fields and densities. The recent CABB and C/X receiver upgrades have significantly improved the efficiency of the ATCA for maser work, as it is now possible to observe multiple transitions simultaneously with high spectral resolution. The ATCA covers all of the major maser transitions at frequencies <100 GHz.

ATCA also provides a crucial role, particularly in concert with ALMA, in understanding the distribution of dust grains of different sizes in both protoplanetary and debris disks, leading to a better understanding of planet formation. The ATCA 7-mm band plays a fundamentally complementary role to ALMA observations (Wright et al. 2015).

In summary, ATCA key science projects include:

- An NH_3 survey to measure the small scale gas temperature distribution within selected cluster-forming clumps observed as part of MALT90 (~3000h). ATCA is the only interferometer that can provide high-angular resolution observation of NH_3 at 23 GHz in the southern hemisphere and provides a unique complement to ALMA.
- Multi-transition Galactic Plane/Bulge surveys of thermal and maser transitions in the 15- and 7-mm bands, which include the water, ammonia, SiO, CS and class I methanol transitions, at high spectral resolution and with full polarisation information.
- Millimeter observations of protoplanetary and debris disks to study the formation of planets from dust grains of various sizes (requires the ATCA 7-mm, 15-mm and 4-cm bands).

The Milky Way and Magellanic Clouds provide the only opportunity for us to study the role of the interstellar gas at the parsec and sub-parsec scale as it is caught up in their dramatic tidal interaction. In addition, observations of most of the fourth Galactic quadrant are not possible from the northern hemisphere since Galactic longitudes from about 260 to 346 degrees lie below −40 degrees declination. In the 21-cm and 18-cm spectral lines, the ATCA allows much more sensitive spectroscopy of small regions both for emission mapping and for measurement of absorption toward compact continuum sources. The 21-cm line traces the structure and dynamics of the atomic hydrogen, which always surrounds and to some extent penetrates the star formation regions. Thus 21-cm mapping provides the context for the more compact, dense clouds that become gravitationally unstable. The recent discovery of "Dark Molecular Gas" shows that tracers revealing the density and velocity field in diffuse regions are indispensible to understand the structure of the interstellar medium. To fully understand the complex processes that determine galaxy formation and evolution, the Compact Array is the only telescope that can provide this vital information.

2.3 Transients and the Unknown

Transient astrophysical phenomena mark the sites of most extreme physics in the Universe. The high sensitivity, frequency flexibility and wide bandwidth provided by CABB make the ATCA ideal for radio follow-up in the cm and mm bands. Follow-up targets include the traditional optical transients such as Novae and Supernovae; high energy transients such as gamma-ray bursts, and X-ray binaries; radio transients including Fast Radio Bursts (FRBs; e.g., Keane et al. 2016);

and gravitational wave transients from the LIGO detectors (Abbott et al. 2016a,b). FRBs and gravitational wave transients deserve particular mention. The origin of FRBs remains a mystery, and to date, FRBs have only been detected in appreciable numbers by the Parkes 64-m telescope. The ATCA is ideally suited to following-up Parkes detections, as it can observe the same areas of sky as Parkes simultaneously. Gravitational wave transients are also a hot topic, with LIGO having detected their first event in 2015 (Abbott et al. 2016a). LIGO detections have large error boxes on the sky and so a search for the electromagnetic counterpart requires a large field of view such as available with ASKAP (Abbott et al. 2016b). Should an electromagnetic counterpart be found, the ATCA is ideally suited for targetted radio follow-up over a large frequency range.

The wide instantaneous bandwidth of the upgraded ATCA also makes it ideally suited to study radio propagation in the interstellar medium, which is strongly frequency dependent. Searches and studies of interstellar scintillation have yielded important constraints on the nature of nearby scattering screens (e.g., Bignall et al. 2003), as well detailed probes of the microarcsecond structure of quasar jets (e.g., Macquart et al. 2013). The recent ATCA discovery and follow-up of a rare Extreme Scattering Event (ESE; Bannister et al. 2015), an unsolved mystery since their discovery in 1987, has provided the first wide-band radio data of an ESE in progress, enabled real-time multi-wavelength follow-up observations, and provided new constraints on the nature of the plasma lenses that create these events. An ATCA survey of 2400 AGN monthly over 5 years could detect ∼20 ESEs and measure the sky distribution, covering fraction and optical depth of ESE lenses. Such measurements will place constraints on their contribution to baryonic dark matter in the Milky Way.

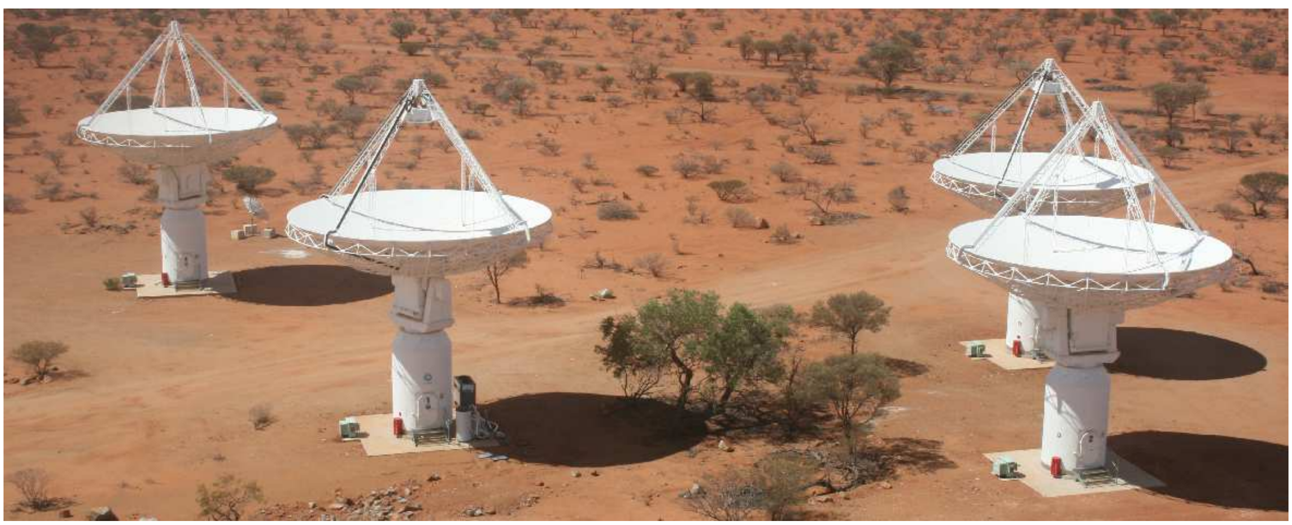

Figure 6: Four dishes of ASKAP (Photo credit: Simon Johnston)

3 ATCA Key Science during full ASKAP operations

This section outlines the role ATCA will play in the era when ASKAP is fully operational (SSPs are producing excellent results ...), ALMA is seven years old and upgraded to cover 31 – 84 GHz, and MeerKAT is close to science-ready.

3.1 Targeted ASKAP follow-ups

EMU (Norris et al. 2011) will detect ∼70 million radio sources (mainly AGN and star-forming galaxies). ATCA can provide the SEDs from 1 – 50 GHz and imaging of a fraction of the sources which are rare/interesting. The EMU team is planning targeted follow-up at all frequencies of a well-defined sample of (a) ∼100 extreme, unusual or otherwise interesting objects (eg., gravitationally lensed starburst galaxies, high redshift ($z > 6$) radio galaxies, merging clusters, SZ clusters or candidates, and other parameter outlier); 12h synthesis at each band; and (b) interesting Galactic sources, supplemented by ALMA observations, to allow comprehemsive analysis of the complete chemistry available, supplemented by broadband luminosities for star forming regions, dark clouds, and related targets.

WALLABY (Koribalski 2012) aims to discover and examine the distribution and H I properties of up to 500 000 galaxies out to a redshift of 0.26 (equivalent to a look-back time of ∼3 Gyr). The WALLABY team plans to carry out ATCA H I follow-up observations at higher angular resolution and sensitivity than possible with ASKAP, targeting new, extreme, unusual or otherwise interesting objects: (1) the extrema of the galaxy population such as *dark* galaxies and H I-massive galaxies, which guide our understanding of galaxy formation and evolution, (2) new gas-rich Local Group galaxies whose dynamical characteristics will allow us to better define the sphere of influence of the early ionizing cocoon and hot halo of the Milky Way, (3) new Local Volume galaxies to measure the faintest end of the H I mass function, and (4) new interacting systems including H I clouds/debris in a variety of environments (field, group, cluster), to quantify the relative influence of tidal and ram-pressure forces. Parkes multibeam or Phased-Array Feed H I observations will also be needed to map the low surface brightness H I gas in the outskirts and between galaxies.

- **POSSUM:** Targeted follow-up of the brightest 10 000 polarised sources at 1 – 3 GHz and 4 – 8 GHz (30m per source; ∼7 months total). The extended frequency coverage will result in a very large improvement in the quality of the resulting Faraday depth spectra, helping in the understanding of magnetism and radio polarisation (some overlap with EMU program).
- **FLASH:** (a) Targeted follow-up of ∼1000 radio sources, where intervening H I absorption lines are detected, with the ATCA at 3 – 25 GHz (5m each; total ∼200h) to characterise their radio spectrum (some overlap with EMU & POSSUM) and the LBA (∼25 days) to determine their small-scale structure. (b) Search for H_2O megamasers in a sample of 25 galaxies ($0.4 < z < 1.0$) where associated H I absorption is detected (∼12h each; total of ∼300h). See Allison et al. (2014, 2015) for an outline of the science motivation.
- **GASKAP:** Targeted follow-up of Galactic OH masers and H I absorption lines at high angular resolution with full Stokes parameters to study the local and large-scale Galactic magnetic field; also H I Zeeman measurements.
- **VAST/CRAFT:** Rapid ATCA and VLBI/LBA follow-up of ASKAP-detected transient sources.

3.2 Enhancing ALMA Science

The production phase for Band 1 (35 – 50 GHz) was just approved by the ALMA Board of Directors, with receiver delivery scheduled for Dec 2019, while Band 2 (67 – 116 GHz) is still being explored. The science that these frequency windows allow includes the study of the deuterated molecules in cold, dense, quiescent gas, redshifted emission from galaxies in CO and other species, very small dust grains in the ISM, ionized gas (e.g., in H II regions), masers, magnetic fields in the dense ISM, jets and outflows from young stars. For details see Di Francesco et al. (2013) and Fuller et al. (2016).

The niche for ATCA will remain in the 16 – 25 GHz (15-mm) window, where key diagnostic tracers of dense gas and star formation arise (NH_3 and masers). Having identified and characterised the global properties of sites of current and future high-mass star formation in the Galaxy in the previous decade, progress will be achieved by focusing on the smaller 0.05 pc scales where individual stars form. Observations at 16 – 24 GHz with the ATCA can provide robust estimates of the gas structure, temperature, and kinematics on these important spatial scales. The observations will characterise the turbulent structure within the clumps and to directly measure the locations, temperatures, masses, temporal sequence, and kinematics of their individual ∼0.05 pc size star-forming cores. Not only will these observations identify the key targets for in-depth studies of individual objects with ALMA and SKA, they provide, robust measurements of gas temperatures, which are critical for reliably interpreting any future ALMA data (e.g., Jeans masses, internal and external heating, temperature gradients, etc.). These datasets are the only means to provide the key spatial information on smaller scales to guide our understanding of extragalactic star-formation.

3.3 Long Baseline Array (LBA)

The ATCA forms a vital element in the LBA, the only array capable of observing at milli-arcsecond resolution in the southern hemisphere. The LBA presently has ongoing large projects monitoring the parsec-scale evolution of AGN (Müller et al. 2014, Kadler et al. 2016) and measuring the parallax and proper motion of 6.7 GHz methanol masers to study the structure of the Galaxy (Krishnan et al. 2015).

With the commencement of the ASKAP SSPs, LBA follow-up will be important for a number of teams. LBA observations are a critical tool in differentiating AGN from starburst galaxies for EMU; conducting high-angular resolution dissection of the (lower redshift) absorption lines detected by FLASH; probing 21-cm H I absorption towards bright continuum sources for GASKAP; and enabling follow-up of transient sources detected by VAST to search for events of jets, expansion, or proper motion.

4 ATCA Science during MeerKAT and SKA Phase 1 operations

Once MeerKAT (64 × 13.5-m dishes; single-beam receivers) becomes fully operational in the planned 0.6 - 14.5 GHz range (see Table 1), the large science survey projects, which have already been allocated time, are likely to occupy all of the available observing time for several years. The science and survey strategy will be discussed at an international MeerKAT meeting on May 25–27, 2016. As the timeline for full MeerKAT, including receiver roll-out and availability of observing time to the international astronomy community becomes clearer, we will re-evaluate the ATCA key science areas within the overlapping frequency range. Several factors will be important to consider: MeerKAT performance as a function of frequency, RFI occupancy, open sky and merit allocation processes, time availability and oversubscription rates. The transition of MeerKAT into SKA1-MID (ie., adding around 130 × 15-m antennas with baselines up to 150 km; see Table 1) needs to be taken into account. The funded frequency bands for SKA1-MID are 0.35 – 1.76 GHz and 4.6 – 14 GHz, with early science estimated to start around 2023. This would allow only the allocated surveys to be conducted on MeerKAT itself before it is incorporated into SKA1-MID, open primarily to SKA members (under the current policy only 5–10% of the observing time will be traditional ‘open skies’.).

The Murchison Widefield Array (MWA) is a low-frequency radio telescope (80 – 300 MHz) and precursor for SKA1-LOW, co-located with ASKAP at the Murchison Radioastronomy Observatory (MRO) in Western Australia. The GLEAM survey (Wayth et al. 2015) covers the entire radio sky south of declination +25 degrees at frequencies betwenn 72 and 231 MHz. This will complement all-sky surveys with ASKAP, and the two will identify unusual sources to be followed up with the ATCA. The power of this approach is illustrated by Callingham et al. (2015), who combined broadband spectral data from an extreme Giga-hertz Peaked Spectrum source in order to study the physical processes at work in this object. Unique scientific capabilities that are enabled or strengthened by the combined use of ATCA and MWA datasets include detailed analysis of broadband radio galaxy SEDs, mapping the magnetised ISM of the Milky Way, and wide-area searches for transients.

5 Requirements and future upgrades

In the short term, the following developments are needed/desirable:

- transition to unattended and eventually fully automated observing modes (with SMS alerts for observer input), where suitable;
- support for ATCA Large and Legacy Projects (e.g., pipeline development, project webpages, provision of database tools and upgrades to ATOA);
- continued effort in RFI mitigation;
- fast response system for transient follow-up; and
- create 16 MHz CABB zoom mode(s) for efficient and reliable H I observing (desirable) at high velocity resolution.

Future upgrades, enhancing the ATCA science output:

- replace the FPGA-based CABB correlator with a wide-band GPU software correlator, enabling 8 GHz (possibly 16 GHz) of instantaneous bandwidth, flexible zoom modes, RFI mitigation and high reliability;
- construction of a focal plane array at 20 GHz would vastly improve the survey speed at this frequency and provide a potential development path to similar arrays at even higher frequencies on ALMA.
- fill gaps in the frequency coverage;
- upgrade ATOA with standard data reduction pipelines (desirable); and
- improved RFI mitigation, both to existing systems and in the design of any new correlator or digital systems. An example is the capability of removing periodic radar signals in the time domain before the data are correlated.

The advantages of a versatile and robust GPU software correlator include a factor 2–4 increase in the observing bandwidth, more flexibility, better/easier maintainance, and higher reliability.

6 ATCA Operations

6.1 Large Projects & Legacy Projects

From the Oct 2016 semesters onwards ATCA Legacy Projects will be allocated up to a quarter of the available time. Legacy Projects will be 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. They will typically require more than 2000 hours over the lifetime of the project, with the expectation of over 300 hours to be allocated per semester. The previous categories of standard and ATCA Large Projects remain, with the latter requiring 400+ hours, which can be distributed over many array configurations throughout one or more semesters.

A few outstanding ATCA Legacy Projects, which have to be of high value to a broad community with the data made public immediately, will be allocated blocks of time each semester. ATCA Legacy Projects need to be compelling in many ways: outstanding science goals and a well-defined method to get the desired outcomes, legacy value and delivery through a public archive / VO service, outreach and education components, all delivered by an excellent & diverse team. Such a program would require substantial involvement and/or leadership of the local ATNF Astrophysics and Operations groups. For very large observing programs, we propose that a member of the project team is present at the ATNF to work with the Operations and Astrophysics Groups on the successful observing, data reduction, cataloguing, and database creation of the project.

6.2 RFI concerns

The broad-banding of ATCA receivers, particularly at lower frequencies, results in a greater susceptibility to Radio Frequency Interference (RFI) from other (licensed) users of the spectrum. Most RFI at the ATCA is detected in the 16-cm band, particularly in the 1.1 - 2.2 GHz range, with sources including local point-to-point communications, mobile phone bands, and satellite transmissions (see, e.g., https://www.narrabri.atnf.csiro.au/observing/rfi/rfisurvey_viewer.html). Typically ∼30% of the 16-cm band is contaminated by RFI, with the actual amount depending on the chosen array, as it is the shortest baselines that are the most affected. Short baselines in the 16-cm band can also be strongly affected by solar interference unless care is taken to observe sources at least 40 degrees away from the Sun (or at night). Narrow-band RFI is also present in the 4-cm band, e.g., at 5.6 GHz (Moree weather radar) and at 9.3 & 9.5 GHz (aircraft radar), but affecting a much smaller fraction of the spectrum.

The MIRIAD task *atlod* (options=birdie,rfiflag) removes CABB self-interference channels and known RFI as specified in the rfiflag.txt file provided by the observatory. Observers are recommended to use the task *pgflag* to flag any intermittent RFI in their data. It remains important for all users to report RFI seen during the observing run and/or data reduction so that RFI generated internally can be shielded and external RFI investigated.

Contributors

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Publications from ATCA projects

Extensive publication statistics exist for all ATNF facilities; some of these are presented in Table 2 and Figure 7. The ATNF publication statistics are also available in the ATNF Annual Reports.

	ATCA	Parkes	Mopra	LBA	ASKAP
2006	55	57	10	5	—
2007	63	39	6	1	—
2008	59	33	8	4	3
2009	51	43	12	10	2
2010	54	39	15	3	4
2011	62	51	15	8	5
2012	76	44	15	7	18
2013	77	48	23	1	4
2014	71	49	16	6	4
2015	72	48	22	5	3

Table 2: Publication numbers for CSIRO telescopes. – Note: the CABB upgrade required a long shut-down and progressive installation period (from Mar 2009 to end of 2010); for ∼1.5 year no H I spectral line observations were feasible. — Data provided by Jessica Chapman and Phil Edwards.

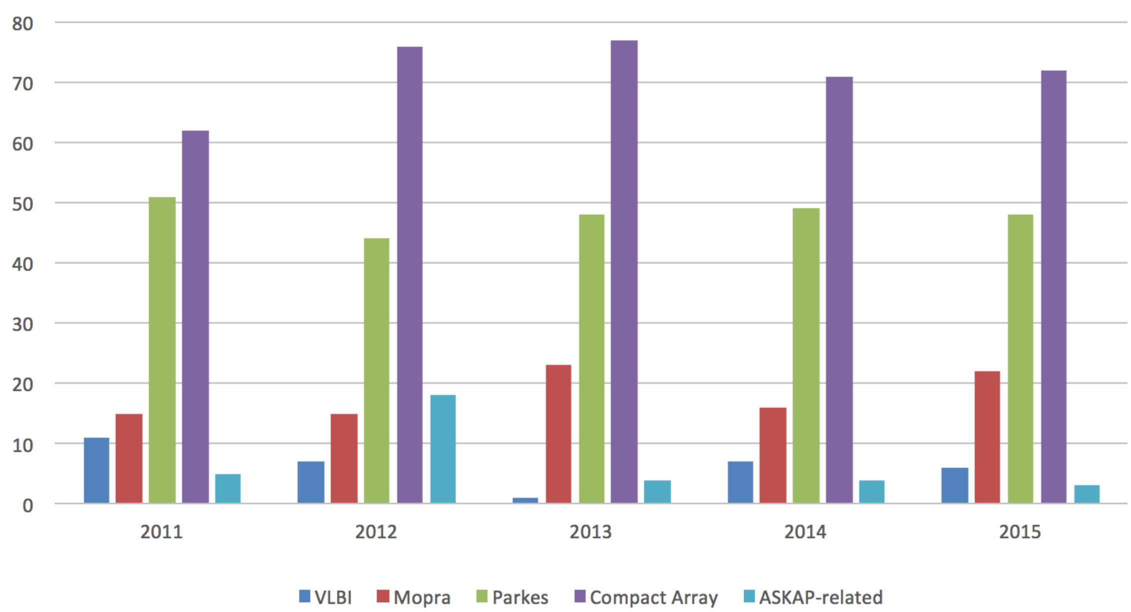

Figure 7: Publication numbers for CSIRO telescopes (see Table 5) over the last five years.

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