Australia Telescope National Facility

ATNF Science in 2010-2015:
Part 1 – Overview

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Context and purpose of this document

Over the period 2010-2015 the ATNF needs to deliver ASKAP, a $100M new facility, restructure its operation to accommodate the new facility, maintain the world-class scientific productivity of its telescopes that are used by astronomers from around the world, and continue to implement Australia's strategy of maximising Australian involvement in the SKA.

This document comprises five parts, an overview of the expected scientific priorities that will be addressed by the full complement of ATNF telescopes and instrumentation, and four attempts to detail the science expected to be the priority for users of specific telescopes. It is important that the documents are treated as a set as they have been prepared as such and no one part is expected to stand alone.

The priorities outlined in this document have been identified through a process of extensive user consultation. They draw on, for example, the millimetre white paper, the Science with Parkes forum on 5 November 2007, the Compact Array Science day in June 2008, and the extensive ASKAP science case. Ongoing feedback on the document and the priorities identified here are welcomed.

This document is intended to be a part of the Future ATNF Operations plan. A preliminary version of that plan was written for the Australia Telescope Steering Committee in December 2007 and provided publicly soon after. Version 2 of the Future ATNF Operations plan, including this document on the science priorities, is due for completion by the end of August 2008. A more complete version (number 3), including considerably more detail of implementation plans and an updated version of this document incorporating user feedback, is due in December 2008.

The science priorities identified here are intended to inform decisions and choices by the ATNF over the coming years. They will provide a framework within which those decisions and choices will be made. They are not intended to determine the usage of the ATNF telescopes in detail, as that is the role of the Time Assignment Committee and the international astronomy community, but they will of course do so in a very broad sense.

This document only attempts to identify the likely science priorities over the period 2010-2015. The end of this period marks the start of the next Decadal Plan for Australian astronomy, and it is likely that by then the picture will have evolved significantly, particularly with likely progress towards the SKA and giant optical telescopes.

Executive summary

The ATNF needs to change in order to operate its current and future radio astronomy facilities efficiently as a single entity. These changes must be consistent with the science that these telescopes do best. In this set of documents we identify the most likely scientific priorities for the ATNF facilities: ATCA, Mopra, Parkes, ASKAP, and the LBA for the period 2010–2015. In ordering these priorities, consideration has been given to the international radio astronomy context. The intention is that the highest priorities identified for each facility represent the highest impact science to which the facility can contribute uniquely well.

The picture that emerges is of a set of world-class facilities sited in Australia, with a high degree of complementarity both within the set and more broadly as part of the international suite of radio astronomy instruments. The dominant science from Parkes will be pulsar searching and timing. The Compact Array and ASKAP will be directly complementary, with the ATCA concentrating on low-surface-brightness science at high frequencies whereas ASKAP will concentrate on large area surveys at frequencies around 1 GHz. Mopra will continue to provide a unique capability for wide-field mapping at wavelengths from 3-12mm and high spatial resolution observations with the LBA will be more sensitive and straightforward than ever.

The highest scientific priority for Parkes follows directly from the expectation that the Parkes Telescope will remain the foremost facility in the world for pulsar searching and timing throughout the period 2010-2015. It is therefore expected that 60-70% of telescope time will continue to be used for pulsar searching and timing. The next-highest scientific priorities lie in diffuse mapping of interstellar and intergalactic gas and finally star formation. These priorities require continued frequency agility and frequent, regular blocks of pulsar timing.

For Mopra, the main science priority will remain star formation and the dense interstellar medium, achievable through large surveys. This priority requires large continuous blocks of scheduled time, efficient survey software and other measures that maximise survey speed.

For the ATCA, the science priorities in order are: star formation, understanding the magnetic universe, understanding the variable sky, gas in and around the Milky Way and nearby galaxies and finally, evolution of galaxies at high red-shift. These priorities, in the context of the international radio astronomy scene, will push toward sensitive compact configurations and high frequency observations scheduled for good weather conditions. Once ALMA becomes operational the ATCA may no longer be competitive in the 3mm band, in which case the compact array 3mm systems could be decommissioned.

For the LBA, the science priorities are Galactic structure, local group galaxy motions, understanding the variable sky, megamaser cosmology, jet motions and pulsar proper motions and parallaxes. These priorities can best be met through the inclusion of long E-W baselines provided by ASKAP in the 20cm band and an increased number of regularly spaced short VLBI observing blocks.

Finally, for ASKAP the priorities in order are: understanding galaxy formation and evolution through extragalactic HI surveys, characterisation of radio transients, determining evolution and population statistics of galaxies at high redshift, and exploring magnetic fields in the universe. The priorities will be best served by moderate (~2km) to extended (~6km) configurations.

1 Table of Contents

The holistic ATNF

As the world scene of radio astronomical facilities will change dramatically over the next five years it is useful to identify the strengths and synergies of the ATNF telescopes, and to identify those areas where the ATNF cannot be competitive. This process of identifying scientific priorities for the individual facilities naturally highlights their complementarity. In our priority setting we have attempted to minimise the scientific overlap and maximise the complementarities. Broadly speaking the facilities of the ATNF have different strengths that can be categorised in terms of surface brightness sensitivity and frequency coverage. The LBA has very high resolution at frequencies of 1 – 22 GHz and is particularly powerful for studies of motion, including maser and pulsar parallaxes, proper motions, and high-resolution jets, all limited by sensitivity. ASKAP will operate in the 1 GHz band with moderate to long baselines (2 – 6km), driven by a requirement for good imaging performance of HI galaxies and extragalactic continuum sources. The ATCA operates over a much wider range of frequencies and to minimise overlap with ASKAP it is expected to focus increasingly on higher frequencies (2 – 50 GHz) and the compact configurations where its surface brightness sensitivity exceeds most other interferometers. Mopra will work in conjunction with the ATCA and in the future ALMA to provide fast mapping of extended areas at frequencies greater than 20 GHz. Finally, Parkes will continue to excel in areas such as pulsar timing and searching where its close packed collecting area is vital and similarly large scale mapping studies that require the extreme surface brightness sensitivity of a single dish.

Across the science areas outlined in the later sections the degree of synergy between facilities varies. Here we outline the complementarities in six broad science areas:

1.1 Galaxy formation and gas evolution in the nearby universe

- ASKAP will survey large numbers of HI galaxies in the nearby universe to understand galaxy formation and evolution to z<1.
- Parkes will provide the extremely large-scale context of diffuse intergalactic material between galaxies, and crucial large-scale information for combination with ATCA interferometric data.
- ATCA will provide context of galaxy formation and gas evolution from diffuse interstellar mapping of the Milky Way and nearby galaxies, extended disks, intergalactic gas.

1.2 Pulsar science

- Parkes will conduct large area surveys and undertake regular high precision timing of millisecond pulsars and general timing on regular pulsars.
- LBA will provide information on proper motions and distances.
- ASKAP will ultimately provide precision timing and a wide-field survey capability once the technical and computing challenges are overcome.
- ATCA and Mopra are not expected to have major roles in pulsar science.

1.3 Star formation

- ATCA will provide detailed studies of star forming regions and the dense interstellar gas in the centimetre, 12-mm and 7-mm bands..
- Mopra will specialise in large surveys at 3, 7, & 12 mm to be used for defining ATCA and ALMA samples. Mopra will also provide the large-scale interstellar medium context through millimetre surveys that make use of its large bandwidth.
- Parkes will probe star formation processes through studies of masers.
- LBA studies of maser internal motions will probe the evolution of star formation.
- ASKAP is not expected to have a significant role in Galactic star formation studies.

1.4 Galaxy evolution and population studies across cosmic time

- ASKAP will measure population statistics of AGN and star-forming galaxies through deep, confusion limited all-sky surveys at 1.4 GHz.
- ATCA will be crucial in measuring the spectral energy distribution of AGN and star-forming galaxies between 1 and 50 GHz.
- Parkes and Mopra are not expected to have significant roles in this science area.

1.5 Magnetic fields through cosmic time

- ASKAP will create a grid of rotation measures across the sky to understand the origin cosmic magnetic fields.
- ATCA will study the diffuse, line-of-sight resolved magneto-ionic medium in the Milky Way and nearby galaxies through broadband spectro-polarimetric observations.
- Parkes will provide essential zero spacing diffuse polarization surveys in the 1-10 GHz range for combination with ATCA and ASKAP data.
- Mopra and the LBA are not expected to have a significant role in this science area.

1.6 Understanding the variable sky

- ASKAP will monitor the entire sky everyday – a unique capability for detecting transients and monitoring variable sources.
- ATCA will provide multi-frequency follow-up of ASKAP/MWA transients.
- LBA will provide high angular resolution follow-up to ASKAP/MWA transients.
- Parkes has the capability to find very fast transients as part of its major pulsar surveys.
- Mopra is not expected to have a significant role in this area.

	Gas Evolution in Nearby Universe	Pulsars	Star Formation	Galaxy Evolution at high z	Magnetic Fields	Understanding the Variable Sky
LBA		•	•			○
ASKAP	●	•		○	●	●
ATCA	○		●	•	○	•
Mopra			○			
Parkes	○	●	•		○	•

Table 1 Breakdown of facilities by science areas. This table shows both the impact of the individual facilities on the six major science areas (read by columns) and the relative priority of the science areas to each of the facilities (read by row). The circle size indicates the priority/impact of a given facility in an area, with the largest circles indicating the highest impact and priority areas.

2 A Year in the Life of the ATNF

To provide an integrated picture of the operation of ATNF's telescopes based on the science priorities identified here we offer the following scenario. We stress that this is an exercise in crystal ball gazing, albeit by a group of well-informed seers.

The year is 2013 and ASKAP has just come on-line. After 4 years of planning and community consultation, the 6 km ATCA antenna has been moved onto the main track and 6 km array configurations are no longer available. The final winter of 3mm ATCA observing occurred in 2011 having achieved its primary goals of paving the way for 100GHz science in the pre-ALMA era. The compact array 3mm systems have now been decommissioned with high-sensitivity ALMA observing in this band now well established. Mopra is preparing for a 3 mm multibeam system to be installed in 2015 and has seen significant upgrades to its observing software enabling near automated surveying – this software was developed as a test-bed for ASKAP. The Parkes back end systems can now be reconfigured via computer control for all common observing modes, and routine observations with the Parkes telescope can be conducted with full staff support from the ATNF's Science Operations Centre in Marsfield, or at other remote locations by sufficiently experienced users. A few non-standard observations are still being undertaken at the observatory by experienced users and staff members. The LBA is increasingly used in e-VLBI mode with data rates of 8Gb/s from all ATNF telescopes providing greater sensitivity than ever before. The real-time correlation of data, improved sensitivity, and availability of tools to streamline data reduction have led to a much larger community of VLBI users.

The principle activities of the ATNF telescopes during the year are as follows:

- ASKAP will spend 80% of its time conducting large surveys. At night, the HI survey will operate in point and stare mode, providing a 12-hr data cube over 30 square degrees of sky. During the day, the entire sky will be covered with snapshot observations, searching for transients and monitoring thousands of variable sources. Simultaneously, point source and polarization images of the sky are being made.
    - ASKAP will operate remotely, and pipeline data reduction means that high quality data will be available in the archive for public use on a short timescale.
- Mopra single-dish observing is restricted at 3mm to April–October, with large surveys being conducted in 2–3 weeks blocks with minimal support.
    - Software has been developed for Mopra to enable near-automated surveying, which improved its efficiency as a survey facility.
- Parkes is conducting a large pulsar survey, occupying observing blocks of 2 months at a time interrupted for timing sessions of 5 days every two weeks. Cadence of pulsar survey is 4 months to allow data processing time. During this time Parkes is conducting deep HI surveys for extended, extragalactic emission and an all-sky polarization survey at night. Day times are used for small projects and additional pulsar timing.
    - Parkes is able to rapidly switch between 'standard' observing modes in a near automatic fashion.
- ATCA is conducting a large polarization survey during the summer nights. The winter nights are devoted almost exclusively to 7 and 12 mm to maximise phase stability even on baselines up to 3 km. Daytimes are spent on smaller projects.
    - The ATCA has been modified to move the 6km antenna onto the track, markedly improving the surface brightness mapping speed and the 2-d snapshots with hybrid configurations.
- The LBA scheduled in six blocks of 3-4 days to allow good time baselines to the multiple parallax, proper motion and jet motions projects. The LBA has developed a

plan to respond rapidly to Targets of Opportunity from x-ray and gamma-ray triggers and for when ASKAP switches to a faster sky survey cadence.

- eVLBI observing has been bedded down so that switching into this LBA mode takes very little time and teams can have new epoch results within days of observation.

3 Timeline and next steps

This document draws together an ongoing process of establishing the scientific priorities for the astronomy community and the ATNF telescopes and instrumentation, and forms part of the process of determining the future operation of the ATNF. Key milestones include the following:

2006 *Millimetre Science* meeting at Chowder Bay,and mm white paper
23 Oct 2006 *VLBI science* workshop facilitated by ATUC
5 Nov 2007 *Science with Parkes* workshop, Marsfield
Dec 2007 *Future ATNF Operations v1* released
Dec 2007 *Science with ASKAP*, Johnston et al. published in PASA
Mar 2008 *Future ATNF Operations* roadshow meetings, U. Sydney, UNSW, Melbourne, Hobart, Canberra, Perth
Feb 2008 Web forum for feedback on *Future ATNF Operations v1* opened
19 March 2008 *Future ATNF Operations* open forum, Marsfield
11 Jun 2008 *Science with the ATCA of the Future* workshop, Marsfield
8 Jul 2008 *ATNF Science Priorities* discussion, ASA meeting, Perth
10 Jul 2008 *ATNF Science Priorities roadshow* meeting with UWA & Curtin, Perth
21-25 Jul 2008 *ATNF Science Priorities roadshow* meetings, Hobart, Melbourne, Canberra, Sydney
8 Aug 2008 *ATNF Science Priorities v1.0* (this document) released for feedback

end Aug 2008 Summary of feedback on *Future ATNF Operations v1* released
end Aug 2008 Response to feedback on *Future ATNF Operations v1* released
end Sep 2008 *Future ATNF Operations v2* released
end Oct 2008 *ATNF Science Priorities v3* released
Dec 2008 *Future ATNF Operations v3* released

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ATNF Science in 2010-2015: Part 2 – ASKAP

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Summary

We identify four main science areas where ASKAP will excel in the period 2010-2015. These are: understanding gas evolution in the nearby Universe through HI emission surveys, determining the evolution of galaxies at high red-shift through high resolution continuum surveys, characterising the transient and variable radio sky and uncovering the nature of the magnetic fields throughout the Universe. Setting the priority science for ASKAP also leads to a definition of the optimum configuration of the antennas and drives the development of the software instruments.

1 Context

In the Decadal Plan for Australian Astronomy, the Square Kilometre Array (SKA) was listed as the highest priority new program for Australian radio astronomy. Engagement in the SKA is being realised through the development of new radio astronomy infrastructure in Western Australia - the Australian SKA Pathfinder (ASKAP).

Over the period considered here (2010 - 2015), ASKAP will be in transition from a 6 dish test array (BETA) through commissioning of the 30+ antenna array to full scientific operation. Although the current target for ASKAP is to be operational by 2012, it is inevitable that routine operations of the fully commissioned telescope will not occur until towards the end of the period under consideration.

It should also be stressed that neither the final system parameters for ASKAP (number of antennas, system temperature and so on) nor the configuration are yet determined and will only be determined once the budget breakdown and technical hurdles are completely worked through. The difference between the `baseline' (30 antennas and Tsys of 50 K) and the `stretch' goals (45 antennas and Tsys of 35 K) is a factor 5 is survey speed (see the science case; Johnston et al. 2007). The eventual use of ASKAP therefore strongly depends on the final system specifications and this caveat should be kept in mind throughout this document.

The period 2010-2015 will see a number of SKA demonstrators come on-line, new instruments such as ALMA will be operational, and other telescopes such as the VLA and GMRT will be upgraded. In the science context therefore, ASKAP must carve out a slice of parameter space unique to its capabilities as a fast survey machine in the 20cm band.

The SKA is the goal of the international radio astronomy community (in the 0.1 - 20 GHz band) and it will provide orders of magnitude increases in sensitivity and survey speed over the current generation of instruments and telescopes. The current time line has the SKA operational in 2020. Neither the site nor the technologies have yet been chosen for the SKA. Apart from enabling great science, additional ASKAP drivers are to influence both the site and technology choices for the SKA and the achievement of these additional goals may not always coincide with the science expectations.

Here we briefly list the radio telescopes operational in the 2010-2015 time-frame which overlap in phase space with ASKAP. Note that we concentrate here on radio instruments. There will be significant synergy between ASKAP and optical and shorter wavelength telescopes but these are not in direct competition in phase space.

- MeerKAT is the South African SKA demonstrator. With the current proposed specifications it will have more instantaneous sensitivity than ASKAP but a factor 5 less survey speed. Meerkat will likely have greater frequency coverage. The proposed timescale for completion of Meerkat is 2012, although all funding beyond the KAT-7 demonstrator is apparently contingent on international matching. Meerkat and ASKAP can be seen as complementary in some ways and some collaboration to utilize that scientific complementarity may be valuable.
- The ATA is currently running a 42 antenna array operating at frequencies between 0.5 and 10 GHz. Funding is being sought for a 350 antenna system which would have a comparable survey speed to ASKAP at 1.4 GHz. If this expansion is funded and completed by 2011 as hoped, then there will be some overlap in survey capabilities. The ATA will also be complementary to ASKAP as there is an early emphasis on higher frequencies as well as its access to the northern sky.
- APERTIF is a focal plane array project planned for the WSRT in the Netherlands. It is potentially ahead of ASKAP in its time-line although funding has not yet been secured for a suitable back-end system. If completed it will have a similar survey speed to ASKAP but has severe RFI problems near 1 GHz. It can provide (as the ATA-350) northern hemisphere coverage complementary to ASKAP.
- EVLA is the upgraded VLA with final operations on a similar timescale to ASKAP. Although it will not compete on survey speed with ASKAP it has much greater

instantaneous sensitivity, bandwidth and frequency coverage (1 to 50 GHz). The eVLA is excellent for follow-up studies of ASKAP results.

- FAST is the Chinese very large (500m) single dish with very high instantaneous sensitivity. It is likely to only have a small multi-beam system initially and its survey speed will therefore be less than ASKAP. It will be a prime instrument for pulsar observations. Timescales for construction are unclear and it suffers for Galaxy science as it cannot see southwards from the Galactic Centre. VLBI between FAST and ASKAP is a possibility worth exploring.
- PARKES is the largest single dish in the southern hemisphere and will provide zero spacing information necessary for ASKAP in areas such as diffuse HI and polarization. Depending on exact ASKAP parameters, Parkes will likely be superior for pulsar timing and vastly superior for pulsar and fast transient surveys at least up to 2015.
- The COMPACT ARRAY is operational to 105 GHz with wide bandwidths once CABB comes on-line. Significant follow-up work from ASKAP can be done on the ATCA, especially at high frequencies (e.g. for transient follow-up and to determine the SEDs of continuum sources) and in the HI band (for HI mapping of galaxies).

In addition, there are a number of new telescopes coming on-line which will be complementary to ASKAP in terms of frequency coverage.

- LOFAR is a low frequency (below 300 MHz) high resolution array in Europe. Although not in the same wavebands as ASKAP, it will compete on pulsar and transient science but will be complementary for producing eg SEDs of extragalactic sources.
- The MWA will target the Epoch of Reionisation part of the SKA key science project and will be co-located with ASKAP. It would be useful to develop a combined science case between MWA and ASKAP, especially on clear areas of overlap such as transient science.
- ALMA will be the most sensitive mm array ever built and will operate at frequencies of 100 GHz and above with its focus largely on star formation.
- At the GMRT there are plans to upgrade the front and back ends at the GMRT to provide broad frequency coverage especially at the low end. The GMRT will therefore be an excellent complement to ASKAP at low frequencies. VLBI capability between the GMRT and ASKAP (and other Australian telescopes) is worth exploring further.

ASKAP will have the highest survey speed in the 1 GHz band of any of the planned instruments. This implies it should be exploited in such a fashion as to maximise its advantages (i.e. for large-area surveys) and not for projects in which other telescopes are clearly superior. The Australian Long Baseline Array will greatly benefit from the large collecting area in Western Australia. ASKAP will provide long east-west baselines albeit only at 1.4 GHz. The LBA will likely be fully operational in e-VLBI mode by 2010. Connecting ASKAP to the east coast telescopes on cross continental baselines is a good demonstrator of SKA readiness. Finally, ASKAP must demonstrate that focal plane arrays are a viable option for SKA, since the SKA will likely require focal plane arrays to achieve the Dark Energy Key Science Project.

2 Science with ASKAP

The technological innovation of ASKAP and the unique radio quiet location in Western Australia will enable a powerful synoptic survey instrument that will make substantial advances in SKA technologies and on three of the SKA key science projects: the origin and evolution of cosmic magnetism, the evolution of galaxies and large scale structure, and strong field tests of gravity. In addition ASKAP will make inroads into the exploration of the unknown, a further key SKA science imperative.

Science with ASKAP depends heavily on the final survey speed and the configuration of the antennas. A 30 antenna system is a minimum requirement for ASKAP scientifically and all efforts should be made to ensure that the survey speed does not fall below 10^5 $m^4K^{-4}deg^2$. As regards configurations, low surface brightness imaging cannot be done well with a very extended array and, conversely, high dynamic range imaging cannot be done with a very compact array. For ASKAP, the relatively small number of antennas does not allow us to provide an array which is fully optimized for all the science. This implies that prioritising the science also influences the configuration. However, reasonable performance can be achieved for a wide range of applications (Gupta et al. 2008, Feain et al., 2008).

ASKAP must concentrate on survey programs where its superior survey speed wins over other telescopes and not just on incremental increases from surveys done to date. All the science goals listed involve major surveys with a plethora of expected scientific outcomes. The following are the headline science goals as listed in the science case. For each section, the appropriate technical and configuration requirements are also listed.

2.1 Extragalactic HI

An HI survey with ASKAP will lead to the detection of a million galaxies in atomic hydrogen emission across 80% of the sky out to a redshift of 0.2 to understand galaxy formation and gas evolution in the nearby Universe. An ASKAP HI survey will be two orders of magnitude better than anything so far. The combination of HI and optical data (from redshift surveys such as WiggleZ and/or GAMA) over 100s of square degrees makes a very powerful tool for understanding galaxy formation. Blind HI absorption surveys (which probe damped Lyman-alpha systems) and OH megamaser surveys (which probe ultra luminous star forming galaxies) to z~1 are also very powerful with ASKAP.

2.1.1 Why ASKAP?

Current deep searches of HI emitting galaxies (with the WSRT and the GMRT) are limited to small areas of the sky. Generally these regions are chosen because they contain e.g. a galaxy cluster and are therefore not representative of the sky as a whole. The Arecibo survey covers a larger region of sky but has problems associated with single dish observing and radio interference. ASKAP excels in this science because of its fast survey speed and because the radio spectrum (in Western Australia) from 700 to 1450 MHz is relatively free of interference.

2.1.2 Requirements

- Maximum sensitivity on baselines less than 2 km (resolution 30 arcseconds).
- Low point-spread-function side-lobes to avoid the need for deconvolution.
- Data processing of 16,000 frequency channels across the entire field of view.
- Automatic detection and classification of HI galaxies in a pipeline process as visibilities will not be archived.
- The ability to perform long (days, weeks) integrations and continue to reduce noise levels.

2.2 The Evolution of Galaxies at High Redshift

A high resolution continuum survey with ASKAP would yield the detection of synchrotron radiation from 60 million galaxies to determine the evolution, formation and population of galaxies across cosmic time and enabling key cosmological tests. Such a survey would be an enormous data gold mine for decades to come. The impact of the NVSS, and very deep surveys of small regions (e.g. ATLAS), cannot be overstated. ASKAP can do better than the NVSS by more than an order of magnitude in flux density and a factor 5 in resolution over the whole sky. Complementary observations at lower and higher frequencies and in the optical band will be necessary to extract all the science.

2.2.1 Why ASKAP?

With the current generation of radio telescopes, continuum surveys are either wide-area but shallow (e.g. the NVSS and SUMSS) or very deep but only over a tiny (and perhaps not representative) region of sky (e.g. ATLAS). ASKAP can change the paradigm by covering the entire sky to very deep levels and therefore open up a big area of phase space not previously explored.

2.2.2 Requirements

- Baselines out to 6 km to provide 8 arcsecond resolution.
- The ability to produce dynamic range limited images. This requires a dynamic range at least 10^5 over many parts of the sky.

2.3 Unveiling the Magnetic Universe

A continuum survey with ASKAP would also lead to the detection of polarized radiation from over 500,000 galaxies, allowing a grid of rotation measures at 10′ resolution to explore the evolution of magnetic fields in galaxies over cosmic time. ASKAP is capable of delivering more than an order of magnitude improvement over current knowledge.

Galactic polarization, including the diffuse (all-sky) signal and Zeeman splitting of the HI line is a further powerful probe of the magneto-ionic medium of our own Milky Way.

2.3.1 Why ASKAP?

ASKAP excels in this area because of its large survey speed and relatively good angular resolution. Surveys with single dish telescopes such as Parkes and Arecibo can cover large areas of sky but only at arcminute resolution. Interferometric surveys in contrast have good spatial resolution but can only cover small regions of sky in a finite time. The very high survey speed of ASKAP allows the entire sky to be covered relatively quickly.

2.3.2 Requirements

- To some extent the rotation measure grid science does not depend on the configuration of ASKAP although neither very compact nor very extended arrays are ideal.
- Galactic polarization science requires high surface brightness sensitivity (compact configurations).
- Polarization calibration accurate to 1 part in 10^3 over the entire field of view.

2.4 The Milky Way and Near-Field Cosmology

Galaxy formation and evolution is perhaps best arrived at through a detailed study of the Milky Way and the environs of nearby galaxies. The understanding of the evolution of the interstellar medium of our own Galaxy and the processes that drive its chemical and physical evolution can be achieved through a sensitive survey of the sky at HI. By targeting the extended environment of galaxies in the Local Universe, the trace atomic constituent (the 1% neutral fraction) of the intergalactic medium can be directly imaged. The long dynamical timescales in these low-density regions insures that they preserve a many Gyr record of the tidal interaction and galactic wind feed-back history, and so document the process of galaxy formation in a unique way that is completely inaccessible to any other branch of astronomy.

2.4.1 Why ASKAP?

The high survey speed of ASKAP will enable it to cover significant fractions of the sky, or permit ultra-deep integrations on targeted 30 deg^2 fields, to probe faint HI emission which currently can only be done in very small regions of interest. The excellent RFI environment of the ASKAP site should permit sensitivity to increase with time over long time periods.

2.4.2 Requirements

- Good surface brightness mapping speed is required which implies a degree of central concentration to the configuration.
- The ability to deal with large data cubes which are mostly filled with emission.

2.5 The Transient and Variable Sky

The characterization of the radio transient sky through detection and monitoring of transient sources such as gamma-ray bursts, radio supernovae and intra-day variables can be well achieved with ASKAP. Transient science in the radio domain is currently coming into its own and we know very little at present. However, instruments such as the ATA will make significant advances in our knowledge prior to the advent of ASKAP and it is difficult to see how the science will evolve. Variable source science will be a big strength of ASKAP. This includes deciphering the nature of the Extreme Scattering Events and other rare events, the detection of which only all-sky, sensitive surveys can provide. Both transient and variable science contain a strong component of VLBI follow-up observations.

2.5.1 Why ASKAP?

The fast survey speed and good sensitivity of ASKAP allows it to survey the entire sky to ~mJy levels in a single day. This is the only way that rare transient and variable events can be detected. ASKAP is far ahead of existing instruments in being able to explore this region of phase space. In the near future its major competitor will be the ATA which is gearing up to do relatively shallow surveys of most of the sky with a rapid turnover.

2.5.2 Requirements

- Broadly speaking, ASKAP will be an excellent transient instrument almost irrespective of system parameters and configuration although accurate identification means that angular resolution should not be worse than 10''.
- Detection algorithms (software pipelines) for transient detection.
- Responding to triggers and generating triggers.
- Prompt e-VLBI follow-up of interesting transients using the Australian LBA.
- A mode of operation which involves observing the whole sky every day.
- The case to provide a capability to image transients at 1 ms resolution by 2015 should be given high priority.

2.6 Pulsar survey and timing

The discovery and timing of up to 1000 new radio pulsars to find exotic objects and to pursue the direct detection of gravitational waves is potentially possible with ASKAP although it is only just competitive with the world's largest single dish telescopes. However, a large pulsar survey is Key Science for the SKA and so developing relevant techniques on ASKAP will be of value.

Pulsar timing can be carried out on ASKAP through the provision of tied array beams. For pulsars in the galactic plane, where the density is ~1 per square degree, the large field of view of ASKAP makes the simultaneous timing of multiple pulsars possible. This is not the case for the (much rarer) millisecond pulsars.

2.6.1 Why ASKAP?

In this area, ASKAP does not have major advantages over its single dish competitors like the GBT, Arecibo and Parkes. However, the traditional pulsar use of large single dishes will come to an end with the arrival of the SKA. ASKAP will therefore play a key role in the transitional phase from single dishes to interferometers and techniques need to be developed on ASKAP which will then be used for the SKA.

2.6.2 Requirements

- Surveys are most effectively done with compact configurations to minimise computing.
- Timing requires high instantaneous sensitivity.
- Timing requires provision of multiple tied array beams.
- Specialised back-end equipment for folding and de-dispersion.

2.7 VLBI

The high-resolution imaging of intense, energetic phenomena through improvements in the Australian and global Very Long Baseline networks is a key ASKAP science area. VLBI follow-up of transient sources may well be critical to their identification.

2.7.1 Why ASKAP?

ASKAP adds significantly to the capabilities of the Australian LBA because it has significant collecting area (thus improving sensitivity) and is situated in Western Australia adding E-W baselines to the current LBA telescope configuration (thus increasing resolution and providing better u-v coverage).

2.7.2 Requirements

- e-VLBI connectivity to other LBA telescopes.
- Provision of multiple tied array beams.

3 Scientific Priorities for ASKAP in 2010 – 2015

The strengths of ASKAP are (i) its fast survey speed in both line and continuum, (ii) its excellent u-v coverage, (iii) its southern hemisphere location, (iv) its radio quiet site. Over the period 2010-2015 ASKAP will be starting operations and needs to make a big impact both scientifically and as an SKA demonstrator. The early science with ASKAP should therefore concentrate on those areas where the gains will be largest and the impact greatest. The highest scientific priorities for ASKAP are (in order):

- Understanding galaxy formation and gas evolution in the nearby Universe through extragalactic HI surveys;
- The characterization of the radio transient sky through detection and monitoring (including VLBI) of transient and variable sources;
- Determining the evolution, formation and population of galaxies across cosmic time via high resolution, confusion limited, continuum surveys;
- Exploring the evolution of magnetic fields in galaxies over cosmic time through polarization surveys.

This prioritisation also drives the requirements on the software instruments. In order briefly, these would then be (i) the ability to process HI data, (ii) transient detection, (iii) the ability to image at high dynamic range, (iv) polarization calibration. These are all challenging in their own right and are key demonstrations for FPA capability for the SKA.

The prioritisation then leads to requirements on the configuration. A discussion document on ASKAP configurations and a accompanying technical document are given by Feain et al. (2008) and Gupta et al. (2008). If ASKAP consists of only 30 antennas, the initial configuration might be one which achieves the best possible science returns for an extragalactic HI emission survey. This involves arranging the antennas inside a circle of diameter ~2km, yielding a 30" beam with an excellent point spread function which obviates the need for image deconvolution. Reconfiguration after 2-3 years of observing might be considered. If ASKAP consists of 45 antennas, the configuration might be a hybrid array providing good performance on a range of spatial scales down to ~10”, corresponding to a maximum baseline of ~6 km. Such a hybrid configuration satisfies the requirements of the 4 science priorities listed above and potentially allows multiple science surveys to be carried out in parallel.

4 A year in the life of ASKAP

The User Policy for ASKAP is currently being developed and will be completed by the end of 2008. This will give an indication of what fraction of the time will be devoted to large surveys as opposed to smaller projects. At the same time we are developing an operational model for ASKAP, also to be in place by the end of 2008, which will largely determine various operational modes of the telescope. Taking these factors into account, what follows below is only indicative of what the conclusions of the User Policy and Operational Model might be.

We assume that large surveys will occupy some 75% of the telescope time with the remaining 25% dedicated to smaller projects. The HI survey will operate during the night in point and stare mode, providing a 12-hr data cube over 30 square degrees of sky. These data will be used to find HI emitting galaxies as well as nearby intergalactic HI streams and to make a deep continuum image. Simultaneously the data will be searched for transients, uncovering weak transients not possible to detect in a shallow all-sky survey. During the day, the entire sky will be covered in snapshot observations. These data will be added to the previous day's, therefore building up a deeper and deeper image of the entire sky. The data will be combed for variables and transients, adding to the light curve of tens of thousands of objects.

During the year, blocks of time will be reserved for VLBI time with other telescopes in the Australian LBA and perhaps for pulsar timing programs for millisecond and young pulsars. Other small projects e.g. involving 'special' areas of sky will also be scheduled.

At rare intervals, some very exciting trigger will be generated by ASKAP, or perhaps ASKAP will receive a trigger from a high-energy satellite observing a transient in the distant Universe. A VLBI response will be initiated and ASKAP and other telescopes in the LBA can be trained onto the source in a matter of minutes.

Meanwhile, and importantly, the archives are filling up with the vast amounts of data pouring off the telescope over the course of the year. Astronomers from around the world, hunched over their laptops, are able to tap into this vast, public access resource that ASKAP is producing. We know from past experience with telescopes like the HST and Chandra that interesting science comes from trawling the archives. ASKAP will be a unique resource in the radio domain and will provide a lasting legacy for the next decades.

REFERENCES

Feain, I., Johnston, S., Gupta, N. 2008, ASKAP Memo Series, 017

Gupta, N., Johnston, S., Feain, I. 2008, ASKAP Memo Series, 016

Johnston et al. 2007, PASA, 24, 174 (Also available as ASKAP Memo Series, 014)

For the memo series please see the web page
http://wwwatnf.atnf.csiro.au/projects/askap/Memoseries.html

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ATNF Science in 2010-2015: Part 3 ATCA and Mopra

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Summary

We identify five main science areas where the ATCA and Mopra will excel in the period 2010-2015. For the ATCA these are: Star Formation, Magnetic Fields throughout the Universe, Understanding the Variable Sky, Gas in and around the Milky Way and Nearby Galaxies, and the Evolution of Galaxies at High Red-shift. For Mopra the priority areas are Star Formation and Dense Gas in and around the Milky Way and Nearby Galaxies. We also recognise an additional category for both telescopes, Exploring the Unexpected, which acknowledges that science will advance over the next few years and it is never possible to predict what will drive the telescopes of tomorrow. We explore the requirements, including desirable upgrades, for each of the scientific areas and provide a prioritisation of the science areas with the aim of better informing future operations decisions.

1 Context

The ATCA is one of the most highly cited radio facilities in the world (after the VLA and Parkes; Trimble & Ceja 2007). The breadth of highly cited papers published from ATCA data extends from local star formation and interstellar medium studies to the evolution of high redshift galaxies, from searches for planetary disks to the rapid follow-up of gamma-ray bursts. Undoubtedly contributing to the ATCA's success and breadth of studies is that it is one of the most flexible radio telescopes in the world; with a frequency range of 1 GHz to 105 GHz and the ability to image structures on the scale of one degree down to less than an arcsecond. As science priorities have shifted since commissioning in 1990, the ATCA's flexibility and major upgrades have ensured that it has continued to make high impact contributions. The latest major upgrade, the 4 GHz broadband backend (CABB), will be operational in 2009.

With the installation of the Mopra Spectrometer (MOPS) in 2007 the profile of the Mopra Telescope has been raised considerably, particularly in the international community. Mopra has developed into a world-class niche instrument, performing extremely well in studies of star formation and the dense interstellar medium with its suite of receivers at 3, 7, and 12mm. The telescope remains the largest millimetre single dish in the Southern Hemisphere and the only in the South to be operating in the 3 & 7 mm wavebands.

The radio interferometry scene is changing rapidly with the anticipated arrival of the EVLA, ALMA, and a number of SKA pathfinders all before 2013. The EVLA will operate with continuous frequency coverage from 1 to 50 GHz with 8 GHz of instantaneous bandwidth, making it powerful for sensitivity-limited continuum observations and providing improved spectral line capabilities. Full EVLA operations are scheduled to commence in 2013 but many of the capabilities, including the fully commissioned new correlator, will be in place from 2011. In the next five years the Southern hemisphere will gain ALMA, operating initially at frequencies from 90 GHz to 690 GHz. ALMA will commence early science operations in late 2009, with as many as 10 antennas operating, and the full array due to be operational in 2012. The ATCA and ALMA frequency coverage, as currently specified, overlaps only in the 90 GHz band, at these frequencies ALMA will be more sensitive than the ATCA by about two orders of magnitude.[1] Several key SKA pathfinders will come on-line between now and 2012. The Allen Telescope Array (ATA) is already operating with 42 of an expected 350 antennas, a wide field of view and complete frequency coverage from 0.5 – 11 GHz. ASKAP, due to come on-line at the end of 2012, will operate in the frequency range 0.7 – 1.8 GHz with a 30 deg^2 field of view and a 300 MHz bandwidth. Though not currently settled, the configuration for ASKAP will likely be tailored to its primary scientific driver of high redshift HI surveys. The South African pathfinder, MeerKAT, may also become available at around the same time as ASKAP with a likely frequency range of 0.5 – >10 GHz, more collecting area and a smaller field of view. The MeerKAT configuration is currently undecided. Clearly the field of centimetre wavelength interferometry is expanding with the SKA pathfinders, but it is worth noting that these are designed for specific science projects, technology and site demonstration, rather than as general purpose telescopes.

The field of millimetre single antennas will also change significantly in the next decade with future focal plane arrays underway at 12 mm and possibly 3 mm for the GBT 100 m, and a 3 mm focal plane array plus 12 GHz bandwidth planned for the IRAM 30 m. These will provide significant competition for Mopra in its current state, leaving the southern hemisphere as its main niche. Although 12 mm is available on the larger antennas at Parkes and Tidbinbilla, the 8 GHz bandwidth of Mopra will continue to provide strong scientific advantages.

As we look to the future, there are a number of areas that immediately distinguish the ATCA and Mopra from other radio facilities. For example, Mopra will remain the only large millimetre single dish in the southern hemisphere at 3 and 7 mm and an invaluable complement to the ALMA interferometer for star formation and molecular interstellar medium studies. ATCA remains the only telescope in the world that offers a frequency coverage

[1] However, the University of Chile is exploring options to build a 7 mm system for ALMA.

spanning 1 to 105 GHz, making it very powerful to use for studies of spectral energy distributions (SEDs). In the 7 and 12 mm bands, the ATCA will be the only Southern complement to the higher frequency ALMA. The compact configurations of the ATCA will continue to differentiate it from many other facilities, including the EVLA and possibly ASKAP. Array configurations of 750 m or less currently account for 65% of all time requests, while ~75% of millimetre requests are for configurations less than 350m in extent. HI mapping, which currently accounts for ~50% of scheduled time depending on season, focuses on array configurations less than 750m. Given the high brightness sensitivity of the ATCA's compact configurations, for diffuse mapping of extended areas the ATCA will likely remain one of the fastest mapping interferometers.[2] At mid-frequencies (2.4 – 12 GHz), the ATCA will be the only Southern hemisphere interferometer until MeerKAT or possibly SKA Phase-I come on-line. Although the EVLA will be clearly superior to the ATCA in high-resolution, sensitivity-limited experiments at the mid-frequencies that are not hemisphere specific, the hemispheric advantage and compact configurations may be critical to some experiments.

In order for the ATCA and Mopra to remain internationally outstanding in the next decade we seek to identify the scientific areas in which these telescopes can contribute uniquely to radio astronomy. These priorities will inform decisions about operational requirements. This document identifies six key areas that are likely to each occupy on the order of 15-20% of the telescope time during the period 2010 – 2015. It is expected that many other high impact science areas will be explored with the ATCA and Mopra but that the ones listed here will dominate the time requests. While it is impossible to completely predict the course of science during this period we hope that these encompass the majority of the highest priority science fields and also allow for the continuously evolving nature of science.

2 Science with the ATCA and Mopra

At a recent meeting about *Science with the ATCA of the Future* held on 11 June 1008 several key strengths of the ATCA were highlighted. These were: frequency coverage and agility, the southern hemisphere location, the range of array configurations covering a factor of 80 in linear scale, excellent linear polarization and most importantly, continual upgrades. We emphasise that the ATCA is changing rapidly. CABB, together with the forthcoming upgrades to the broadband centimetre receivers, will enable new operational modes.

The most recent upgrades, viewed in the international context, lead to the identification of five main science areas where the ATCA and Mopra will excel in the period 2010-2015. These are: Star Formation, the Evolution of Galaxies at High Redshift, Gas in and around the Milky Way and Nearby Galaxies, Magnetic Fields throughout the Universe, and Understanding the Variable Sky. We discuss these in detail below.

2.1 Star Formation

Understanding the nature of star formation is a primary science goal for the current ATCA and Mopra, as well as being a dominant goal for ALMA. Some of the areas where the ATCA and Mopra can contribute to the field of star formation are: characterising the dust grains in the debris disks around young low-mass stars; identifying phenomena associated with the early phases of massive star formation such as masers, molecular disks and ionized HII regions; measuring the structure and turbulence of the gas in molecular clouds; and analysing the chemistry of the molecular gas associated with star formation. ATCA, Mopra and ALMA have a critical southern advantage, allowing them to see most of the active parts of the Galactic Plane, including 30% that is not accessible to northern telescopes.

The role of Mopra as a source finder will be absolutely critical in the ALMA era. As a large single dish with a wide backend its role will be studying large samples at low angular resolution to guide high-resolution follow-up with the ALMA and the ATCA. Mopra will continue to complement the sub-millimetre single-dish telescopes operating at the ALMA site because it can be used to collect data on the lower-state molecular line transitions (in the 3-

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[2] See https://wikio.nrao.edu/bin/view/GBT/GBTSensitivityComparison for an instructive comparison of point source and extended source mapping speeds at 1.4, 24, 90 and 115 GHz with facilities worldwide.

and 7 and 12 mm wavebands), which are important for chemical modeling and the easiest to detect. The 8 GHz spectral bandwidth provided by MOPS currently makes Mopra the best telescope in the world to use for chemical-line surveys. However, this will change as other single-dish mm facilities (such as the the IRAM 30 m in the north) catch up and continue to push the broadband limits. In the ALMA era there will be an strong need for large-scale star formation surveys. To ensure that Mopra can best assist this field and remain the premier instrument for large-scale surveys it will be necessary to consider further enhancements to improve surveying speed. These may include bandwidth enhancements, multi-beam/focal plane array systems, and software improvements for automated surveys.

The ATCA is the only southern facility able to provide the wide frequency coverage needed to complement ALMA star formation studies. With CABB, the ATCA millimetre facilities will be more sensitive to continuum emission and the 4 GHz broadband coverage (up from 128 MHz) will transform the ATCA into a powerful spectral-line instrument. Although 100 GHz will be superseded by ALMA, the ATCA will continue to study the spectral energy distributions of star-forming regions at frequencies from 1 to 50 GHz. These studies 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 massive star formation. The 7 mm and 12 mm bands are fast becoming known as the most suitable wavelengths for studying the extreme phenomena associated with the formation of massive stars, such as optically thick circumstellar disks, hyper compact HII regions and jets.

2.1.1 Requirements

- Access to good winter weather for ATCA 7 and 12mm and Mopra 3 and 7 mm. Some interesting 12 mm science can be performed at Mopra in the summer months.
- Large blocks of time scheduled on Mopra for surveys including semi-automation of surveys.
- ATCA compact configurations. Although the configuration requirements are not as stringent at 7 and 12 mm as at 3 mm, it is expected that most millimetre science will continue in compact configurations.
- Desirable: An extension of the N-S baselines to ~400 m for higher resolution millimetre work at the ATCA.
- Desirable: Placement of the 6 km antenna on the track for greatly improved u-v coverage and enhanced sensitivity.
- Desirable: Focal plane arrays or multi-beam systems on Mopra at 3 or 12 mm to increase its mapping speed.

2.2 The Evolution of Galaxies at High Redshift

Understanding the evolution of galaxies throughout cosmic time is a high priority goal for astrophysics in the next decade. At the heart of this effort lie studies of the population of radio sources at high redshift. Most of what we know about relative populations of radio AGNs and starburst galaxies as a function of redshift is derived from deep, small area and shallow, large-area surveys at 1.4 GHz. However, the shallow AT20G survey has shown that the radio population at 20 GHz cannot be predicted by the 1 GHz population, suggesting that extrapolation between the 1.4 GHz surveys and ALMA surveys will be difficult. Although ASKAP will conduct confusion limited all-sky surveys at 1.4 GHz, there is an obvious case for wide-area surveys at 10 – 20 GHz with similar depth to the ASKAP surveys. The ATCA's very compact configurations and fast mapping speed at 20 GHz will keep the ATCA competitive against the EVLA for wide-area 20 GHz surveys. Deep surveys of targeted areas at mid frequencies (6-8 GHz) are also needed to provide a bridge between the deep 1.4 GHz surveys and planned ALMA surveys to provide crucial information about the spectral shape, morphology and polarization of high redshift galaxies. The ATCA will be the only telescope capable of surveying the mid-frequency range of southern deep fields planned for ALMA with multi-wavelength companion datasets.

Also crucial to understanding the evolution of galaxies at high redshift is an understanding of the evolution of gas with redshift. Lambda-CDM theory predicts fewer massive galaxies at high redshift than are observed. Observations of the star formation and gas reservoirs, as traced by molecular gas, in distant, massive, red, active and dead galaxy populations as a function of redshift are critical to studying how galaxies evolve with redshift. ALMA will be a very powerful instrument for detecting high order transitions of CO at redshifts greater than z=2.5 with its 100 GHz band and above. However, a good understanding of the low-order CO transitions is important for studying the full gas reservoir in these galaxies and understanding galaxy formation. The ATCA, with its broad bandwidths in the 7 and 12 mm bands, will have a southern monopoly on low-order molecular gas studies out to redshifts of z=7 and provide an important complement to ALMA studies of high redshift, very dense molecular gas.

2.2.1 Requirements

- Broad bandwidths at 7 and 12 mm to maximise detection rates for high redshift galaxies
- Maximum sensitivity in compact configurations for high redshift CO work, through, e.g. the inclusion of the 6 km antenna.
- Fast scanning speeds for large-area continuum surveys.
- High angular resolution for deep fields.
- Desirable: extend N-S track to ~400 m for improved resolution in 2-D snapshots.
- Desirable: 6 km antenna on the 3 km track for faster 22 GHz surveys.

2.3 Gas in and around the Milky Way and nearby Galaxies

The evolution of galaxies is largely controlled by the evolution of interstellar gas within a galaxy. The interstellar gas provides the fuel for star formation and acts as an atmosphere for transferring information from one part of a galaxy to another. The evolution of a galaxy's interstellar medium (ISM) is also significantly impacted by the flow of matter between the galaxy and the surrounding intergalactic medium (IGM). These processes are traced through a variety of ways including atomic hydrogen (HI) mapping of the diffuse gas within and around galaxies, detailed mapping of the structure and kinematics of molecular gas in star-forming regions, and measurements of the distribution of molecular gas in nearby galaxies. The ATCA and Mopra between them have the ability to study both atomic and molecular gas over a wide range of scales providing a powerful probe for studying the full evolution of the ISM from atomic to molecular and linking with star formation.

Mopra is an immensely powerful facility for large-scale mapping of the dense molecular gas in the Milky Way and nearby galaxies. The broad bandwidth available in the MOPS spectrometer allows fast, multi-line mapping of regions for chemistry studies, providing an outstanding complement to ATCA and future ALMA star formation studies. Obvious future legacy projects will include a multi-line Galactic Plane survey. Now, and continuing into the ALMA era, there is an enhanced need for a southern millimetre antenna capable of large area and large sample surveys. To best take advantage of this scientific need we should consider investment in techniques that facilitate efficient large-scale mapping, including software for automated surveys, and a multi-beam or focal plane arrays.

The ATCA has a tradition of detailed mapping of diffuse HI emission in and around galaxies, providing a context for galaxy structure, galaxy interaction and structure of the IGM near galaxies. One of the main goals of ASKAP is to study the evolution of HI in the universe through detection of hundreds of thousands of HI galaxies. Depending on configuration choice, ASKAP may not initially have the surface brightness sensitivity to provide maps of the diffuse HI in and around extended low redshift galaxies and the Milky Way. For the period 2010-2015 the ATCA will continue to play an important role in HI studies of mid-size (<100 deg^2) areas at low (2-3 arcmin) resolution with images of the structure of the diffuse gas between galaxies, tracing extended disks and interactions. Similar studies will be made in even more detail around the Milky Way.

The ATCA also has a vital role to play in complementing and extending its star formation studies with detailed mapping of the dense interstellar molecular gas surrounding star-forming regions both in the Milky Way and beyond. Much of this work relies on the compact configurations available to the ATCA.

2.3.1 Requirements

- Compact ATCA configurations for diffuse gas and millimetre observations.
- 12 mm, 7 mm and 3 mm bands at Mopra.
- 20 cm, 12 mm and 7 mm bands at ATCA.
- Baseline overlap with Parkes for total power.
- Highly desirable: Focal plane arrays or multi-beam systems on Mopra.
- Highly desirable: Placement of the 6 km antenna on the 3 km track for improved u-v coverage and additional collecting area in <750 m configurations.
- Desirable: Focal plane array at 12 mm on the ATCA.

2.4 Magnetic Fields throughout the Universe

Magnetic fields remain in many ways the last uncharted frontier of astrophysics and one in which radio astronomy can make unique contributions. Magnetic fields account for as much as one third of the energy density of the interstellar medium (ISM) and play a crucial role in structuring galaxies, the intergalactic medium, the ISM, and star formation. For years the ATCA has led the world in work on magnetic fields owing largely to its linear feeds and excellent polarization purity. The polarization purity achievable with the ATCA cannot be achieved with any other facility current or planned. With the wide bandwidths anticipated from CABB and the centimetre receiver upgrades, the ATCA will play an even more important role in studies of magnetic fields throughout the universe in the years to come.

Recent developments in a technique called Faraday tomography have demonstrated the power of measuring polarization across many frequency channels covering a wide bandwidth. These measurements are able to resolve Faraday rotation along the line-of-sight allowing us for the first time to separate magneto-ionic structures in the interstellar medium much as high velocity resolution HI observations allow observers to separate atomic structures along the line-of-sight. Faraday tomography can be applied to the Milky Way and resolved nearby galaxies. The ATCA has the perfect combination of polarization purity, surface brightness mapping speed, frequency coverage in the 1 – 10 GHz range, spectral resolution and bandwidth to allow it to probe rotation measure structures better than any other facility in the world.

The ATCA will remain strong in mid to high frequency studies of the polarization properties of individual objects. In the pre-ASKAP era the ATCA will continue to be used extensively for point source polarization as a probe of the Milky Way, high velocity clouds, nearby galaxies and the diffuse IGM. Once ASKAP comes on-line the majority of polarization work with the ATCA will focus towards diffuse mapping, Faraday tomography and high frequency polarization properties.

2.4.1 Requirements

- Good polarization purity across the full primary beam, including 13cm where this is currently poor.
- Broad instantaneous bandwidth, coupled with access to frequencies from 1 – 10 GHz.
- Compact configurations for diffuse polarization.
- Baseline overlap with Parkes for total power.
- Highly desirable: Placement of the 6 km antenna on the 3 km track for improved u-v coverage and additional collecting area in <750m configurations.

2.5 Understanding the Variable Sky

Detection and monitoring of the variable sky are key science drivers for ASKAP, the MWA and many other SKA pathfinders. The large fields-of-view of these telescopes will enable them to detect orders of magnitude more transients and monitor more variable sources than current telescopes. However, characterisation of the newly discovered sources will require follow-up at multiple frequencies and often at higher angular resolution. Although little is known about the nature of many of the transients to be detected, we can extrapolate from what we know about gamma-ray bursts (GRBs), supernovae (SNe) and intra-day variables (IDVs). These sources provide a wealth of information about the nature of the intergalactic and interstellar medium, how stars explode and many other topics. Most variable sources are point sources so monitoring can be done with any array configuration. For transients, high angular resolution is preferred for source localisation and cross identification with other wavelengths. Frequencies greater than 1 GHz are best for SNe and GRBs, which suffer from optical depth effects at lower frequencies. For all types of known variables (IDVs, GRBs, SNe) simultaneous multi-frequency lightcurves are invaluable for interpretation.

The ATCA has published some of its most highly cited papers on transient and variable sources and it is likely that it will have an even more important role to play in this field in the future by characterising the multi-frequency and high resolution properties of the numerous sources found by ASKAP, the MWA, and high energy telescopes such as GLAST. For example, ASKAP can be used to trigger intensive ATCA studies of IDVs and Extreme Scattering Events for which the broad-band capability of the ATCA will explore the highly frequency dependent nature of wave propagation through the ISM. The increased bandwidth provided by CABB will dramatically improve the instantaneous sensitivity thereby doubling the redshift range of SNe detectable with the ATCA. For sources south of -25° declination, the ATCA will remain the only centimetre wave radio telescope capable of critical multi-frequency follow-up of transient and variable radio sources.

2.5.1 Requirements

- Broad instantaneous bandwidth for maximal instantaneous sensitivity.
- Frequency agility and dual simultaneous frequencies.
- Clear guidelines for ToO and NAPA overrides and possibly a replacement time policy.
- Rapid response times for ToO and NAPA projects.
- Continued availability of 6 km baselines.

2.6 Exploring the Unexpected

Much of what any telescope does during its lifetime was never predicted during its initial science planning. Although we cannot predict exactly what science the ATCA and Mopra will do throughout the period 2010-2015, it is important to predict the areas of parameter space in which the ATCA and Mopra can excel. By 2010 the ATCA will operate with almost continuous frequency coverage from 1 GHz to 12 GHz and with very small gaps between 17 and 100 GHz. This broad frequency coverage ensures that experiments requiring nearly continuous coverage of the centimetre band can be done efficiently. An example experiment, probing the Epoch of (Re)Combination (R. D. Ekers) would require the ATCA coverage of 1 – 10 GHz and its flexible mode of operation to use all antennas individually. We can expect that the areas of parameter space where the ATCA and Mopra will excel are as identified in the other sub-sections. These include broad frequency coverage, fast mapping and moderately high surface brightness sensitivity. In addition, with the relatively small number of antennas the ATCA has the flexibility to demonstrate new techniques and new technologies. The high impact value of this attribute has been demonstrated in the past with mosaicing, the AT20G survey, and LUNASKA, among many others. An important strength of the ATCA is system knowledge allowing for highly adaptable operational modes.

2.6.1 Requirements

- Broad instantaneous bandwidth and frequency agility.
- ATNF staff, students and other astronomers with in-depth system knowledge for innovative engineering solutions to new scientific problems.
- Ability to supply custom built hardware for unusual projects.

3 Scientific Priorities for the ATCA and Mopra

In the ASKAP and ALMA eras the strengths of the ATCA will lie in its compact configurations, broad bandwidths and wide frequency coverage up to 50 GHz. Bearing in mind the likely competition at centimetre and millimetre wavelengths the ATCA should set its priorities to be the areas where it can contribute uniquely or better than any other facility and in areas of highest impact science. These priorities should not, however, unduly limit the extensive capabilities and flexibility of the ATCA, which have led to its long history of high impact science. The top priorities for the ATCA that are likely to take 15- 20% of the observing time are therefore (in order):

- Star Formation;
- Understanding the Magnetic Universe;
- Understanding the Variable Sky;
- Interstellar Gas In and Around the Milky Way and Nearby Galaxies;
- The Evolution of Galaxies at High Redshift.

A small number of possible future upgrades which will better enable many of the science priorities described here have been identified. Relocation of the 6km antenna onto the 3 km track, thereby improving the sensitivity of compact configurations, single configuration image fidelity and mapping speed would significantly increase the ATCA's ability to deliver on the top science priorities. It may also lead to operational savings through a reduction in the number of reconfigurations required each year. The effect of such a move on other high priority science, particularly variables, needs to be considered carefully. Extension of the N-S track to ~400 m would provide higher resolution for millimetre studies and 2-D snapshot images and would benefit several of the highest science priorities.

Mopra holds a niche in star formation and dense interstellar medium studies, focusing on large samples and large area surveys. In many ways Mopra is just reaching maturity in these fields as evidenced by its ever-increasing telescope subscription rates. Its role is likely to be even more important in the ALMA-era, which will show an increased interest in star formation and molecular gas in the Southern sky. Upgrades to enable more efficient surveying, including software enhancements for improve automated surveys, multi-beam or focal plane array technologies and even wider bandwidths may be warranted to maintain Mopra's competitive advantages in this niche.

4 A Year in the Life of the ATCA

The scientific role of the ATCA will continue to evolve throughout the period 2010 – 2015 as ALMA and ASKAP come on-line. By 2013 we expect to have decommissioned the 3 mm receivers, focusing millimetre efforts on 7 and 12 mm instead. Following extensive community consultation, we may have moved the 6 km antenna onto the main rail track, significantly enhancing the u-v coverage and sensitivity of compact configurations. An extension of the north-south track is being costed and considered against other priorities.

The year 2013 may be spent on projects of a variety of sizes from ~8 hours to larger, 400 plus hour, projects. Star formation and high redshift molecular gas studies will dominate winter observing to take advantage of optimum weather for phase stability on longer baselines. Summer nights may also be used for millimetre observing. Projects focusing on diffuse polarized emission will operate mainly at night to avoid the polarized solar interference. To enable rapid follow-up of transient sources a clear policy of over-rides and make-up time for affected observers will have been developed. Following the 6 km antenna move, the number of configurations required for good u-v coverage of each project has been reduced. For example, many millimetre projects that previously required three hybrid configurations can be completed with only two hybrid configurations. The reduced need for multiple configurations means that the frequency of reconfigurations has decreased. The year will be broken by six blocks of 3-4 days each spaced evenly throughout the year for VLBI observations.

5 A Year in the Life of Mopra

The major science priorities for Mopra are star formation and dense interstellar medium studies, which dictate that the telescope will operate almost exclusively at 3, 7, & 12 mm. It is anticipated that Mopra will focus particularly on surveys of large areas or large samples. By 2013 Mopra may have completed its first large Galactic Plane Survey mapping multiple spectral lines in a single 8 GHz band and be engaged in a second large Galactic Plane legacy survey in a second 8 GHz band. This survey is being observed in a near-automated fashion, made possible through surveying software developments linked to ASKAP. Mopra observers are planning for a 3 mm multibeam system, which will be installed in 2015. Observations during the winter months are made in all wavebands, while the summer months have only 7 & 12 mm projects, for which the weather conditions are not as critical. Projects scheduled for summer months are almost exclusively large projects, running for many weeks each. As an important component of the LBA, Mopra will continue to support 3, 6, 13, & 20 cm observations during the six 3-4 day LBA blocks each year.

Australia Telescope National Facility

ATNF Science in 2010-2015: Part 4 –Parkes

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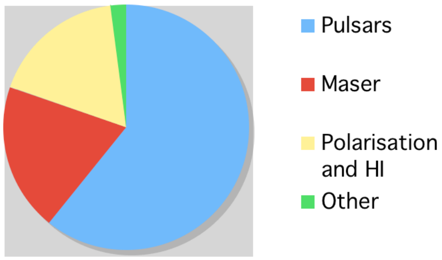
Summary

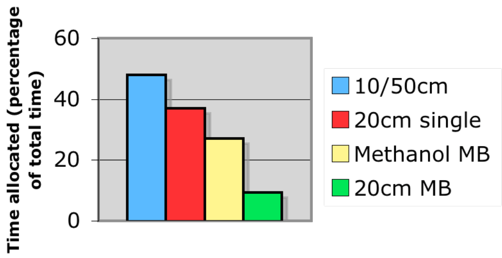
We identify two main science areas in which Parkes will continue to excel in the period 2010-2015. First and foremost is in pulsar timing and pulsar searching, for which Parkes will remain the premier instrument in the world with access to the scientific richness of the southern sky. Parkes will also play a leading role in sensitive surveys of diffuse emission and in studies of star formation if equipped with a 22GHz focal plane array or multi-beam system.

1 Context

In a recent survey of radio astronomy papers, the Parkes Observatory was found to produce the highest number of citations per paper of any facility worldwide. The lack of development of large single-dish instruments in the Southern Hemisphere suggests that Parkes will remain at the forefront of many research topics into the foreseeable future. During the three observing semesters between October 2006 and March 2008, 9622.0 hours of observing time were scheduled for single-dish research (i.e. not including VLBI observations). This time was divided into pulsar observations (62% of the allocated time), maser surveys (20%), observations to study the diffuse Galactic emission and Galactic and extra-Galactic polarisation and HI surveys (18%). This research was facilitated by cutting-edge receiver and back-end systems. The Parkes telescope clearly has international renown as 86% of these proposals included an overseas-based astronomer (as principal investigator on 63%).



Observing Time (excluding VLBI)



Receivers (note many proposals requested more than one receiver and therefore the total time allocated in this Figure is greater than 100%). Small amounts of time were also allocated to higher frequency receivers.

Over the period 2010-2015, Parkes will remain the only large single-dish telescope in the southern hemisphere that is dedicated to astronomical observations. It will therefore remain an essential element for many projects that require either a site in the southern hemisphere, complete spatial frequency sampling, multi-beaming capability and/or focus on pulsar studies. The advantages of a single-dish system together with the suite of front-end receivers and back-end systems will ensure that Parkes has little competition in millisecond pulsar searching and timing in the southern hemisphere.

During November 2007 a workshop was held at the ATNF to discuss the unique science that could be carried out at Parkes over the next decade. In this workshop, 12 talks were given on topics that can be broadly categorised as 1) pulsar searching and timing, 2) mapping experiments and 3) detection experiments. The science topics ranged from pulsar research, star formation, Galactic ISM and extra-Galactic HI. In the next section of this document we present an overview of these major science topics. We subsequently highlight various priorities that need to be considered as the operational model of the telescope evolves. We conclude by describing the possible use of the telescope for a single year.

2 Science with Parkes

Future planning for new instrumentation at Parkes and the way of operating the telescope requires input on the type of science that is likely to have the highest impact. Using notes from the Parkes workshop, the existing proposals and user input, we present the requirements for the some of the major science topics that are likely to be undertaken until 2015. The following sections are ordered roughly according to anticipated decreasing telescope time in 2010-2015. Priorities are given in section 3.

2.1 Pulsar timing

During the last three semesters 62% of the available time was allocated to pulsar research. Pulsar experiments are generally divided into pulsar time binning experiments and pulsar searching. Time binning experiments can further be divided into pulsar timing experiments and observations required to study the properties of individual pulsars. Timing experiments have led to some of the most exciting astrophysical results including 1) testing the general theory of relativity, 2) limiting the existence of a gravitational wave background, 3) probing turbulence in the interstellar medium and 4) studying pulsar timing irregularities. With its new digital backend systems, Parkes is now achieving the most precise pulsar timing results ever obtained. Analysis of individual pulsars allows the study of the 1) pulsar emission mechanism, 2) properties of neutron star birth and 3) Galactic magnetic field.

Pulsar timing experiments currently are allocated ~43% of the Parkes observing time. It is likely that a few large-scale timing programs will require almost half of the available time over the period 2010-2015. The Parkes timing array project (16% of Parkes time) is an ambitious science program that will require at least a further five years of observing in order to achieve its goal of detecting gravitational wave signals. It is also expected that large amounts of time will continue to be allocated to support of the GLAST and AGILE gamma-ray telescope missions and to study highly relativistic binary pulsar systems.

2.1.1 Why Parkes?

- No other Southern Hemisphere telescope has the sensitivity, receivers and back-end systems that can undertake high-precision pulsar timing experiments.
- The majority of known young pulsars are in the Galactic plane and are therefore best observed from a southern hemisphere site.
- It may be possible for other instruments (such as ASKAP) to carry out young-pulsar monitoring experiments (such as for the GLAST mission), but this would require significant fractions of the available telescope time to observe all the required pulsars often enough for the requirements of the gamma-ray analysis, and the instrumentation required is unlikely to be developed before 2015.

2.1.3 Requirements

Timing with Parkes is essential for high precision millisecond pulsar experiments that require extremely well calibrated observations at multiple observing frequencies. The main requirements are:

- Large amounts of observing time. The timing array project requires that ~20 pulsars are observed at 20cm and with the 10/50cm dual-feed receivers at least once every two weeks. Each observation takes approximately ~1 hour. It is also required that the young pulsars observed for the gamma-ray telescopes are regularly monitored.
- 20cm receiver. Pulsars have steep spectral indices making them harder to observe at high frequencies. However, lower frequency observations are affected by the interstellar medium and pulse widths are often wider at lower frequencies. The most accurate timing of the majority of pulsars is therefore obtained at observing frequencies close to 1400MHz. A single beam receiver (such as the H-OH) is adequate, the HI multi-beam is not required.
- 10/50cm receiver. The interstellar medium significantly affects pulsar signals and it is therefore essential, for high timing-precision experiments, that observations are made on a ~2-weekly timescale, with the dual-band 10/50cm receiver. This allows dispersion measure variations to be tracked and the best datasets (normally at 20cm) to be corrected.
- Good quality back-end systems. We require the use of the digital filter-bank systems (PDFB2/3) at 20cm and at 10cm (which covers the entire 1GHz band available at 10cm) and the PDFB3/APSR system for observations at 50cm.
- RFI-mitigation at 50cm. The 50cm band at Parkes is becoming corrupted by digital television signals. Although a planned band change will bypass the worst of the

problems, it will be necessary to use an adaptive, on-line, RFI-mitigation algorithm for all observations at this frequency.

The majority of the pulsar timing observations could be carried out remotely. It is essential that any remote observing allows the 20cm and 10/50cm receivers to be changed and for the backend systems to be monitored, reset and configured as needed.

2.2 Pulsar searching

Pulsar searches with Parkes have led to the discovery of approximately two-thirds of the known pulsars. The majority of these pulsars were discovered in a handful of large-scale surveys with the remainder in smaller observations of regions where pulsars are expected such as supernova remnants or EGRET error boxes. Some of the pulsars discovered have huge astrophysical importance; the CSIRO strategic plan listed the double pulsar discovery among 20 CSIRO *"achievements in recent years".*

During the last three semesters pulsar surveys required 16% of the time available at Parkes. However, the new surveys planned for the forthcoming years will require a larger fraction of the available time - a realistic estimate being ~30%.

2.2.1 Why Parkes?

- During the 2010 and 2015 timescale, Parkes will be the only southern hemisphere telescope capable of detecting millisecond pulsars in a blind survey. We note that ASKAP may be able to undertake a pulsar survey for normal (non-millisecond) pulsars, but is unlikely to detect millisecond pulsars. It is unlikely that ASKAP will carry out any pulsar survey before 2015.
- A southern hemisphere site is highly advantageous for pulsar searches, providing long tracks on the richest part of the Galactic plane and Magellanic Clouds.

2.2.2 Requirements

- Large-scale surveys will require the use of the 20cm multibeam receiver for ~30% of the available time. There is no requirement for particular observing times in order to carry out pulsar surveys, but logistically it is much simpler if large blocks of time are available (although the ability to carry out observations remotely may partially mitigate this requirement).
- Future pulsar surveys will require the new 13 beam digital filterbank systems currently being designed, the PDFB3 system and APSR.
- Because of the pulsar steep spectral index and small beams at high frequencies, it is unlikely that much large-scale pulsar surveying will be carried out at frequencies greater than 3GHz. It is therefore likely that the existing suite of receiver packages (particularly the 20cm multibeam receiver) will dominate surveys until 2015. It is possible that smaller scale surveys will be planned at higher frequencies.

As pulsar survey teams usually have many international members, it would be advantageous if the survey observations could be carried out remotely from overseas. The remote operations required would be selecting the receiver and monitoring the various backend systems being used for the survey.

2.3 Galactic ISM

Approximately 17% of the available Parkes time during the last three semesters was allocated to Galactic or extra-Galactic projects. The versatility of Parkes was demonstrated by the 20cm polarisation survey designed to probe the Galactic magnetic field being able to piggy-back on the S-PASS survey to study, amongst many other goals, CMB cosmology. Even in the ASKAP era, it is likely that the Parkes telescope will continue to carry out large-area surveys of diffuse emission. Surveys to probe the Galactic magnetic field are required in order to understand the physical processes in the ISM including 1) turbulence, 2) energy balance, 3) cosmic ray propagation and 4) gas dynamics. Analysis of large-area polarisation surveys will continue to be used in order to characterise Galactic foregrounds of the CMB polarisation, necessary for probing inflationary models. Such surveys also provide maps of the Galactic magnetic field allowing analysis of the magnetic field structure in the Galactic disk and halo, to study the disk-halo interaction and to provide observational input into models of the formation of the Galactic magnetic field and cosmic ray propagation. Even though polarisation surveys have already been carried at 1.4 and 2.3 GHz, further surveys at other frequencies will allow deeper understanding of the magneto-ionic medium.

2.3.1 Why Parkes?

- Independent of the configuration chosen for ASKAP, a single large telescope will still be required in order to measure total power, which is always required for large-scale diffuse emission surveys.
- Parkes is required to provide full spatial frequency sampling and complements data from ATCA and ASKAP.
- Parkes is ideal for moderate surveys at high resolution – at 2.3 GHz, the resolution matches the comic microwave background polarisation requirements.
- Parkes is ideally suited for studying the polarisation at the Galactic centre and the disk-halo connection in the inner Galaxy. Clearly, a southern-hemisphere site provides the best opportunity to observe the Galactic centre, the richest part of the Galactic plane and the Magellanic clouds.
- A large surface-area, single-dish telescope is required in order to study low surface brightness objects.

2.3.2 Requirements

- Wide frequency coverage is required to analyse the ISM in detail. The current all-sky polarisation survey proposal requests receivers at 1.3cm, 5cm, 10cm, 13cm, 20cm, 50cm and 70cm.
- It is essential to have broadband receivers with good polarization capability.

2.4 HI in galaxies

The Parkes telescope has also been used for large-scale extra-Galactic HI surveys that have been extremely productive; the HIPASS survey and related research produced more than 129 publications. The multi-beam receiver has also been used to search for optically obscured galaxies behind the Galactic plane. More recently, it has been proposed that the atomic hydrogen in the local universe could be detected using deep integration with the multi-beam system. By targeting the extended environment of galaxies in the Local Universe, the trace atomic constituent (the ~1% neutral fraction) of the intergalactic medium can be directly imaged. The long dynamical timescales in these low-density regions insures that they preserve a many Gyr record of the tidal interaction and galactic wind feed-back history, and so document the process of galaxy formation in a unique way that is completely inaccessible to any other branch of astronomy.

2.4.1 Why Parkes?

- The Parkes 20cm multi-beam receiver is the only current system that allows practical imaging surveys that are sensitive enough to detect such diffuse intergalactic HI structures.
- Depending on the degree of central concentration, ASKAP may or may not be competitive for such surveys of diffuse emission.

2.4.2 Requirements

- Parkes 20cm multi-beam receiver
- Achieving useful first generation surveys of diffuse intergalactic HI is expected to require about 20% of available telescope time for several years. Follow-up programs are likely to continue this level of demand.

2.5 Star formation

During the previous three semesters, maser surveys were allocated 20% of the time available at Parkes. Such surveys at Parkes have provided the most comprehensive studies of Galactic OH and methanol masers. During the period between 2010 and 2015 it is expected that Parkes will continue maser surveys and monitoring projects. Talks at the *"Science with Parkes"* workshop highlighted that in order to carry out the key science in this area a new 22-GHz focal plane array or multi-beam system would be required. A survey at this frequency would allow water masers to be observed from star formation regions, around late-type stars and in stellar outflows. The high frequency and intrinsic high source variability have made previous untargeted searches extremely challenging. However, a large-scale survey at Parkes could lead to a determination of the luminosity function of water masers and investigation of the evolution of star forming regions.

A second science driver for a new 22-GHz system is to study Galactic ammonia emission. The outcomes from ammonia surveys will provide input into studies of star formation such as the role of turbulence in star formation, but also into extra-Galactic research such as tracing the formation of galaxy clusters through observations of molecular gas.

In summary the science drivers for a 22-GHz multi-beam system include:

- NH_3 Galactic plane survey;
- H_2O maser Galactic plane survey;
- Continuum surveys;
- Studies of highly red-shifted CO.

2.5.1 Why Parkes?

During the 2010-2015 timeframe Parkes will be "competing" with Tidbinbilla, ATCA, Mopra, GBT and ALMA in this science area. However, ALMA will not have receivers at 22 GHz (only higher frequencies).

- The large collecting area of Parkes is critical for spectral line sensitivity and makes Parkes the instrument of choice for detection experiments and monitoring projects. The main "competitors" for Parkes will therefore be Tidbinbilla and the GBT. However, only restricted amounts of observing time and frequency coverage are available at Tidbinbilla. The main advantages of Parkes over Tidbinbilla are therefore: 1) unlimited access for radio astronomy projects, 2) full operational support and 3) frequency flexibility.
- Large-scale Galactic plane surveys require a site in the southern hemisphere.

2.5.2 Requirements

- Broad spectrometers, many channels.
- A 22-GHz multi-beam (or focal plane array) system.
- As with pulsar surveys there is no requirement for particular observing times, but logistically it is simpler if large blocks of time be made available.

2.6 Miscellaneous

During the last observing semester the versatility of the Parkes telescope was demonstrated by follow-up radio observations after the detection of radio emission from magnetars. This work led to significant scientific interest; the discovery paper has citations on topics as diverse as the birth rates of magnetars, models for the neutron star surfaces, the origin of neutron star magnetic fields and new searches for other radio emitters. The 2006 ATNF annual report lists 118 publications that described observations using all the ATNF instruments. The *Nature* paper describing the first magnetar was the most highly cited. Much of this work was made possible by the ability at Parkes to observe a source at multiple wavelengths and with different back-end systems. Observations at Parkes using the 6GHz and 8.4Hz receivers showed that these magnetars have far flatter spectra than expected. This was confirmed and extended to higher frequencies with observations at other observatories (GBT, ATCA, IRAM) but without the initial higher-frequency follow-up observations at Parkes it is unlikely that there would have been the science case for these observations with other instruments. We note that the first publication of science results from the ATCA 7mm system was a follow-up of the Parkes magnetar discovery.

2.5.1 Why Parkes?

It is likely that Parkes will have a role in many small projects between 2010 and 2015.

- Observations may be needed in order to follow-up on 1) transients detected using ASKAP, 2) discoveries with other new telescopes such as ALMA, GLAST, etc., 3) pulsars discovered in the Arecibo, Green Bank and Parkes surveys and so forth.
- The Parkes Observatory will remain an icon of Australian science and will be devoted (for short periods of time) to outreach/educational use. Currently only a small fraction of observing time (2 hours/month) is dedicated to educational use. It is unlikely that this will grow significantly due to manpower requirements.

2.5.2 Requirements

In order to follow up new discoveries and carry out small projects it is necessary that:

- Time is allocated for small projects. It is likely that this will stay at a few percent of the total allocated time.
- Target-of-opportunity time can be made available at short notice.
- All receiver systems that are already installed in the focus cabin prior to a small project should be available for use along with any of the existing back-end systems. There should be the opportunity to carry out unscheduled receiver changes at short notice if the science case justifies this effort.
- Educational projects will be significantly improved by full remote observing capability from science centres and schools around Australia and abroad.

3 Scientific priorities for the Parkes telescope

The strengths of Parkes are 1) its large collecting area, 2) its site in the Southern Hemisphere, 3) the range of front-end and back-end systems and 4) its frequency agility. We note that a single dish will always be more adaptable than an array. For instance, development of a new system at ATCA requires the building of six receivers and more complex backend systems.

Parkes will be important in following-up new discoveries made with the various new telescopes that will be operational during 2010 and 2015 (including both ground and space-based telescopes). As shown by the recent magnetar discovery, effective follow-up of new source classes requires a varied suite of receivers and back-end systems that can be installed and used at short notice.

In the following part of this section we prioritise the science described in Section 2 (noting that future discoveries may change the key-science topics for the observatory) based on our current knowledge of likely science trends and driven by the goal of maximising science impact.

Having obtained the world's highest timing precision and discovered the majority of known pulsars, Parkes is currently the world-leading pulsar timing and searching telescope. It is likely that pulsar science will continue to take up more than 60% of the available time and therefore is clearly the top priority for science at Parkes. In order to achieve this science, we require:

- Regular timing observations using PDFB2, PDFB3 and ASKAP and the 10/50cm and a 20cm receiver;
- Large blocks of time allocated to pulsar searching. These searches will require the new 13-beam DFB systems and the 20cm multi-beam receiver.

It is more challenging to prioritise the remaining science goals at Parkes. However, Parkes will remain the only large single-dish instrument in the Southern Hemisphere that is dedicated to astronomical research. In terms of developing a new operations model for Parkes, it is therefore necessary to ensure that Parkes can still carry out the science that can only be done using a single dish. The second priority is therefore to allow Parkes to undertake sensitive surveys of diffuse emission. This requires:

- The 20cm multi-beam receiver.
- A suite of receivers covering a wide frequency range up to at least 22 GHz.

The large collecting area of Parkes is critical for spectral line sensitivity. The third priority at Parkes is therefore to study star formation. This requires new developments including

- A 22GHz multi-beam/focal plane array receiver system. If such a system can not be taken into operation, then the role of Parkes for star formation research diminishes.

4 A year in the life of the Parkes Observatory

The major science goals require that time is allocated to pulsar timing experiments and to various surveys. The surveys are best carried out with large blocks of time, but these blocks can be separated by many months. However, it is essential that regular observations be made for pulsar timing experiments. During a typical year it is therefore necessary that a significant number of receiver changes are made:

- Pulsar timing array observations require the 10-50cm dual-band receiver and a 20cm receiver for fortnightly observations. These will continue to interrupt any other long duration survey being undertaken.
- Diffuse HI emission surveys will require the 20cm multi-beam receiver to be available for sessions lasting for weeks or months at a time.
- Polarimetry surveys will require specialized receivers; for example each S-PASS observing session requires the 13cm and 20cm H-OH systems. To circumvent solar interference, these surveys will need night-time scheduling, implying 3 – 4 sessions per year to get the required sidereal coverage. So ~6 or more receiver changes/year are required for one such project alone.
- Star formation surveys, utilizing the methanol multi-beam or a new 22 GHz multi-beam would again imply a receiver change for each scheduled session, since one of the pulsar timing receivers would need to be displaced.

Australia Telescope National Facility

ATNF Science in 2010-2015:
Part 5 Long Baseline Array

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Summary

We identify the science areas where the Long Baseline Array will excel in the period 2010-2015. These are: pulsar proper motions and parallaxes, local group galaxy motions, the evolution of astrophysical jets, the structure of our Galaxy, megamaser cosmology and understanding the variable sky.

1 Context

The technique of Very Long Baseline Interferometry (VLBI) enables the highest angular resolution imaging in astronomy. The milli-arcsecond angular resolution achievable with VLBI corresponds to AU-scale linear resolution at the Galactic centre, and parsec-scale linear resolution in nearby galaxies.

The Long Baseline Array (LBA) is a National Facility operated by ATNF using the three ATNF telescopes (Parkes, ATCA, Mopra) and two telescopes of the University of Tasmania (Hobart and Ceduna), together with Tidbinbilla and Hartebeesthoek (South Africa), subject to their availability. Telescopes in China, Japan, and Hawaii have been used on occasions. The LBA antennas are all equipped with hydrogen masers, forming an internationally competitive network, which is unique in providing VLBI capabilities to study the southern sky. Until recently the LBA operated for three ~week-long blocks each year. This is now evolving to more frequent, shorter blocks, driven in part by the scientific need for more frequent monitoring of some LBA targets and facilitated by near-real-time fringe checking which has improved the observing efficiency.

The move to disk-based recording and a software correlator, with data correlation being outsourced to the Swinburne University of Technology, has significantly enhanced the LBA's capabilities, providing more spectral channels, pulsar gating, and operational advances. Improved internet connectivity has enabled eVLBI observing with real-time correlation on baselines between the ATNF antennas and (at lower bandwidth) Hobart – with eVLBI demonstrations to China, Japan and Europe also having been carried out.

Globally, VLBI has been dominated for the last ~15 years by NRAO's Very Long Baseline Array (VLBA) the first dedicated, full-time VLBI network. The VLBA is an array of ten, 25-m diameter, homogeneous antennas, located so as to provide good (u,v) coverage and offering frequency agility. However, despite a productive and wide-ranging scientific output, the VLBA is currently under threat, with the NSF imposing a requirement that it find one-half of its scientific operating funds from other sources.

The European VLBI Network (EVN) offers somewhat greater sensitivity than the VLBA by virtue of several large constituent telescopes, but is a heterogeneous array with the attendant complexities in amplitude and polarization calibration. The EVN operates in 3-4 blocks for a total of ~16 weeks per year, with additional 24 hour periods reserved for eVLBI observations. MERLIN is a component of the EVN and a stand-alone VLBI array in its own right of up to 7 telescopes with a maximum baseline of 214 km.

An ad-hoc array of Japanese telescopes has been formalised in recent years as the JVN (formerly, J-Net), comprised of 10 telescopes across Japan, with two 11m telescopes complemented by several larger apertures. A key subset of this network is VERA, an innovative array of four 20-m telescopes with a dual feed system that allows simultaneous phase referencing to a calibrator within 2.2 degrees of the target source. The main aim of VERA is the study of proper motions and parallaxes of galactic masers in the 12mm and 7mm bands in order to map out the 3-D structure of our galaxy.

The Korean VLBI Network (KVN), currently under construction, will initially be a three-element array on relatively short baselines, but with a novel beam-splitting capability that will allow simultaneous observations in four frequency bands between 22 and 129 GHz, with separate 2/8 GHz feeds planned for geodetic observations. Integration of the KVN, JVN and Chinese network of telescopes is a goal of the East Asian VLBI Network (EAVN), with the extension of this to the wider Asia Pacific Telescope (APT) network under discussion.

The ATCA and Mopra, together with Hobart, Ceduna, Tidbinbilla and Hartebeesthoek telescopes in the southern hemisphere, played a key role in the Japanese-led VLBI Space Observatory Programme (VSOP). The telescopes participated in General Observing Time (peer reviewed) observations at 1.6 and 5 GHz, with Mopra, Hobart and Hartebeesthoek also making significant contributions to the VSOP survey of ~250 AGN at 5 GHz. The VSOP-2 mission, which offers order of magnitude increases in angular resolution and sensitivity over VSOP, has been approved and funded in Japan, and is aiming for a launch in 2012.

Opportunities will exist in the coming years to co-observe with antennas of the AuScope array, an NCRIS-funded VLBI array of three 12m antennas being constructed for geodetic observations, together with an identical antenna currently under construction in New Zealand. These 12m diameter antennas will initially have co-axial 2/8 GHz receivers and will be able to contribute to astrometric observations to improve the southern grid of phase reference sources, which is a necessity for LBA follow-up of faint transient sources. There are also possibilities of collaboration between Parkes, ASKAP, the Indian GMRT array and Chinese FAST telescope, particularly for observations of red-shifted HI and equatorial pulsars.

Here we seek to identify the scientific areas in which these telescopes are most likely to contribute uniquely to radio astronomy over the period 2010-2015. This document identifies six key areas that are likely to each occupy on the order of 15% of the LBA time over that period. While it is impossible to completely predict the course of science during this period we hope that these encompass the majority of high priority science fields and also allow for the continuously evolving nature of science.

2 Science with the LBA

2.1 Pulsar Proper Motions and Parallaxes

Over 1500 pulsars have been discovered, yet accurately determined distances and proper motions are known for less than 30. Distances are conventionally estimated using a pulsar's dispersion measure and a model for the free electron distribution in the Galaxy. Such models have become more sophisticated with time, but become increasingly uncertain as galactic latitude increases and are unable to reflect small-scale structure in the electron distribution. Accurate distances, determined from measurements of annual parallax, are important in understanding pulsar energetics (as calculation of the spin-down luminosity requires knowledge of the distance) and enable improvements to be fed back into models of the free electron distribution.

Pulsar proper motions are critical for studies seeking to associate pulsars with supernova remnants, and for studies of general relativity with binary systems (as kinematic effects contribute to the observe rate of decay of the binary orbit). Furthermore, measured proper motions and distances enable the "kick velocities" received by pulsars at their birth to be investigated. Multi-epoch LBA observations have a demonstrated capability to address these questions, with approximately one-third of known pulsar parallaxes resulting from LBA observations. There are a further ~20 pulsars for which parallaxes could be measured, and ~100 pulsars for which proper motions could be determined, by the LBA in the 2010 – 2015 timeframe.

As pulsars generally have steeply falling spectra, observations are usually made in the 20cm band. The addition of a 20cm receiver to Ceduna this year will extend the LBA's capability, and the addition of ASKAP will improve both the angular resolution and sensitivity of the LBA in this band.

2.1.1 Why the LBA?

- The majority of pulsars have been discovered with Parkes and so these pulsars are accessible to LBA.
- The DiFX software correlator has demonstrated capability to operate in pulsar gating modes.

2.1.2 Requirements

- Require at least four LBA blocks each including 20cm observations per year.
- Accurate pulsar ephemerides are available from Parkes monitoring.
- VLBI capability for ASKAP (tied array capability, hydrogen maser standard).

2.2 Local Group Galaxy motions

Measuring the motions of local group galaxies is important for an understanding of the age, structure and fate of the local group, a group of about 35 galaxies contained within a 3Mpc diameter. Water megamasers have been used with other information to determine the space velocity of M33: a similar study has measured the proper motion of the local group galaxy IC10. A corresponding study of the LMC with the LBA has recently commenced, and is timely given the recent claims that the Magellanic Cloud system is in only its first orbit around the Galaxy, and fundamental in its ability to independently measure the distance to the LMC.

2.2.1 Why the LBA?

- 22 GHz capability of all telescopes, with a new receiver being added to Parkes this year.
- The LMC is a critical rung on extragalactic distance ladder.
- The LBA is the only VLBI array able to observe LMC and SMC.

2.2.2 Requirements

- Four epochs per year at 22 GHz (for water masers).

2.3 Jet Motions

For many years one of the main areas of study of VLBI has been observations of the apparent motions of the jets of AGN. The early discovery of superluminal motion has confirmed that bulk relativistic motion is common in AGN, with similar observations in Galactic X-ray binaries illustrating that the effect is not limited to AGN. The apparent speeds observed in AGN, up to at least 30c, have long posed problems for magneto-hydrodynamic (MHD) models.

With VLBI moving to high frequencies and (with space VLBI) longer baselines, observations are closing in on the scale on which jet formation, acceleration and collimation can be studied. The ejection of new jet components appears to be correlated with gamma-ray outbursts in AGN, and the precise relationship between these two will be examined in the next few years with GLAST monitoring of AGN. The LBA has a current program, TANAMI, started before the launch of GLAST, to monitor bright EGRET sources at 8 and 22 GHz, which will be expanded in the future to incorporate GLAST-detected AGN.

There is also growing interest in VLBI studies of TeV-gamma-ray sources. The Doppler factors inferred from rapid gamma-ray time variability suggest that superluminal motion will be commonplace in these sources, and yet this is not the case. A number of models, invoking jet deceleration, composition, or opening angle effects have been proposed in efforts to resolve this.

2.3.1 Why the LBA?

- Predominance of Galactic sources in the southern hemisphere.
- LBA provides southern coverage essential to complement northern VLBI capabilities in matching the all-sky GLAST coverage.
- Presence of HESS TeV array in the southern hemisphere.
- eVLBI capabilities allow detection to potentially trigger full LBA follow-up.

2.3.2 Requirements

- Rapid follow-up of galactic sources following high-energy outbursts.
- Higher frequencies for best angular resolution.
- Improved polarization calibration.
- Continued 8, 22, 43 GHz capabilities across the LBA for co-observations with VSOP-2.

2.4 The structure of our Galaxy

Measurements of statistical parallaxes to maser sources provide a means of mapping the structure in our Galaxy. Methanol (6.7 and 12.2 GHz), water (22 GHz), and SiO (43 GHz) masers are best suited to this task, with the latter two the mainstays of the VERA program (described above) to determine positions with 10 micro-arcsecond accuracy, sufficient to measure parallaxes well beyond the Galactic centre. The 6.7 GHz transition of methanol masers is of particular utility in mapping the spiral structure of the Galaxy, as these masers are associated with young, high-mass star formation regions and hence trace the leading edges of the spiral arms. The trigonometric parallax observations of masers spots also yield information about the internal proper motions of the system, in turn providing valuable information on star formation processes.

2.4.1 Why the LBA?

- The LBA is only VLBI array with good visibility of the third and fourth quadrants of Galaxy at high zenith angles (as astrometric accuracy depends strongly on zenith angle).
- Potential collaboration with VERA to offer significant improvement in north-south (u,v) coverage at 22 and 43 GHz (once VERA moves to disk-based recording).

2.4.2 Requirements

- Retaining 6.7 GHz (methanol), 22 GHz (water vapour), 43 GHz (SiO) capabilities.
- Determination of phase reference sources around target masers.
- Multi-epoch observations to disentangle parallax and proper motion effects.
- Accurate correlator model incorporating effects such as solid Earth tides and polar motion.

2.5 Megamaser Cosmology

The discovery of a Keplerian disk containing highly red- and blue-shifted water maser lines in addition to those near the systemic velocity of NGC4258 is arguably the key achievement of VLBI in the last two decades. These observations enabled the binding mass to be accurately measured, and a geometric distance of 7.2±0.5 Mpc to be measured. Megamaser cosmology aims to use similar water megamaser systems to directly measure distances out to 200 Mpc in order to determine the Hubble Constant to better than 3%. Such a measure would be the best complement to cosmic microwave background data to constrain the equation of state of Dark Energy. Significant progress has been made in discovering maser systems analogous to NGC4258, including the detection of southern candidates with the Tidbinbilla 70m. These will require single-dish monitoring to measure the acceleration of gas in the disk, and sensitive multi-epoch VLBI imaging to measure the angular size of the disk, measure the rotation curve, and model radial displacement of the systemic maser features. The phase-referencing techniques used to detect these weak maser features require accurate determinations of background continuum sources, perhaps most readily achieved as part of International Celestial Reference Frame (ICRF) astrometric studies at 2/8 GHz.

2.5.1 Why the LBA?

- 22 GHz capability on all antennas.
- Long baselines to Hartebeesthoek.
- Southern hemisphere coverage.

2.5.2 Requirements

- Sensitive 22 GHz receivers.
- Accurate determinations of telescope positions.
- Accurate determinations of phase reference sources.
- Multi-epoch observations.
- Wide bandwidths for weak continuum phase reference sources.
- On-going single-dish monitoring of megamaser candidates.

2.6 Understanding the Variable Sky

The availability of broadband links between the ATNF telescopes enables eVLBI follow-up of transient phenomena such as gamma-ray bursts, supernovae, objects undergoing outbursts at high energies, and transient phenomena (lasting at least several days) detected in ASKAP's large field of view. Many of these are likely to be faint, and so eVLBI detections will require phase-referencing techniques based upon a finely-spaced grid of reference sources over the sky. The VLBA has invested significant time (ten 24 hour epochs of 2/8 GHz observations for the first VLBA Calibrator Survey) in enhancing the grid of reference sources above a declination of -30 degrees, and efforts to refine the grid at more southerly declinations have recently commenced, using the results of the AT20G survey to identify candidate sources. LBA observations of transients will enable morphological changes in transients to be studied, such as those arising from jet motions, source proper motions, or source expansion.

2.6.1 Why the LBA?

- The LBA is best placed to follow-up ASKAP detections.
- eVLBI capability allows detections which can be used to trigger full LBA follow-up.

2.6.2 Requirements

- Clearly established over-ride criteria on scheduled programs.
- Real-time or near-real-time correlation capability, with improved connectivity to Hobart and Ceduna highly desirable.
- Finely-spaced grid of potential phase reference sources as determined by dedicated 2/8 GHz observations (which would be facilitated by upgrading of the Parkes MARS receiver to dual concentric 2/8 GHz capability).
- Sufficiently accurate positions of transient sources from ASKAP and/or ATCA follow-up at higher frequencies.

3 Scientific priorities for the LBA

All the areas identified above constitute priority areas for the LBA in the 2010 to 2015 timeframe, and the diversity of science now able to be addressed highlights the advances made with VLBI studies in general, and the LBA in particular, over recent years. We can envisage that any ordering of priorities will change with time over the five year period, however some over-riding considerations can be stated: the observations of the LMC and of masers in the third and fourth galactic quadrants can only be carried out with the LBA and should be accorded the highest priority. The variable sky is an unexplored parameter space which will undoubtedly reveal new classes of astrophysical objects which will require VLBI follow-up to help elucidate their nature, and the geographical overlap of the LBA with ASKAP will be critical. Megamaser cosmology is a high-impact field which should be actively pursued, although it is not yet clear how many candidate sources from single-dish observations will prove to be suitable VLBI targets. Pulsar proper motion and parallax observations, which will be enhanced when ASKAP comes on line, and astrophysical jet studies, which will be boosted by the launch of GLAST in June 2008 and the VSOP-2 satellite in late 2012, will continue to address fundamental astrophysical questions and enable key sources (new binary pulsars or flaring gamma-ray sources) to be investigated.

Thus, in order of decreasing priority, the areas discussed in the preceding sections would be ranked:

- The structure of our Galaxy;
- Local Group proper motions;
- Understanding the variable sky;
- Megamaser cosmology;
- Jet motions;
- Pulsar proper motions and parallaxes.

LBA observing in these priority areas, and more generally, will benefit from planned enhancements to the array over the next few years in improving array connectivity, replacing the current DASs, and upgrading Parkes receivers to improve performance and reduce the need for receiver changes. The LBA has a demonstrated capability for remote observing, and also remote recording, and is in the process of addressing issues associated with user friendliness, which will place it on an even firmer foundation for the future.

4 A year in the life of the LBA

A year in the life of the LBA in the 2010 to 2015 timeframe might entail six blocks of 3-4 days spread evenly throughout the year, with observations at 1.6, 6.7 and 22 GHz at all epochs to contribute to the parallax and proper motion studies. Participation in VSOP-2 observations will, as for VSOP, require more frequent observations in ~12 hours blocks by at least some elements of the LBA. Participation in national and international geodetic and astrometric programs will also require "out of session" observing, primarily by Parkes and Hobart due to their 2/8 GHz capability. Rapid follow-up of ASKAP transients or high-energy phenomena will necessitate a clear policy on eVLBI over-rides of scheduled observations and some means of making up lost time for affected observers.