Radio Astronomy Component of the NCRIS Investment Plan

Update Report to support Facilitator National Visits – May 13, 2006.

Introduction:

We are currently on a cusp of a revolution in radio astronomy. At the moment, most radio telescopes consist of large dishes, derived from heavy engineering, which require mechanical steering around the sky. The receivers are cryogenically cooled, highly labour intensive devices capable of producing only a single pixel on the sky. In the future, all this will change. Radio telescopes will consist of thousands to millions of small, cheap elements capable of being steered and combined electronically to provide many thousands of pixels across a very wide field of view. Massive parallel computing will be required and in some sense the system becomes a software telescope. At present, computer power and cost restrict the pure "software telescope" to below about 300 MHz. Above this frequency we still need to build collecting area to focus the radiation but can now provide electronic beam-forming and sufficient computational power to provide wide field of view imaging.

The international radio astronomy community is collaborating to work towards the realization of a next-generation radio telescope, the Square Kilometre Array (SKA), and Australia is playing a leading role in the development of science and technology for the telescope.

In 2005 the Australian radio astronomy community considered and prioritized the various projects proposed for the next decade, as part of the process of production of the Australian Astronomy Decadal Plan 2006-2015. The highest priority project selected for 2006-15 within radio astronomy in Australia is maximizing participation in the SKA (Australian Astronomy Decadal Plan 2006-2015 (2005)).

The radio astronomy community has further resolved that the most valuable contribution that Australia can make to the development of SKA Phase 1 is the construction and operation of a next-generation radio telescope of unparalleled capability, according to the international SKA Reference Design, sited on the radio-quiet zone at Mileura Station in WA. Construction of this Mileura radio telescope is therefore the highest priority radio astronomy project to receive funding under the Commonwealth Government National Collaborative Research Infrastructure Strategy.

Indications are that between AUD35M-AUD50M may be available for astronomy projects from the NCRIS funds. The Australian astronomy community has resolved that 40% of these funds should be available to the radio astronomy sector and 60% of the funds should be available to the optical sector. Thus the radio astronomy component of the NCRIS Investment Plan is being developed for total investment from NCRIS of AUD20M. A contingency plan is also being considered in case only the lower limit of AUD14M is available.

Development of the Plan:

The radio astronomy Investment Plan is being developed by a team of individuals spread across 12 institutions. Team members are:
Frank Briggs (ANU/ATNF), Tim Cornwell (ATNF), John deLaeter (Curtin), John Dickey (Uni. Tasmania), Bryan Gaensler (Harvard/Uni. Sydney), Anne Green (Uni. Sydney), Colin Jacka (CICT), Carole Jackson (ATNF), Simon Johnston(ATNF), Geraint Lewis (Uni. Sydney), Diana Londish (ATNF), Colin Lonsdale (MIT), Mervyn Lynch (Curtin Uni.), Mark McAuley (ATNF), James Murray (Swinburne), Peter Quinn (ESO/UWA), Elaine Sadler (Uni. Sydney), Lister Staveley-Smith (ATNF/UWA), Michelle Storey (ATNF), Tony Sweetnam (ATNF), Rachel Webster (Uni. Melbourne).

An outline proposal was presented to the NCA, and subsequently to a "Town Hall" meeting of the astronomical community at the University of Sydney on April 20. The proposal was endorsed by these meetings, and the team is now in the process of developing an Investment Plan in detail. Below I summarise progress in various areas of the Plan to obtain feedback during the national visits to astronomical institutions scheduled for May 15-19, 2006. The sections below are progress reports, and do not represent Investment Plan summaries. Team members are identified below who have responsibility for particular areas, and who can be contacted for more detailed information.

Summary:

The NCRIS radio astronomy component of the Investment Plan is to construct and operate the Mileura radio telescope, utilising the latest advances in technology to open new windows onto the Universe. The telescope will deliver new science and be an important test-bed for the creation in 2020 of the Square Kilometre Array. The proposal builds on past and current investments to make the next generation of technologies accessible to the Australian and international research community.

As part of the Gemini and SKA Major National Research Facility, the two most important technical questions regarding the Mileura radio telescope have already been answered:

- Large fractions of the Earth's surface are no longer suitable for carrying out exquisitely sensitive radio astronomy observations. The site of Mileura in Western Australia has been characterised for radio quietness and selected as Australia's premier site for radio astronomy. The Western Australian Government and the Australian Communications and Media Authority are in the process of establishing Mileura as a radio quiet zone, future-proofing Mileura's suitability for radio astronomy. The Government of WA has established a Radio Astronomy Park at Mileura and this is the selected site for the Mileura radio telescope.

- Several technologies have been assessed, and the fundamental technology solution has been agreed: parabolic reflectors with focal plane arrays, combined with dipole array tiles for lower frequencies. There is existing investment at the demonstrator level in both these technologies.

CSIRO is leading the development of the technology solution involving parabolic dishes and focal plane arrays, with most input from two Divisions, ATNF and CICT, and other collaborators including the South African SKA team, and the LFD team (see below). CSIRO has provided initial funding of AUD20M to support the development of a demonstrator telescope of 20 dishes at Mileura, the xNTD.

A consortium of Australian universities: (University of Melbourne, University of Tasmania, University of Western Australia, University of Sydney, Australian National University and Curtin University of Technology), along with CSIRO and two USA universities: Massachusetts Institute of Technology and Harvard-Smithsonian Centre for Astrophysics, has secured USA funding (~USD5.5M) and commenced early prototyping for a radio-astronomy instrument at Mileura, the Low Frequency Demonstrator (LFD).

The Mileura radio telescope will build on these initial Australian and international investments to create an accessible integrated telescope that will ensure a lead role in these vitally important future technologies for Australian radio astronomers, engineers and industries. The Mileura radio telescope will provide astronomical observing capability in two high-priority frequency bands for next-generation radio astronomy. Together with already planned developments at the SKA Molonglo Prototype (SKAMP), Australian astronomers will then have access to facilities covering the hydrogen line from red-shift 0 to red-shift 17. This would be the most complete spectral coverage anywhere in the world.

NCRIS funds could enable an increase of a factor of two in the survey speed of the xNTD, to secure science outcomes for the telescope at this frequency range and optimize technology development on the path towards SKA. Upon completion of the LFD and its NSF-funded experiments in 2009, NCRIS funding will enable an extension of the LFD, and incorporation of the LFD into the Mileura radio telescope.

Through progressing establishment of the Australian candidate SKA site and progressing development and industry engagement in two of the leading technologies for SKA antenna systems, NCRIS funds will position Australia to reap maximum benefit from the SKA project in all the areas of site, organisation, technology and science.

Update on Science Case:

The group who have offered to assist with development of the science case for the radio astronomy Investment Plan are: Simon Johnston (coordinator), John Dickey, Carole Jackson, Bryan Gaensler, Lister Staveley-Smith, Frank Briggs, Elaine Sadler. Note that a full Science case for the LFD already exists and will be incorporated into the final NCRIS Investment Plan.

The innovative design and technology of the Mileura radio telescope and the quest for a radio quiet site have been driven by the science imperatives. A number of identified Key Science Projects require that we survey the entire sky to good sensitivity; this is only made possible with wide field of view imaging and the next generation of radio telescopes. The four main science drivers are:

- The evolution of neutral hydrogen gas over 15 billion years of cosmic time
- The origins and evolution of magnetic fields
- A revolution in our knowledge of the transient radio sky
- Characterisation of the plasma driven, magnetic solar wind and its impact on terrestrial satellites

The sections below briefly outline the headline science aims for these four projects. Many other science projects will be enabled with these telescopes. Full science cases will be provided in the final Investment Plan.

Hydrogen line surveys
Hydrogen is the most ubiquitous element in the Universe. Hydrogen provides the fuel which ignites stars and provides a tracer of galaxies in all stages of their evolution and environments. Its most common form is as neutral hydrogen (HI), which is most easily detected through its hyperfine transition line which has a rest frequency near 1.42 GHz. As such, mapping of the Universe in HI remains the domain of the radio astronomer. Furthermore, the shift of the spectral line from its rest frequency allows a direct measure of the redshift of an object without recourse to extra observing.
HI is therefore an amazingly powerful tool for mapping the Universe in both spatial and temporal coordinates.

The Universe has been mapped at redshifts of 1000 through observations of the Cosmic Microwave Background. At this early time, the Universe was largely neutral. Then, between redshifts of 20 and 5, the earliest luminous sources switched on and started to ionize the neutral gas, until, at the present time, almost complete ionization of the intergalactic medium has been achieved. When did the gas become re-ionized? Did it occur suddenly or not? What were the first sources to switch on and how did they ionize the medium?

We know that at redshifts around 2-3, both the gas content and the star formation rate was at least 100 times greater than we see today. Presumably most of the gas present then has been turned into stars but how this occurred is unclear. What drives the evolution of gas? How do galaxies form and interact in different environments?

In the Milky Way Galaxy the gas between the stars acts like the Galactic ecosystem, from which new stars form and into which old stars send much of their mass as they die. The best tracer of this interstellar medium is the HI line, because hydrogen is the most common element in the Galaxy and the most ubiquitous. The Mileura radio telescope will be able to survey Galactic HI emission over large areas of the sky faster and with better sensitivity than any existing telescope.

With the advent of the Mileura radio telescope we can, for the first time,

- determine the epoch of re-ionization through mapping of the HI gas distribution in the very early Universe
- determine the evolution of gas and galaxies at redshifts less than 1 through the detection of 500,000 galaxies in \HI\ emission.
- survey the gas in our own Galaxy to greater depths than previously.

These observations are only made possible with the new generation of radio telescopes. They require a combination of high sensitivity, wide Field-of-View and supercomputing capabilities.

Cosmic Magnetism
Magnetism is one of the four fundamental forces of Nature and understanding the Universe is impossible without understanding magnetic fields. Magnetic fields fill space, they affect the evolution of galaxies and stars and control the distribution of cosmic rays. In spite of their importance the evolution, structure and origin of magnetic fields are all still open questions in astrophysics. Most of what we know about magnetic fields in astronomy comes via the detection of radio emission; in particular determining the rotation measure of an object gives direct information on the magneto-ionic medium through which its radiation travels.

One method of determining the role that magnetic fields play is by detecting many thousands of polarized sources across the sky. By obtaining the rotation measure of these sources, one can then construct a grid containing information on the strength and direction of the magnetic field. To obtain enough sources to develop models requires a telescope capable of observing the whole sky to high sensitivity over a large observing bandwidth. The telescope will therefore

- detect 10 million sources across the sky and obtain the rotation measure for some 60,000 of these to determine the magnetic field structure of the intergalactic medium
- probe the small-scale structure and turbulence in our own Milky Way using a technique known as Faraday tomography.

Pulsars and the Transient Sky

Almost 2000 pulsars are known in our own Galaxy; less than 10% of the potentially detectable total. Large scale surveys for pulsars are required to find the rare and exotic objects which provide the greatest opportunities for physical experiments. Pulsar timing can provide the most stringent tests of strong field gravity and has the potential to directly detect gravity waves from merging black holes in the early Universe. Historically, pulsar searches have been carried out using single element telescopes. The advent of supercomputers, however, means that it is now possible to survey for pulsars using interferometers such as the LFD and the xNTD.

Up until now, virtually all large radio telescopes have very high forward gain (sensitivity) at the expense of a relatively small field of view (less than 1 square degree). As this is such a tiny fraction of the sky, the chances of detecting transient sources are very small. The transient sky at radio wavelengths is thus poorly understood but there are a huge variety of sources which are known to produce transient emission. These include everything from planets and brown dwarfs in our local neighbourhood through to giant pulses, radio supernovae and gamma-ray bursts, the most energetic explosions in the Universe.

The telescope should:

- discover more than 1000 new pulsars, possibly including a pulsar in orbit about a black hole
- radically alter our understanding of the radio transient sky

The Active Sun

The active Sun produces violent events known as Coronal Mass Ejections (CMEs). These CMEs propagate outwards from the Sun and are responsible for space weather and geomagnetic storms which can have malign influence on satellites and communications systems with the potential to cause millions of dollars of damage. Tracking CMEs as they leave the Sun can therefore allow a determination of whether they will impact the Earth and provide an early warning system.

Radio observations can also determine the magnetic field and plasma density fluctuations in the vicinity of the Sun and allow a mapping of the solar wind.

Summary

The science case outlined above is an ambitious and wide ranging one. The science programme is enabled through new and innovative technology located on the world's best site for radio astronomy. This project keeps Australia as world leaders on three fronts; the development of a radio quiet site for radio astronomy, smart feed solutions for wide field of view telescopes and ground breaking and unique science. The radio astronomy community worldwide is building towards the SKA in 2020, the enabling of the Mileura radio telescope will place Australia in the vanguard of this effort.

Update on Strategic Assessment:

The group who has offered to assist with the Strategic Assessment section of the Investment Plan are: Michelle Storey (coordinator), John Dickey, Carole Jackson, Bryan Gaensler, Lister Staveley-Smith, Rachel Webster. Some key points are summarized below and further information will be provided in the Investment Plan.

Evidence that the proposal above optimally satisfies the national requirements for the radio astronomy capability includes:

- The innovative design and technology of the Mileura radio telescope and the quest for a radio quiet site have been driven by the science imperatives. The science case for the Mileura radio telescope addresses Key Science Projects for the SKA, and these projects are those that have been identified internationally as the highest priority science targets for the international community. This ensures high demand from Australian and international researchers, thus increasing links with the global research community.
- Engagement of Australian industry in construction of the Mileura radio telescope will enhance Australian competitiveness for the full SKA. The demonstrable interest in and success of SKA industry cluster, including new contributing members requesting to join the core cluster, is clear evidence for industry interest nationally in development of SKA technologies.
- Development of ICT in WA has been identified by the Government of Western Australia as a priority area for research support. The Mileura radio telescope will provide a superb incubator for innovation in the ICT area, and give WA industries opportunities for development of new technological expertise.
- The Australian Astronomy Decadal Plan highlighted the importance of astronomy as an attractive science, technology and innovation education tool in Australia. The development work required for the Mileura telescope will support research in a very large group of universities throughout Australia, due to the large number of groups actively involved and the range of workpackages available for development of the instruments. The telescope thus will provide inspiration and training in next-generation radio-science and ICT areas for a very wide range of students, providing essential training for future generations of wealth creators for the country
- The Mileura radio telescope puts Australia on the “front foot” in areas of technology, siting, science and organization for maximizing participation in the SKA.

It is also important that the infrastructure bring maximum benefit to the Australian community, be accessible on the basis of merit, and encourage collaboration.

CSIRO has funded xNTD and its incorporation into the ATNF. Access to the existing national facility is completely open to researchers on the basis of merit with peer assessment of proposals. NCRIS funds will expand the xNTD, and integrate it into the Mileura radio telescope, operated as an international facility along similar lines to the ATNF.

USA-NSF funding requires that the MIT-led Low Frequency Demonstrator first demonstrate targetted science outcomes with the proposed 500 tile system. Collaboration in individual science programs is accessible to interested scientists by joining a particular science team. Groups in Australia are already members of science collaborations for the LFD.

Once the key science outcomes specified in the NSF grant have been achieved, NCRIS funds could enable a 100% expansion of the collecting area of the LFD system at Mileura and incorporation of the LFD into the Mileura radio telescope.

Encouraging Collaboration:
The exceptionally wide bandwidth obtainable with the joint facility will encourage collaboration across traditional discipline boundaries, as science will be able to be tackled in ways less limited by wavelength specialities than in the past. Similarly, cross-fertilization across national and technology boundaries is already occurring as joint facility planning occurs. For example, MIT, Uni. of Sydney, and ATNF produced in 2005 a combined White Paper on digital signal processing technologies for the combined facilities.

Both the LFD and xNTD are already attracting further international collaboration on technical developments and science collaborations.

One feature of the Investment Plan is the complementarity of the Mileura radio telescope with the existing SKAMP facility and correspondingly increased collaboration opportunities. SKAMP builds on existing infrastructure, i.e. the large collecting area of 1.6 km Molonglo radio telescope. The new digital signal-processing techniques developed for the SKAMP correlator and filterbanks provide a prototype for use in the LFD. The final stage of SKAMP upgrade planned will provide access to the spectral window from 300-700 MHz, filling the frequency gap between LFD and xNTD and providing unprecedented frequency coverage of any suite of radio astronomy instruments. There are plans to make SKAMP at least partially available in a national facility capacity, and it may be possible to coordinate science programs and observing time allocation between SKAMP and the Mileura radio telescope, thus enhancing science outcomes.

Industry engagement is currently principally through the Electronics Action Agenda SKA Industry Cluster Mapping project and this will be described in the Investment Plan.

Update on Implementation Strategy:

The team involved in the production of the Implementation Strategy section of the Investment Plan is: Michelle Storey (coordinator), Mark McAuley, Carole Jackson, Lister Staveley-Smith.

IP and procurement issues will be consistent with the international SKA protocols. These will be described in the Investment Plan.

Facility ownership, management structure and governance is currently under active discussion. A draft governance document is being constructed to account for the different phases of the project. It is likely that the LFD, while being constructed and operated in campaign mode under the NSF grant will be owned and managed by MIT, under the governance of an LFD Board with significant Australian representation. The xNTD will be owned and managed as a national facility by CSIRO, or an alternative legal entity established to manage the NCRIS funding. Ultimately, the Mileura radio telescope will be managed as an international facility, alongside the ATNF, and with significant governance input by international partners.

Update on Financial Plan:

The team responsible for construction of the financial plan for the Mileura radio telescope is Mark McAuley and Tony Sweetnam (coordinators), Rachel Webster, Colin Lonsdale.

Currently the CSIRO-led extended New Technology Demonstrator telescope has AUD20M funding from CSIRO to work towards a 20-dish/Focal plane array demonstrator facility on the Mileura site. The MIT-led Low Frequency Demonstrator project has applied for ÀUD7M from the US NSF to build a 500 dipole-tile demonstrator facility at Mileura, and is confident that the application for funds will be successful. A consortium of Australian universities led by Rachel Webster from University of Melbourne is applying for a LIEF grant to support Australian university engagement in the early stages of the LFD telescope during the NSF-funded targeted campaigns and construction.

The Financial Plan will include project plans for the extension of the LFD and xNTD, the integration of the facilities into the Mileura radio telescope, creation of the Mileura Processing Centre and additional computing facilities at Geraldton linked by high bandwidth optic-fibre cable to Mileura.

Update on Risk management:

It would be desirable to have an overarching body responsible for NCRIS funds and for tracking milestones against expenditure. This would enable the flexibility to re-direct resources within the radio astronomy area in case of changing priorities for funding. This question is being examined by a Working Group of the NCA as part of the overall NCRIS Investment Plan.

If less than AUD20M is available for radio astronomy developments the proposal above will be scaled back in scope, but not in overall intent. The resulting telescope would be an effective demonstrator of SKA technologies, but would not be as effective as a catalyst for further investment on the Mileura site. It would also not be capable of being operated as effectively as a national facility, as items like software would need to be managed more cheaply and thus would be more difficult to make accessible and to maintain. The project management required to create an integrated, well-coordinated facility would be reduced, threatening the efficient future operation of the facility. The most successful radio observatories - e.g. VLA and ATCA - have made their mark because of the "full service" that they offer. Others such as GMRT and Effelsberg have lagged behind because of this. So the true return from this proposal will come from investing in personnel/software infrastructure as well as in the nuts and bolts. And of course establishing an international facility mode of operation paves the way for the much more complex operational challenges of the full SKA.

Other risk management issues will be addressed in the Investment Plan

Conclusion:

The Australian radio astronomy community proposes that NCRIS resources be directed towards the development of a world-class radio astronomy telescope, demonstrating key elements of the SKA Reference Design, on Australia's candidate SKA site at Mileura Station in Western Australia. The telescope will:

- Secure the future of Australian radio astronomy for the next 20-30 years by creating a unique science instrument with unmatched capability (wide FOV, wide bandwidth) in high-priority science areas

- Be a catalyst for the establishment of the WA site as the best radio-quiet site in the world for radio astronomy, which will continue to attract international investment and collaboration in radio astronomy to Australia
- Secure a continued international leadership role in the SKA project by Australian researchers and industries, in all areas of technology development, organization, science and siting
- Provide critical mass and focus for the radio astronomy pathfinder arrays in the Southern Hemisphere, facilitating coordinated development to ensure continued coherence and momentum for the international SKA collaboration.

A full project plan and business case will be developed for the radio astronomy NCRIS Investment Plan over the next few months. The proposal enables involvement of Australian industries in critical technologies for the SKA, thus maximizing the potential for Australian industry engagement in the full SKA when it is realised.

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