Highlights of the Gemini and SKA MNRF Program

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Summary

The Gemini and SKA Major National Research Facility (MNRF) was set up in 2002 with the aim of providing significant Australian participation in major new optical, infrared and radio facilities, including the twin Gemini 8-m telescopes and the Square Kilometre Array (SKA). With one year remaining (the MNRF concludes in June 2007), this document provides a status report describing the major achievements to date.

1. Access to Large Optical/Infrared Telescopes

Increased Australian access to 8-m class telescopes has been made available as follows:

- An additional 1.43% share of each of the twin Gemini telescopes, bringing the total Australian share to 6.19%.
- An additional 24 nights on the Gemini South telescope over the semesters 2005B, 2006A and 2006B. In semester 2006A, after removal of time allocated to engineering, commissioning, instrument builders, Gemini staff and host countries, this was equivalent to an additional 9.8%. Another 6 nights was also guaranteed to the ANU-led NIFS team.
- An additional 30 nights on the Magellan telescopes. Excluding time allocated to engineering, shutdowns, and the host country, this is equivalent to 2.6% of the science time on both telescopes over the four semesters 2007A to 2008B.

In total, the MNRF program has increased access to 8-m class telescope nights by 80% compared with that originally available over the period 2002 to 2007.

Progress towards Australia's participation in the design of the next generation of telescope facilities beyond Magellan and Gemini was facilitated as follows:

- Funding for an Extremely Large Telescope (ELT) project scientist and deputy project scientist.

Scientific highlights have so far included:

- *Galaxies are bigger than we thought*. Ken Freeman (ANU) and Joss Bland-Hawthorn (AAO) used Gemini to show that the galaxy NGC300 extended out about twice as far as had previously been thought. As a result, it is now believed that most spiral galaxies, including our own, are much larger than previously believed. Standard theories have difficulty explaining how stars form so far out – a new mode of star formation is required *(Bland-Hawthorn, Vlajic, Freeman & Draine 2005, ApJ 629, 239)*.

- *Chasing Gamma-Ray Bursts*. Brian Schmidt (ANU) leads a large international team using both Gemini telescopes to follow-up gamma-ray burst explosions. Gamma-ray bursts are incredibly bright flashes of gamma-rays, coming from half way across the universe. When one goes off, the direction it came from is pinpointed by one of several gamma-ray satellites, and transmitted to the ground. Brian's team then races to pinpoint the source using Gemini, before it fades. Gemini is crucial to this effort because its queue-scheduled observations allow it to respond more rapidly than other large telescopes. This research has resulted in a string of papers in Nature. The biggest triumph to date was the first identification of a short-hard burst, thought to be caused by colliding neutron stars *(Berger et al. 2005, Nature, 438, 988).*

- *Elliptical Galaxies Do Have Dark Matter*. It has long been know that our own galaxy is dominated by the mysterious dark matter. But what about the largest galaxies in the universe - elliptical galaxies? Theory predicted that they too should be dominated by dark matter. But in 2003, a British group sensationally claimed the reverse - that there was little dark matter in these giant galaxies. Using Gemini, Forbes (Swinburne) and collaborators traced the motions of globular clusters orbiting an elliptical galaxy, and showed that dark matter was indeed present. Orthodoxy was restored *(Pierce et al. 2006, MNRAS, 366, 1253).*

- *Mystery of a changing supernova*. The supernova 2001ig had baffled astronomers. This exploding star showed signs of abundant hydrogen in its spectrum immediately after it exploded. But as it faded away, all traces of hydrogen disappeared. This bizarre behavior had only once been seen before. Stuart Ryder (AAO) used Gemini to find the cause - the exploding star had a companion, which probably stripped the hydrogen away from the star that exploded *(Ryder, Murrowood & Stathakis astro-ph/0603336).*

As of June 2006, there were 27 Australian Gemini papers either published or in press in refereed journals.

2. Optical/Infrared Instrumentation Development

The Anglo-Australian Observatory (AAO) and the Australian National University (ANU) have provided substantial MNRF instrumentation development as follows:

- Supporting Australian use of the Gemini telescopes: AAO has provided the back-end support for processing Australian proposals for Gemini time, and instrument scientists to give expert advice to users on optimising their observations and carrying out data analysis.

- Robotic positioning devices: the AAO has developed Starbugs as a dynamic robotic positioning concept for use in future instruments on large telescopes. Starbugs can deploy multiple payloads, such as pickoff optics, optical fibres and other possible devices, with micron-level accuracy over a flat or curved focal plane. This development addressed some of the limitations of other positioning technologies to provide a reliable, highly parallel and cost-effective way of positioning multiple optical payloads in both ambient and cryogenic environments.

- The KAOS and WFMOS instrument studies for Gemini: the AAO initially developed the KAOS concept for an advanced fibre spectrograph for Gemini. This was adopted under Gemini's Aspen instrumentation plan as the Wide-Field Multi-Object Spectrograph (WFMOS). AAO led an international team of seven institutions in a feasibility study for WFMOS, which resulted in WFMOS being rated as one of the high-priority next-generation instruments for Gemini.

- Ultraviolet and infrared photonic fibres for astronomy: the AAO has investigated the use of new types of optic fibres for astronomical applications. New materials allow fibres to operate at ultraviolet and infrared wavelengths, while micro-structured fibres offer new ways of controlling light within astronomical instruments.

- OH-suppression fibres: AAO has developed a revolutionary new technology for suppressing the atmospheric hydroxyl (OH) emission lines that dominate the near-infrared sky background. Prototype devices have demonstrated that these OH-suppression fibres can reduce the sky background by factors of 20 to 30 in the near-infrared, which will vastly enhance the power of ground-based instruments in this important part of the spectrum.

- The Near-Infrared Integral-Field Spectrograph (NIFS), which was rebuilt by the ANU following the January 2003 Canberra bush fire, was commissioned on Gemini North in October 2005, and scientifically verified in February 2006. This instrument is designed to give detailed spectroscopic information (resolving power 5000) of objects over a region of size 3 arcsec x 3 arcsec at a superb angular resolution of 0.1 arcsec, when used with the Altair adaptive optics system. The wavelength range is 0.95 to 2.4 microns. It is particularly useful for studying the motions of gas around optically obscured, massive black holes in active galaxies.

- The ANU's Gemini South Adaptive Optics Imager (GSAOI), which has recently been completed, is shortly to have an acceptance test. It is designed to work with a Multi-Conjugate Adaptive Optics (MCAO) system to provide HST-like resolution from the ground at wavelengths between 1 and 2.5 microns over a large field of view (85 arcsec).

These instruments and instrumentation developments have enhanced Australia's reputation for building world-class instrumentation for optical and infrared telescopes, building the way for scientific discovery and future instrumentation contracts.

3. Compact Array Broadband Backend (CABB)

The Compact Array Broadband backend is an upgrade to the Australia Telescope Compact Array (ATCA), designed to increase its bandwidth by a factor of 16, and its sensitivity by a factor of up to 4. This will begin to come on-line as a common-access user facility for Australian scientists from July 2007. The technology is similar to that which will be employed on the SKA. Key successes to date have been:

- Successful commissioning of a prototype spectrometer on the 22-m Mopra millimetre-wave telescope; this increases the available bandwidth to 8 GHz, substantially increasing the number of molecular lines that can be simultaneously observed, and boosting the productivity of the telescope. This facility is already available as an open-access user facility.

- Successful design and construction of a sampler and data transmission system. Sampling is done at 4 Gsample/sec, with each sample consisting of up to 10 bits; the resulting data stream of 40 Gbps has successfully been tested over 4 km of optical fibre.

- Successful design, layout and construction of the final CABB board. This board has 26 layers and consists of 10 Field Programmable Gate Arrays (FPGAs). It is similar to the successful Mopra spectrometer, but more powerful due to the correlation and high dump rate (pulsar) capabilities.

The development of the technology used in CABB has had an important international impact on SKA design. Currently, the SKA precursor facility, the xNTD, plans to use CABB boards for correlation purposes.

4. SKA Molonglo Prototype (SKAMP)

The University of Sydney has led a project to upgrade the Molonglo Observatory Synthesis Telescope, using technologies relevant to the SKA. This project will result in a user facility at the end of the MNRF. Key successes so far have been:

- A 96-station continuum correlator completed and running. Final calibration modes and commissioning in progress. This provides a second signal pathway, parallel to the operation of MOST for validation purposes. Correlator design based on programmable logic chips (FPGAs) - used as basis for next stage correlator.

- Spectral line correlator fully designed - layout complete. This will be a 100 MHz BW system, with 6000 channels, 6 sec integration cycle, with flexibility to change. Data rates expected at 0.5 GB/s from 24 boards through ethernet connections. Software being written.

- Optic fibre network for digital signal transport laid. Splicing of glass fibre about 50% complete. LO circuits designed, prototype being tested.

- Test bay for evaluation of feed module and re-meshing tests is nearing mechanical completion. Systems have been designed for support and drive mechanisms. Engineering certification imminent.

- Prototype feed module delivered for testing and mounting. Optimum design requires close mounting of first line LNAs (more than 6000 required). LNAs designed, awaiting prototype completion. Analogue beamformers designed - 2 stages required. This prototype feed (650 - 1100 MHz) has been range-tested in Sydney.

- Main receivers designed. No cryogenics. Prototype board under test.

- New synergies with engineers working on the LFD and xNTD projects as well as at the University of Tasmania.

SKAMP developments have had important international impacts: the MIT-led Low Frequency Demonstrator (LFD) plans to use the SKAMP design for its own filterbank; the SKA precursor telescope, xNTD, plans to use SKAMP technology for focal plane array beam-formation.

5. Software Correlation and Simulations for the SKA

A group led by the Swinburne University of Technology has led a project using supercomputers to further develop SKA technologies and to provide user facilities. Key successes have been:

- A ~300 processor Beowulf cluster supercomputer deployed at the Hawthorn campus of the Swinburne University of Technology, 30% dedicated to SKA research; a 32 node Beowulf cluster deployed at the Parkes radio telescope to process data from pulsar timing observations; and a 16 node Beowulf cluster deployed at the Australia Telescope Compact Array to process data from radio frequency interference, pulsar timing, and very long baseline interferometry observations (VLBI).

- Development of a new disk-based recording system for VLBI observations, forming the basis for the upgrade of the Australian VLBI array, in collaboration with CSIRO. The new disk-based system records data at 1 Gbps at the ATCA, Parkes, and Mopra and 512 Mbps at Hobart, Ceduna, and Tidbinbilla. This compares to the maximum data rate of 128 Mbps for the S2 tape-based system that the disk-based system replaces.

- Development of a software correlator that runs on the Swinburne supercomputer and naturally interfaces to the new disk-based recording system. The software correlator handles high data rates and is particularly flexible in the time and frequency resolution that can be produced. The correlator naturally interfaces to other disk-based recording systems such as the Mark5 and K5 systems, making global VLBI experiments that involve Australian telescopes straightforward to correlate. The first global VLBI experiment using the software correlator and disk-based system in April 2004 used Australian, South African, USA, and Japanese telescopes and recorded three different recording formats *(Horiuchi et al. 2006, ApJ, in press)*.

- The software correlator and disk-based recording system made available as part of the Australia Telescope National Facility in 2005; it has since been heavily oversubscribed. The first data released from the correlator as part of a National Facility took place in June 2006 and CSIRO is now contracting Swinburne to provide correlation services using the software correlator for the two year period 1 October 2006 - 30 September 2008.

- Resulting from the success of the software correlator, an ARC Discovery proposal was funded in 2005 for support a study of weak, compact radio emission in the nearby Universe. A postdoctoral position funded from this grant will work out of Swinburne from 2006 – 2010. Further, an ARC LIEF proposal has been submitted for 2006, in order to extend the availability of the software as a National Facility.

- The Swinburne software correlator has been chosen as the correlator for a proposed Australian geodetic VLBI array, submitted as part of the geoscience NCRIS proposal for important national scientific infrastructure. The US National Radio Astronomy Observatory (NRAO) is also considering the Swinburne software as the basis for an upgrade of the VLBA. This demonstrates strong national and international impact of this MNRF-funded development.

- Leading from the development of the disk-based recording and software correlation systems, a new collaboration has been initiated with the Auckland University of Technology in New Zealand. In response to this, AUT started the Centre for Radioscience and Space Research. The collaboration aimed to extend the Australian VLBI array across the Tasman to New Zealand, extending the maximum baseline. Thus far AUT and Swinburne have developed a proof of concept system based on a 6 m telescope near Auckland. In 2005 the first successful VLBI observation was done between Australia and New Zealand.

New Zealand is now a member of the Australasian SKA consortium and the International SKA Project. The MNRF project at Swinburne has helped New Zealand radio astronomy to get off the ground, with large potential benefits for Australia.

- The initiation of collaborations between Swinburne, CSIRO, and the University of Western Australia, with regard to supercomputing and software correlation. This has led to work contributing to the Australian eVLBI project, whereby telescopes across Australia will be connected in real-time via high speed fibre optics, with the data correlated in software.

- Dr. Tingay was appointed as Chair of the International SKA Project Simulations Working Group and Configuration Simulations Task Force. These working groups and task forces reported to the Director of the International SKA Project Office and the International SKA Steering Committee and formally advised these bodies on issues regarding SKA configuration issues and the international siting competition. Also, through the MNRF project, Swinburne is now a full partner in the EU FP6 SKADS (SKA Design Study) project, aimed at an end-to-end SKA design study. Swinburne is providing supercomputing and simulations expertise.

6. New SKA Receiver Technology

New SKA receiver technology is being developed via the New Technology Demonstrator (NTD), which is an interferometer test-bed based in Sydney, and the Monolithic Microwave Integrated Circuit (MMIC) project which has the goal of producing low-cost, high-performance receiver devices for the next generation of telescopes. The NTD is the technology prototype for the extended NTD (xNTD), which is an SKA precursor telescope capable of producing world-class scientific results. Key outcomes of the NTD and MMIC projects have been:

- Development of a prototype Luneberg Lens: this alternative antenna technology was found not suitable for SKA purposes, but nevertheless led to patenting of a new material with significant commercial applications.

- Installation and commissioning of the NTD 14-m antennas at ATNF headquarters in Sydney; these ex-Fleurs antennas are similar in diameter and focal length to the currently favoured SKA design. The first fringes from the NTD interferometer were obtained in June 2006.

- Acquisition and testing of an 8x8 THEA tile from ASTRON. This tile is serving as a useful test of Focal Plane Array (FPA) technology, prior to the realization of the design and construction of an MNRF-funded array.

- Development of 85-115 GHz and 30-50 GHz Indium Phosphide MMICs for National Facility use on the Mopra telescope and Compact Array. The Mopra receiver is already in use and the Compact Array receivers (the 7 mm band) become available in 2007 as part of an ATNF contract with NASA.

- Development of a ‘Receiver-on-a-chip’ using RF-CMOS technology; these chips, which became available for testing in July 2005, are critical for the cheap mass-production of devices for Focal Plane Arrays, or small dishes.

7. SKA Siting

A key element in developing an Australian SKA proposal has been the selection of a suitable site, free of radio frequency interference (RFI). Such a site has been identified at Mileura Station, near Meekatharra in Western Australia. Progress in the development of the SKA site proposal has been:

- Deployment of a radio interference trailer at Mileura. This trailer successfully gather RFI data for 12 months, which was later processed and submitted to the International SKA Steering Committee as part of Australia’s siting submission.

- Top science ranking for the Mileura site for the LOFAR project. Dutch funding considerations eventually forced the telescope to be located in the Netherlands. Nevertheless, the derivative MIT-led Low-Frequency Demonstrator has chosen Mileura as its site of choice; LFD has just received $6M of funding from the US National Science Foundation.

- Development and submission, as part of the Australian siting submission, of an SKA configuration using the log spiral formula specified by the SKA simulations working group.

- Submission, in 2006, of the Australian bid to site the SKA. This bid is currently being assessed by the International SKA Steering Committee and expects to make an announcement in late-August 2006.

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