Technology developments

MNRF program

Overview

The ATNF, together with the University of Tasmania, has embarked on a set of substantial projects under the Commonwealth Government's Major National Research Facilities (MNRF) program, governed by a contract signed with the Government in February 1997. The contract provides $11M to:

- **upgrade** the Australia Telescope Compact Array to work at high (millimetre-wave) frequencies;
- **extend** the VLBI capabilities of both the ATNF and the University of Tasmania, and operate the University's Hobart and Ceduna observatories as national facilities;
- **extend** international collaboration in astronomy, with funds administered by the ATNF, acting on advice from the Australian Academy of Science's National Committee for Astronomy; and
- **perform** strategic research on mitigating radio frequency interference and on array technology for the next generation of radio telescopes.

Each of these projects has sub-components, which are described below. The choices involved in determining the content of the upgrade were made after extensive consultation with the ATNF's user community. Full details of the MNRF program can be found at www.atnf.csiro.au/mnrf/.

The upgraded telescopes of the ATNF and University of Tasmania will give Australian astronomers important new observational tools. In particular, the millimetre-wave upgrade of the Compact Array, to be completed in 2002, will give astronomers their first chance to image the signature emission from many cosmically important molecules active in southern hemisphere regions. The upgraded array will be able to work in a "tied-array" mode, which will give it a collecting area equivalent to a 50-m diameter millimetre-wave dish — an unusually powerful instrument.

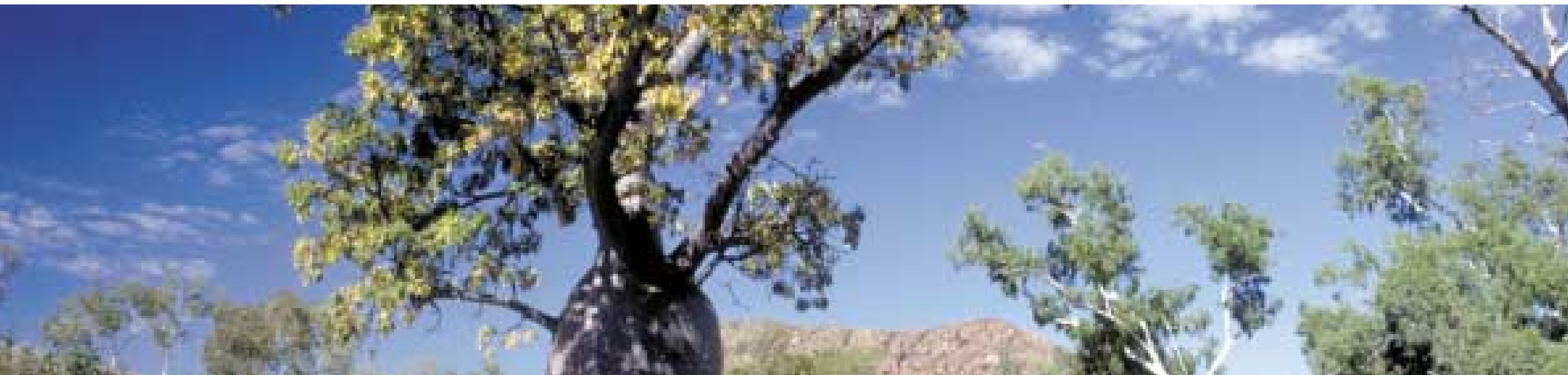
Management of the MNRF program

The ATNF Director acts as MNRF Program Director, while the ATNF Steering Committee provides policy advice and reviews an annual report on its progress. A second, external, committee advises on technical aspects of the upgrade. Committee members are listed in Appendix C.

In September 1999, a sub-group of the ATNF Steering Committee made a formal mid-term review of the MNRF program. Their report found that most of the MNRF projects involved were making excellent progress and were keeping to time and budget estimates.

ATNF MNRF upgrades and extensions in 2000

Good progress continues to be made in the high-frequency upgrade of the AT Compact Array (ATCA) at Narrabri. This



extension adds two new observing bands to the ATCA: 12 mm (16–25 GHz) and 3 mm (85 to >95 GHz); it also increases the maximum angular resolution of the Telescope by an order of magnitude. A major milestone was reached in November 2000 with the first southern hemisphere observations of the upgraded array at 3 mm, taken using two antennas (page 16). While considerable efforts are being used for system testing and commissioning, the success of the first millimetre observations highlights the excellence of the MNRF engineering. It is expected that the full mm-wave systems will be first offered for scheduled observing in 2003.

ATCA high-frequency upgrade

The 12- and 3-mm receivers are a key component of the high-frequency upgrade. An important feature of the high-frequency receivers is that they use MMIC (monolithic microwave integrated circuit) technology in the low-noise systems. In 1999 a decision was made to use Indium Phosphide (InP) MMICs for both the 12- and 3-mm receivers, rather than the Gallium Arsenide (GaAs) MMICs originally proposed for the 3-mm receiver. The InP MMICs will greatly increase the sensitivity of the array.

The high-frequency receivers are contained in a single multiband dewar, with the CSIRO-designed low-noise amplifiers operating at physical temperatures near 20 K. A substantial technology development program has resulted in the ATNF now having the capacity to reliably bond wire connections to the tiny integrated chips and to mount the devices in precision metal housings. Laboratory tests of packaged, cooled, 3-mm amplifiers show typical amplifier equivalent noise temperatures of 55 K at 86 GHz. When used in the test interferometer at Narrabri, system temperatures of approximately 270 K were obtained. At 12 mm, amplifier equivalents of 20 K were measured in the laboratory, and telescope system temperatures of around 100 K were recorded. Interferometer test arrangements were sub-optimal, especially at 3 mm, and system temperatures of less than 200 K at 86 GHz are expected with final (higher gain) designs and average winter observing conditions.

ATCA surface extensions

Five of the ATCA antennas have been resurfaced with solid panels over their full 22-m diameter, doubling their sensitivity at 100 GHz. The antenna panels were adjusted in 1999 and measured to have an

Les Reilly, a member of the ATNF receiver group, working on a newly installed millimetre-wave receiver package.

averaged rms surface accuracy of 0.25 mm.

During the 3-mm interferometry in November 2000, typical antenna efficiencies were still rather low and a pronounced coma lobe was evident in the beam patterns. However, subsequent adjustment of the antennas has led to improved efficiencies and clean beam patterns. At present, the overall antenna efficiencies are approaching 40% at 86 GHz, close to that expected with the originally specified surface accuracy of 0.15 mm.

Atmospheric phase correction

A phase-correction system will be used to correct the wavefront (and hence image) distortion caused, at millimetre wavelengths, by moving cells of atmospheric water vapour. The phase correction system will use a room-temperature four-channel radiometer on each antenna, designed to detect water-vapour emission while rejecting spurious emission from clouds or other sources.

Two prototype water-vapour radiometers have been delivered by Astrowave P/L: these four-channel 22-GHz units were developed in consultation with ATNF engineers and system scientists. The intention is to sense water-vapour emission from the atmosphere, and to use the measurement to correct the image-distorting effects of water-vapour irregularities. First indications are that, while the off-axis optics arrangement will work well, the instrumentation itself requires refinement before further orders are placed. Long-term stability is excellent, but flicker noise in the present high-gain 22-GHz system means that one-second radiometric limits are an order of magnitude too high for satisfactory phase correction. Modifications to the prototypes are currently underway and further tests will be conducted in April 2001.

ATCA local oscillator distribution

The local oscillator (LO) in a synthesis telescope is the master reference signal to which all receivers are frequency-locked, and against which variations in signal phase (caused, for example, by structure in cosmic sources) are measured. The LO distribution must therefore be extremely stable. The new ATCA LO distributor is based on a "star" topology fibre-optic network which uses an optical fibre connection from each of the antenna station posts to the Control Room. Despite weather-related delays, almost all the new fibre has now been installed. However, because of staff changes and accidental damage to a fibre termination facility, the termination schedule has fallen behind the original estimates. While the new LO system will become progressively available for use in test observations, the estimate for completion of the entire system is now June 2002. Field tests of the new LO system indicate that the design specification of

Mark Leach helping with the cable laying for the local oscillator systems at Narrabri. This task involves threading 34 km of optic fibre through the Compact Array cable trenches.

less than five degrees phase jitter at a frequency of 100 GHz will be achieved.

Extra stations and the north spur

Under the MNRF program, four new stations have been built on the east-west track of the Compact Array, to give better short-spacing coverage. Extra funding from the CSIRO Capital Investment program has enabled the construction of a further five stations on a north spur line, 214 m long. This spur will let the array better cover the u-v plane when observing with high antenna elevations; these minimize atmospheric distortion at millimetre wavelengths.

The civil engineering component of these projects was completed in 2000 and, while delays have been experienced at Narrabri in cabling all stations, the new facilities will be available concurrently with the completion of the LO distribution system.

Antenna Control Computers

The stringent demands of high-frequency observing, the expansion of ATCA control and monitoring requirements, and concerns about the reliability of the present Antenna Control Computers (ACCs), have combined to make delivery of new-generation ACCs a priority.

Work has continued for some time to develop object-oriented software to run in the new computers. Development work has also begun on the hardware interfaces between antenna systems and input/output devices in the new computers. Due to some delays in the ATOMS project, mainly associated with staff changes, the new ACCs are expected to be installed by mid-2001, about one year later than originally forecast.

The Australian VLBI array

The MNRF program provides for VLBI upgrades to the ATNF antennas at Mopra, Narrabri and Parkes and the University of Tasmania's antennas at Hobart and Ceduna. The ATNF upgrade of the Australian VLBI network is now complete and the extended network is in routine astronomical use. Figure 29 is an example of the use of the network to probe Centaurus A, a well-known southern radio galaxy.

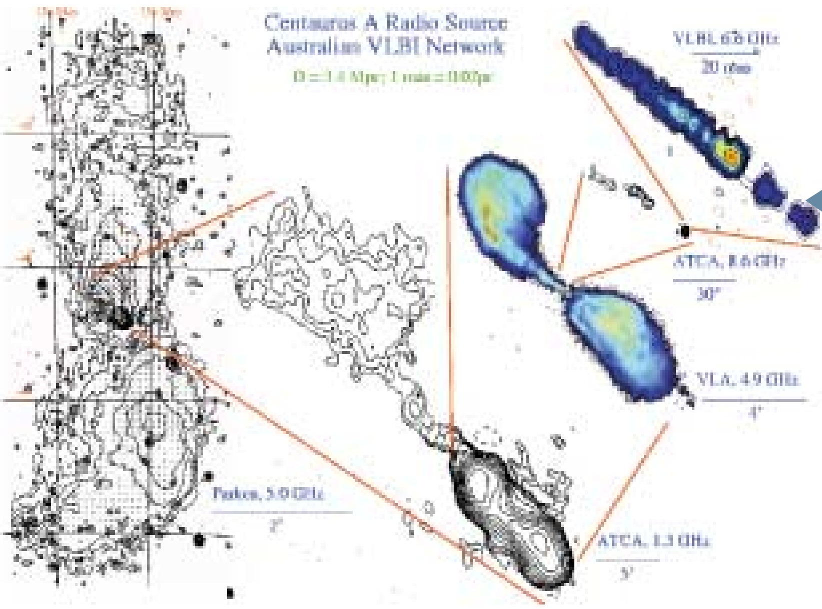


Figure 29 *Images of the radio galaxy Centaurus A obtained using progressively increasing angular resolution. The highest resolution image (right) shows the "jet" of the galaxy and was produced using the Australian very long baseline interferometry (VLBI) array, incorporating the newly commissioned Ceduna antenna operated by the University of Tasmania. The VLBI array has been upgraded substantially in the course of the MNRF Program, with most of the upgrade activities now being complete.*

Technology developments

International collaboration

The MNRF program funding included an allocation of $1.26M for international collaboration. Under this scheme the Australian Academy of Science's National Committee for Astronomy allocated funds for ten projects in 1997 and a further two projects in 1998. Funding for this program is now essentially exhausted and no additional funds were allocated to new projects in 1999 or 2000. Details of the funded projects can be found in the MNRF annual reports, available on the ATNF Web pages.

Executive Special Project

In December 1997 CSIRO's Chief Executive Officer, Dr Malcolm McIntosh, announced a number of projects to be undertaken by large research teams within CSIRO in the 1997–2000 triennium. One of these projects was a joint proposal of the ATNF and CSIRO Telecommunications and Industrial Physics to develop millimetre-wave integrated circuits for radio astronomy and telecommunications. About $2.4M was granted for this work. Devices to be produced under the program include monolithic microwave integrated circuits, a high-speed two-bit sampler and a digitiser with photonic inputs and outputs.

Monolithic microwave integrated circuits

Indium Phosphide (InP) MMICs will be produced for three frequency ranges: 85–110 GHz, 30–50 GHz and 16–26 GHz. The US foundry TRW delivered the first InP high electron mobility transistor (HEMT) wafers in December 1999. Following successful on-wafer tests, the wafers were returned to TRW for dicing in early 2000. The individual chips were then returned to ATNF in August 2000 and bonded and packaged by ATNF staff. The 3-mm and 12-mm InP MMICs were retrofitted to two prototype receivers on antennas 3 and 4 on the Compact Array in November 2000. Both the system temperatures and bandwidths achieved were outstanding. The final foundry run for production numbers of these circuits will take place in late 2001.

A high-speed two-bit sampler (digitiser)

Digitisers sample the radio frequency down-converted from an antenna to produce a coarse digital signal for processing inside a correlator. Leading

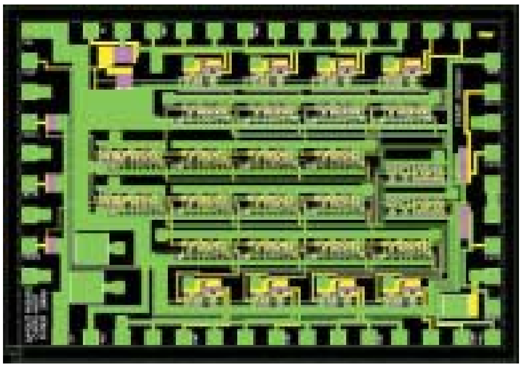


Figure 30 *The circuit layout for a high-speed two-bit digitiser with an integrated demultiplexer, designed by CSIRO to sample astronomical signals at up to eight Gigabits per second. The integrated circuit has a size of 3.2 mm x 2.2 mm.*

digitisers sample at a rate of about two Gigabits per second. To improve on this performance integrated circuits need to be

Photograph
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used, to avoid the parasitics and delay and matching problems that are inherent in discrete components. Several different kinds of digitiser have been designed, the most ambitious of which is a two-bit digitiser with integrated demultiplexer, designed to work at up to eight Gigabits per second. This was implemented in a developmental (not commercially available) InP heterojunction bipolar transistor (HBT) technology.

The HBT designs were completed at the end of March 2000 and submitted to the foundry shortly after, with the fabricated chips being received in mid-October 2000. On-wafer tests of the digitiser were then performed with encouraging results up to at least 10 Gigabits per second. The wafers were returned in late December and work will now proceed on packaging and system integration of the devices, which will allow their performance to be assessed in-system with inputs as expected in typical astronomical use, and hence the real useful speed of the devices to be determined.

A digitiser with photonic inputs and outputs

This device too was fabricated with InP HBT technology, which allows photo-receiver circuits to be integrated with the digitiser. The sampling clock output is delivered by optical fibre and the digitiser's output fed back to fibre via externally bonded laser diodes. This arrangement produces very low radio-frequency interference emission and is an obvious cost-saving pathway for applications such as the Square Kilometre Array.

On-wafer tests for this photonic I/O digitiser were also successful in showing correct operation up to the two Gigabits per second limit determined by the optical source. As indicated before, the wafers were returned in late December. A few test devices will be packaged and placed in a demonstrator system that will initially be sited at Parkes, making use of optical fibres recently installed to the focus cabin.

The Square Kilometre Array

The ATNF is one of a consortium of major radio astronomy institutions in seven countries now planning the world's next-generation large radio telescope, the Square Kilometre Array (SKA). This instrument's one million square metres of collecting area will make it 100 times more sensitive than the best present-day instruments: this area will be distributed across perhaps 2,000 km in a location yet to be decided. Using a combination of technologies, the SKA will cover frequency ranges from 150 MHz to above 10 GHz. Construction of the instrument is expected to start by 2010. The SKA has been identified as the ATNF's major long-term project. A current priority is to secure long-term R&D funding, preferably extending beyond the international technology and site decisions date of 2005.

Technology developments

SKA steering committee

An important milestone in Australian SKA work was reached in late 2000 with the formation of the Australian SKA Consortium, a 14-member steering committee constituted from CSIRO, other research organizations, industry, science policy bodies and professional organizations. The first meeting of the Consortium is scheduled for February 2001 and will include a one-day astronomy and engineering science workshop.

SKA meeting

An international symposium on “Technical pathways to the SKA” was held at Jodrell Bank (UK) in June 2000. The Australian SKA work was well received. A number of oral presentations and poster papers highlighted work in all of the areas outlined in this report and the conference provided a reference against which to check the quality of the ATNF work and the effectiveness of our strategic directions. CSIRO program members will continue to play significant roles in the governance and direction of the international SKA project; these members include R. D. Ekers (Chairman, International SKA Steering Committee), B. MacAThomas (Site Selection Committee) and P. Hall (Engineering and Management Team).

Research program

In late 1999, CSIRO made a $1.5M allocation to the radio astronomy sector for strategic development of the SKA. The SKA research program provides a framework for the coordination of all SKA work. The primary program aims are to:

- produce engineering prototypes of key SKA systems;
- explore the possibility of the SKA being sited in Australia;
- support SKA research by young engineers and scientists; and
- raise public awareness of the international SKA project.

More specifically, the program will include:

- prototyping of a three-dimensional radio lens antenna which will allow many simultaneous, randomly placeable beams on the sky;
- prototyping of an integrated receiver using CSIRO monolithic microwave integrated circuit (MMIC) technology;
- development of radio-frequency interference mitigation techniques and components;
- characterization and testing of potential Australian SKA sites, including the confirmation of possible sites as radio-quiet zones; modelling of different possible array configurations;
- collaboration with other CSIRO divisions and universities on a range of science and engineering issues; and
- liaison with the Australian Government and with international groups on policy issues.

Technology developments

Major projects in the past year have involved work in four areas: antennas, interference mitigation, array configurations and site studies. The antenna work is being undertaken mainly by CTIP staff, with input from the ATNF in framing prototyping and evaluation strategies. In the interference mitigation area, collaborations with US and Dutch colleagues have grown rapidly and have been important in producing impressive early results. Cooperation with the WA Government has been central to framing first-round site and associated outreach projects. For more information about Australian SKA project work, refer to http://www.atnf.csiro.au/SKA

Antennas for the SKA

The SKA specifications call for many simultaneous, widely separated beams. Building antennas which are capable of efficient operation over a wide frequency range, and which yield many beams placeable over the whole sky, is a formidable challenge to designers. CSIRO work is currently assessing the feasibility of spherical refracting antennas (Luneburg lenses) for the SKA application. Cost and loss issues make the refracting solution viable only if new ways of producing artificial dielectrics can be found. Following a number of discussions with materials and manufacturing specialists, small-scale cross-CSIRO projects are now in place. The intention is to produce a range of prototype dielectrics using various processes, including a new chemical technique. In parallel with the materials study, the development of electromagnetic design and analysis software, based on a finite difference time domain formalism, is continuing. If the materials issues are resolved, the intention is to design and fabricate a 3- to 5-m diameter lens by June 2003. A recently established collaboration with Russian radio astronomers and their commercial partner should give CSIRO a demonstration 0.9-m diameter lens by mid-2001.

Interference mitigation

To meet its scientific objectives, the SKA will need to observe outside the narrow bands reserved for radio astronomy. As part of the SKA research program, the ATNF is actively involved in the development of both pre-correlation and post-correlation interference-mitigation techniques.

The ATNF has made extensive use of its "software radio telescope" concept to develop and test interference mitigation algorithms on real data. Using the S2 VLBI system, signals (astronomical and interference) have been recorded coherently from the Parkes radio telescope and individual elements of the ATCA. These recordings have been distributed internationally to several groups interested in new signal processing techniques and, using workstation and super-computer facilities in Australia, it has been possible to experiment with, and evaluate, a number of different approaches. In common with most other groups, initial ATNF work involved coherent adaptive processing. However, new techniques have been developed which invoke post-correlation analogues of the adaptive process, vastly reducing the computational load and making interference mitigation testable, for the first time, on real telescopes (Figure 31). The emphasis is now on evaluating the effectiveness and robustness of the technique using the ATCA and, over the next two years, on making interference mitigation tools available to observers.

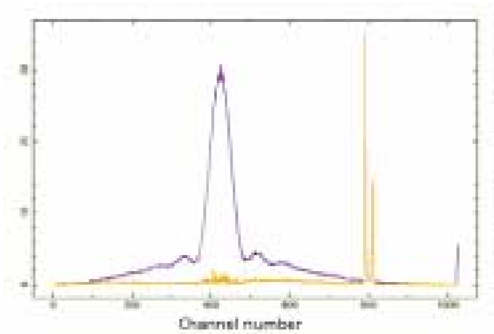

Figure 31 *A post-correlation approach to interference mitigation showing the effectiveness of the technique in suppressing a spread-spectrum satellite signal (centred at channel 420) while leaving an OH-maser source (centred at channel 800) unaffected. The horizontal axis is labelled in ATCA correlator channel numbers over an 8-MHz bandwidth and the vertical axis is an arbitrary linear scale.*

In a complementary interference mitigation study, a research contract with the School of Information and Electrical Engineering at the University of Sydney has produced interesting proposals for incorporating photonic filters into analogue optical-fibre signal transmission systems — potentially useful in the SKA and several present-day telescopes.

Array configurations

At this early stage, SKA designers are studying optimum ways of distributing the one square kilometre of collecting area. In 1999 an initial ATNF investigation of possible SKA array configurations began with the characterization of antenna distributions and u-v plane coverages for a large number of possible configurations. (The u-v plane coverage of an array is related to the image quality that can be achieved). These configurations included random, gaussian, Y-shaped, ring and spiral-shaped arrays of various types. The requirement for both high-brightness sensitivity and good u-v coverage on all scales led to the selection for further study of a close-packed central site, combined with a logarithmic spiral as the best compromise. Sample configurations of VLBI-scale spirals that span the Australian continent have also been generated.

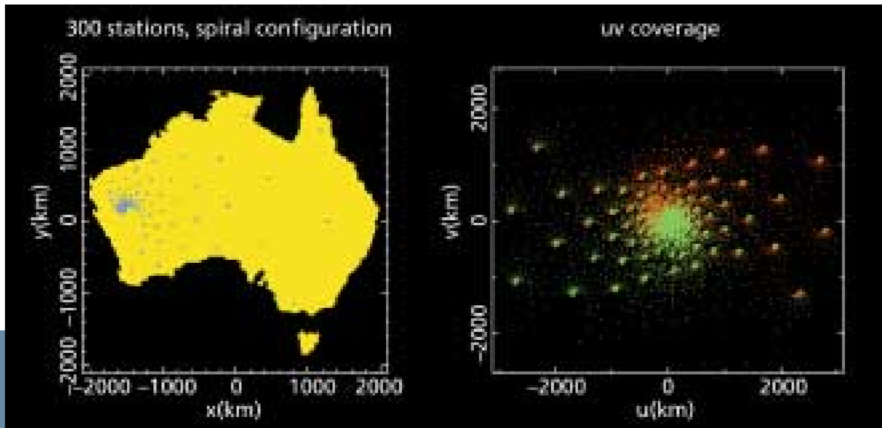

Figure 32 *A possible SKA configuration. The configuration is a combination of a hexagonal central site close-packed with stations and a seven-armed spiral going out to VLBI distances. The total number of stations is about 300 and the effective area per station is 3,300 m^2. Out to about 1,000 km the array has fairly uniform snapshot u-v coverage. To cover the range from 1,000–3,000 km integrations of about 9–12 hours will be needed for optimum u-v coverage.*

While this project has been a small-scale one, it has produced some important insights into array layout principles. As an example, Figure 32 shows a multi-arm "log-spiral" configuration using 300 stations. This configuration yields the required high brightness sensitivity on arcminute scales, good instantaneous u-v (snapshot) coverage to 300 km, and effective coverage on VLBI scales with some time integration. It also produces good synthesised beam patterns and is relatively economical to connect using optical fibre or other media.

Site investigations

While most efforts in this area have centred on formalizing a joint approach with the Government of Western Australia (WA) to evaluate sites in that state, there has also been interest from South Australia and other states in hosting the SKA. In the case of WA, first-round investigations have narrowed the field to two or three promising sites. Contractors funded by the WA Government will begin radio frequency interference characterization around April 2001 and CSIRO will evaluate and present the results. As well as the investigative project, an outreach project aimed at local government and rural communities has also been developed; this promises to be generally useful within Australia. It is important to note that, as well as characterizing specific sites, the CSIRO project is a case study aimed at contributing important principles and guidelines to the international SKA site search. Running in parallel with the site project has been a smaller project to investigate the merits and practicalities of a radio-quiet reserve — an apparently feasible concept in rural Australia and one which could, if implemented, be influential in attracting the SKA to this country.

Integrated RF systems – A new project

From the beginning of 2001, a fifth project will be incorporated into the CSIRO SKA program. Central to the success of the SKA will be low-cost, broadband, low-noise, receivers – probably integrated with feed assemblies and perhaps supporting optical fibre interfaces. With CSIRO's rapidly growing expertise in monolithic microwave integrated circuit (MMIC) design, it is a natural progression to apply this technology to the SKA. The intention is to combine the requirement for a high level of integration with ideas for making "robust" systems able to operate linearly in the presence of man-made interference. Using the mechanism of a shared postdoctoral appointment, much of the expertise generated will be shared with selected honours and postgraduate students at the University of Sydney.

Industry liaison

The ATNF is actively promoting the SKA and welcomes expressions of interest from Australian industry in collaborative research and development programs. Enquiries should be sent to Dr Peter Hall (phall@atnf.csiro.au).

Photograph