Prototyping SKA Technologies at the Molonglo Radio Telescope

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Abstract— **The Molonglo radio telescope near Canberra, Australia, is an east-west array of two collinear cylindrical parabolic reflectors with a total length of 1.6 km. Its 18,000 m^2 collecting area is the largest of any radio telescope in the Southern Hemisphere. We will prototype on the telescope, technologies relevant to the next generation radio telescope, the square kilometre array (SKA). We plan to equip the telescope with new wide-band feeds, low-noise amplifiers, digital filterbanks and FX correlator, and demonstrate 300–1420 MHz continuous frequency coverage and multibeam mode operation. This will allow us to develop and test several new technologies and will provide a new capability for low-frequency radio astronomy in Australia, enabling exploration of the distant universe.**

This project has recently been awarded funding by the Australian Government's Major National Research Facilities (MNRF) program, the University of Sydney and the Australia Telescope National Facility (ATNF). The project is being coordinated in collaboration with the Australian SKA Consortium, of which the University and ATNF are members.

Keywords— **radio astronomy, SKA, radio telescope, cylindrical parabolic reflector.**

I. Introduction

THE next generation radio telescope, the square kilometre array (SKA), will be 100 times more sensitive than any existing radio telescope [1]. A number of groups are prototyping a diverse range of concepts for the SKA. We are developing a prototype based on a linear array of feeds placed at the focal plane of a cylindrical parabolic reflector.

The prototype will use the existing mechanical structure of the cylindrical parabolic Molonglo telescope [2], shown in Fig. 1, but replace, in stages, all the other elements of the signal path. The stages are timed to avoid disruption of the telescope's current task, a seven-year all-sky imaging survey at 843 MHz, the Sydney University Molonglo Sky Survey (SUMSS) [3], which will be completed in 2003. The initial stages involve installation and testing of the 'back-end' of the instrument, the digital filterbank, FX correlator and signal processing software and hardware [4]. These will initially take inputs from the existing 843 MHz feeds and can be operated in parallel with the 843 MHz survey. At the completion of the survey, the new 'front-end,' the feeds, low-noise amplifiers (LNAs), and beamformer [5], will be installed and tested. At this time, around 2005, with the SKA technology prototyping phase completed, the science program [6] will begin in earnest.

Below, we describe the SKA technologies that we intend to develop for the prototype, followed by a brief description of the major new science projects that will be possible with the prototype.

II. SKA Technologies

Our goals in this project are to develop and test technologies relevant to the SKA, and to apply them to a range of science projects. The target specifications for the instrument are shown in Table I. The signal path diagram, Fig. 2,

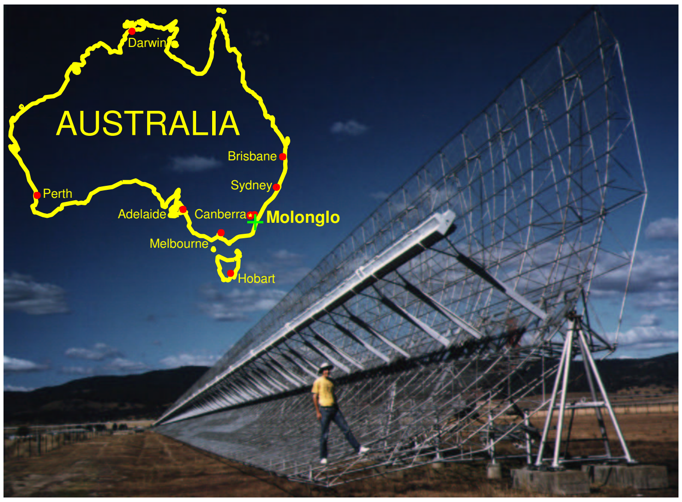

Fig. 1. The Molonglo cylindrical parabolic radio telescope near Canberra. (Photo: D. Bock.)

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TABLE I

Target specifications for the Molonglo SKA prototype

Parameter	**1420 MHz**	**300 MHz**
Frequency Coverage	300–1420 MHz	
Bandwidth	250 MHz	
Resolution ($\delta < -30°$)	$0.007° \times 0.007°$ csc|δ|	$0.03° \times 0.03°$ csc|δ|
Imaging field of view	$1.5° \times 1.5°$ csc|δ|	$7.7° \times 7.7°$ csc|δ|
UV coverage	Fully sampled	
Tsys	< 50K	< 150K
System noise (1σ) 12 hr:	11 μJy/beam	33 μJy/beam
8 min:	100 μJy/beam	300 μJy/beam
Polarisation	Dual Linear	
Correlator	Full Stokes	
Frequency resolution	120–1 kHz (FXF mode: 1 Hz)	
Independent fanbeam	$0.02° \times 1.5°$	$0.1° \times 7.7°$
Indep. fanbeam offset	±6°	±27°
Sky accessible in < 1 s	180 deg^2	1000 deg^2

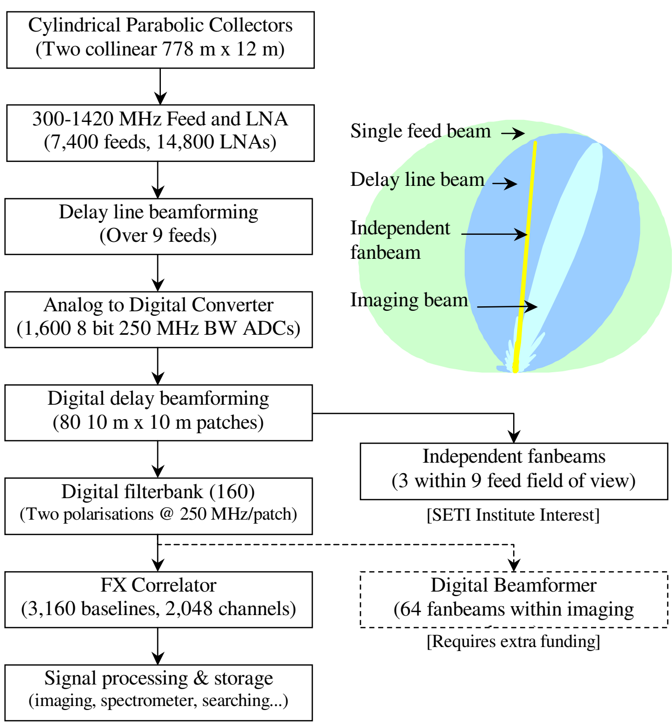

Fig. 2. Schematic of the signal path and antenna pattern for the prototype. The analog delay line beamformer reduces the beam size and the meridian distance range (dark blue). The imaging beam (light blue) is formed in the middle of this range. The independent fanbeams (yellow) can be placed anywhere within the delay line beam. Optionally, 64 fanbeams can be formed within the imaging beam.

shows how these technologies fit together. Details of the individual components are given below. Important features of the telescope include multibeaming, wide instantaneous field of view, digital beamforming, FX correlator, frequency and pointing agility, wideband linefeeds and LNAs, adaptive null steering and adaptive noise cancellation. Some of the design issues to be addressed, due to the cylindrical nature of the prototype, include polarisation purity, beam variability/stability and inter-antenna patch coupling.

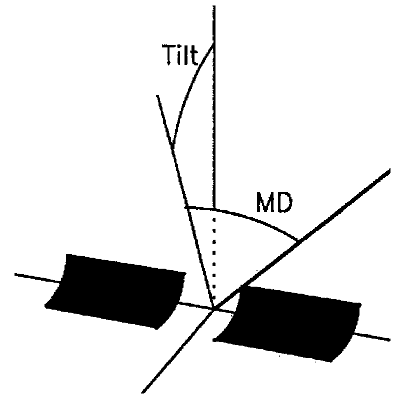

Fig. 3. Beam steering geometry. Beam steering in tilt is obtained by mechanical rotation of the cylindrical paraboloids about their long axis, and in meridian distance (MD), by electronic delays of the feed elements along the arms.

A. Collector

The telescope's collector consists of two collinear cylindrical paraboloids, 778 m long by 12 m wide, separated by a 15 m gap and aligned east west (total area 18,000 m^2). The telescope is currently steered in tilt, see Fig. 3, by mechanical rotation of the cylindrical paraboloids about their long axis, and in meridian distance by a combination of mechanical and electronic delays of the feed elements along the arms. In the prototype, steering in meridian distance will be entirely electronic. This 'altitude-altitude' beam-steering system can follow fields of declination $\delta < -30°$ for ±6 hours.

Whilst the original parabola shape was designed to be accurate for operation at 1.4 GHz, the reflecting mesh was designed for operation at 408 MHz and will have to be replaced for observations above $\sim$ 1 GHz.

B. Feeds

A wideband feed is required to cover the complete 300–1420 MHz band, with optimum performance required at the higher frequencies. A design study is underway to evaluate the performance of a linear array of active dipole antennas. Also under consideration is a linear array of Vivaldi antennas, using the 5:1 bandwidth ratio antennas being developed for the ASTRON THEA project [7], [8]. At lower frequencies, more tolerance in the feed performance is possible due to (i) increased sky noise and (ii) the larger beam size at lower frequencies means that continuum confusion makes the goal of having low noise less demanding.

C. Low Noise Amplifiers

We are currently developing wide-band ambient temperature low noise amplifiers (LNAs) based on the 50Ω two-stage HEMT 843 MHz LNAs used on the existing telescope. Fig. 4 shows the performance of an interim 3.5:1 bandwidth ratio LNA. Work is in progress to extend the bandwidth to cover the 300–1420 MHz range. These LNAs will be used for test purposes prior to the availability of MMIC (Monolithic Microwave Integrated Circuit) devices, currently be-

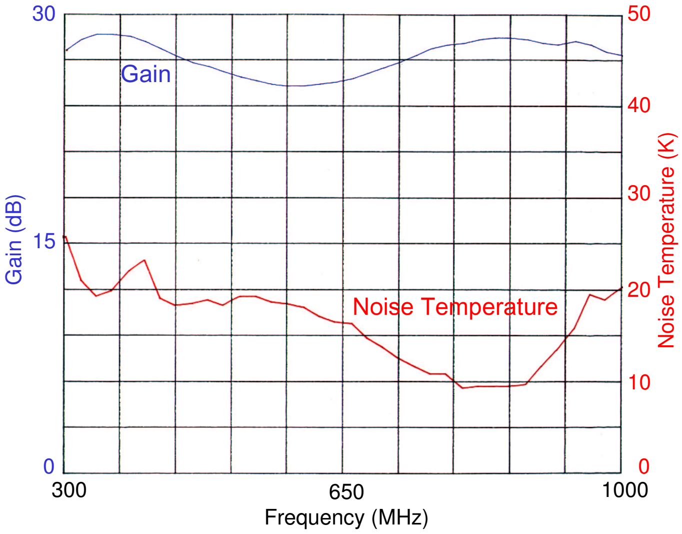

Fig. 4. Measured performance of interim 3.5:1 wide-band LNA based on the design of the 843 MHz LNA used in the existing telescope.

ing developed by ATNF and the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

D. Beamformer

The beamformer for the new telescope will demonstrate multibeaming, pointing agility, modifiable beam shape and adaptive null steering, all of which are relevant to a future SKA. Multibeaming occurs within the primary beam of a 1 m section of the line feed, with a full imaging beam and an independent fanbeam being generated. Extra fanbeams are easily added. As beamforming is electronic, the beams can be rapidly switched in meridian distance. Later stages of beamforming are digital. This allows for continuous adjustments to maintain a consistent beam shape or for adaptive null steering.

Cost constraints prevent the use of a full digital system for the $\sim 6,000$ feeds in the Molonglo line feed. Instead a two-stage beamformer is used. In the first stage the output of the LNAs from 9 feeds are combined in a wideband delay line beamformer. This restricts the field of view to $\pm 6°$ at 1420 MHz or $\pm 27°$ at 300 MHz.

The $\sim$ 700 RF signals from the delay line beamformer are upconverted to a 2.5 GHz intermediate frequency, bandlimited to 250 MHz. Complex IQ downconversion of the RF signal is being investigated. If this is not possible, a higher cost 500 MSamples/s converter will be used to generate a real 250 MHz signal with appropriate changes to the conversion chain. Two local oscillator (LO) signals will be supplied optically. One is a variable frequency LO to select the observing centre frequency and the other is a fixed LO for down conversion.

Details of the multi-output digital beamformer are currently being investigated. Possible implementations for the primary beam fine delay are dithered analog to digital converter clocks, polyphase filters or using additional small analog delay elements. Fan beam delays will be implemented digitally at as large a bandwidth as possible.

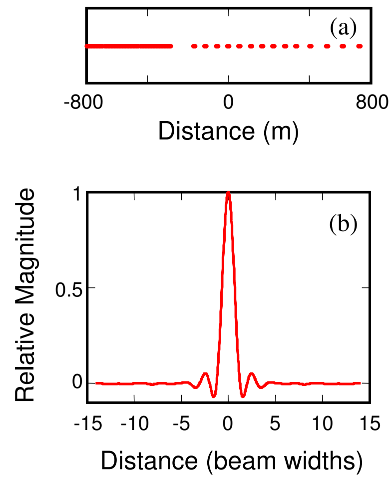

Fig. 5. Patch positions on the antenna for a possible configuration of patches (a), and (b) the resulting shape of the telescope's synthesised beam.

E. Beam Shape

The synthesised beam shape for a possible configuration of antenna patches on the telescope is shown in Fig. 5. This configuration has a contiguous patch covering a third of the telescope area for forming 0.2° wide beams, at 1420 MHz, for pulsar or SETI (Search for Extraterrestrial Intelligence) searches. The remaining part of the telescope is more sparsely covered (with positions calculated from a simple grading function) to give good imaging resolution.

F. Correlator

In imaging mode the FX correlator proposed is ideally suited to handle the large number of baselines ($\sim$ 3,000). Two thirds of the inputs to the correlator come from a contiguous section of the line feed which allows a higher level of beamforming within the area of the imaging beam.

The digital filterbanks use the same technology as the ATNF 2 GHz filterbanks [9]. It is estimated that one XC2V3000 field programmable gate array (FPGA) is needed per filterbank. The correlator cross-multiply-accumulate units (XMACs) are also implemented in FPGAs and operate at 125 MHz. Two 125 MHz banks of XMACs are used to process the full 250 MHz bandwidth. Using a channel reordering approach [10], 20 to 30 low cost FPGAs are needed to implement a full correlator for each Stokes parameter. Spectral line observation will be implemented using decimation in the filterbank and recirculation techniques (FXF mode) on individual frequency channels. With sufficient memory storage in the correlator, sub Hertz frequency resolution is possible.

G. Optional 64 fanbeams

Beamforming within the imaging beam can be performed by summing the outputs of the digital filterbanks. Delays are already correct for the field centre and, as the filterbank outputs are narrow band, phasing of the frequency channels is sufficient to steer the beam.

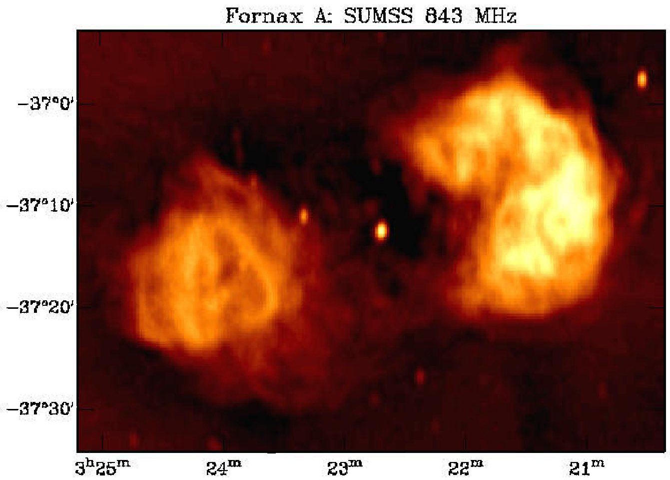

Fig. 6. The nearby radio galaxy Fornax A at 843 MHz, showing the excellent image quality achievable with the Molonglo telescope, due to its full sampling of the Fourier *uv*-plane.

H. Radio Frequency Interference

The telescope is located in the Molonglo valley, about 40 km from Canberra (population $\sim$ 300,000). The site has relatively low level of radio frequency interference (RFI), particularly above $\sim$ 1 GHz. Nevertheless, it will provide a challenging test environment for RFI mitigation techniques.

III. SCIENCE GOALS

The science goals take advantage of several unique features of the Molonglo telescope, its large collecting area, wide field of view and fully sampled *uv*-plane coverage, which provide excellent sensitivity to diffuse and extended radio sources with complex structure, as shown in Fig. 6. The new system will give continuous spectral coverage over the range 300–1420 MHz, re-opening the low-frequency radio spectrum in the southern hemisphere.

Using the telescope for low-frequency radio spectrometry will help identify objects by their radio spectral shape, for example, for detecting candidate high-redshift ($z > 3$) galaxies with ultra-steep radio spectra. Measurements of these objects will allow us to study the formation of galaxies and massive black holes.

Measurements of the redshifted 1420 MHz line of neutral hydrogen in emission will measure the rate at which gas is turned into stars, from the present ($z = 0$) back to when the universe was two-thirds its current age ($z = 0.3$) [6]. Measurements of redshifted hydrogen in absorption against more distant bright continuum sources should be possible over a much wider redshift range ($z = 0$ to 3) allowing us to probe gas clouds in the very early universe.

Measurements of the low-frequency galactic recombination lines of carbon and hydrogen will be used to probe the partially-ionized interstellar medium and place constraints on the physical conditions in the medium.

The telescope will be able to monitor around 5% of gamma ray burster signals instantaneously on being alerted, as the telescope's electronic beam steering in meridian distance enables instantaneous coverage of 5% of the sky.

Use of the independent fan beams will enable concurrent pulsar and source flux monitoring, as well as pulsar and SETI searches.

ACKNOWLEDGEMENTS

The Molonglo Observatory Synthesis Telescope (MOST) is operated by the University of Sydney and supported in part by grants from the Australian Research Council.

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