Prototyping SKA Technologies at the Molonglo Radio Telescope


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 m² 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, the 843 MHz Sydney University Molonglo Sky Survey (SUMSS) [3], due for completion 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’ 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, shows how these technologies fit together. Details of the
TABLE I
Target specifications for the Molonglo SKA prototype

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1420 MHz</th>
<th>300 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Coverage</td>
<td>300–1420 MHz</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>250 MHz</td>
<td></td>
</tr>
<tr>
<td>Resolution (δ &lt; −30°)</td>
<td>0.007° × 0.007° cscδl</td>
<td>0.03° × 0.03° cscδl</td>
</tr>
<tr>
<td>Imaging field of view</td>
<td>1.5° × 1.5° cscδl</td>
<td>7.7° × 7.7° cscδl</td>
</tr>
<tr>
<td>UV coverage</td>
<td>Fully sampled</td>
<td></td>
</tr>
<tr>
<td>Tsys</td>
<td>&lt; 50K</td>
<td>&lt; 150K</td>
</tr>
<tr>
<td>System noise (1σ) 12 hr:</td>
<td>11 μJy/beam</td>
<td>33 μJy/beam</td>
</tr>
<tr>
<td>8 min:</td>
<td>100 μJy/beam</td>
<td>300 μJy/beam</td>
</tr>
<tr>
<td>Polarisation</td>
<td>Dual Linear</td>
<td></td>
</tr>
<tr>
<td>Correlator</td>
<td>Full Stokes</td>
<td></td>
</tr>
<tr>
<td>Frequency resolution</td>
<td>120–1 kHz (FXF mode: 1 Hz)</td>
<td></td>
</tr>
<tr>
<td>Independent fanbeam</td>
<td>0.02° × 1.5°</td>
<td>0.1° × 7.7°</td>
</tr>
<tr>
<td>Indep. fanbeam offset</td>
<td>±6°</td>
<td>±27°</td>
</tr>
<tr>
<td>Sky accessible in &lt; 1 s</td>
<td>180 deg</td>
<td>1000 deg</td>
</tr>
</tbody>
</table>

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.

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 m²). 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 δ < −30° for ±6 hours.

Whilst the original parabolic 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 ~ 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 as sky noise increases and the beam size increases and therefore continuum confusion increases.

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 being developed at ATNF and other divisions of...
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 ∼6,000 feeds in the Molonglo line feed. Instead a two-stage beamformer is used. In the first stage, signals from the LNAs for each set of 9 adjacent feeds are combined in a wideband delay-line beamformer. This restricts the field of view to ±6° at 1420 MHz or ±27° at 300 MHz.

The ∼700 RF signals from the delay-line beamformer are upconverted to a 2.5 GHz intermediate frequency, bandlimited to 250 MHz. Complex in-phase and quadrature 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, 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.

E. Beam Shape

The synthesised beam shape for a possible configuration of line-feed segments on the telescope is shown in Fig. 5. This configuration has two-thirds of the line-feed in a continuous section covering a third of the telescope area and one-third of the line-feed in 10 m segments distributed over the remainder of the telescope. The continuous section of line feed is used for forming 0.2° wide beams, at 1420 MHz, for pulsar or SETI (Search for Extraterrestrial Intelligence) searches. The distributed segments of line-feed are arranged to provide good imaging resolution.

F. Correlator

In imaging mode the FX correlator proposed is ideally suited to handle the large number of baselines (∼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 which are also implemented in FP- GAs 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 set of 64 fanbeams

A set of 64 fanbeams can be formed within the imaging beam from linear combinations of the outputs of the digital filterbanks. The signals from the filterbanks have
the correct delays for forming a beam at the centre of the imaging beam. As the filterbank signals are narrow band, fanbeams can be formed within the imaging beam by combining phase adjusted signals from each frequency band.

H. Radio Frequency Interference

The telescope is located in the Molonglo valley, about 40 km from Canberra (population ~ 300,000). While the site has relatively low levels of radio frequency interference (RFI) in large parts of the 300-1420 MHz spectrum and particularly above ~ 1 GHz, there is sufficient RFI in within other parts of this spectrum to 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 \((z = 0 \text{ to } 3)\), 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.

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REFERENCES