Prototype SKA Technologies at Molonglo:

1. Overview and Science Goals

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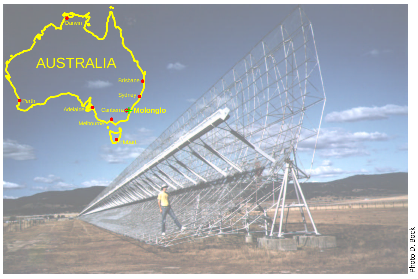
Abstract

The Molonglo radio telescope in south-east Australia is an east-west array of two colinear cylindrical paraboloids with a total length of 1.6 km. Its collecting area is the largest of any radio telescope in the Southern Hemisphere.

We propose to equip the telescope with new feeds, low-noise amplifiers, digital filterbank and FX correlator as an SKA demonstrator with continuous frequency coverage in multibeam mode from 300-1420 MHz. This will allow us to develop and test several new technologies as well as providing a sensitive astronomical instrument for exploring the distant universe. Funding for this project is currently being sought from the Australian Government's Major National Research Facilities (MNRF) program.



The Molonglo Telescope has been operated by the University of Sydney since 1965. Major achievements include the Molonglo Reference Catalogue (MRC; 408 MHz) and a sensitive all-sky imaging survey, the Sydney University Molonglo Sky Survey (SUMSS; 843 MHz) which will be completed in 2003.

Target Specifications

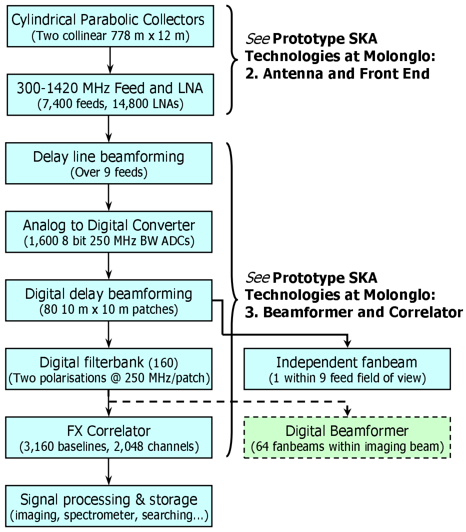
Parameter	1420 MHz	300 MHz
Frequency Coverage	300–1420 MHz	
Bandwidth (BW)	250 MHz	
Resolution (δ < -30°)	26" x 26" csc|δ|	123" x 123" csc|δ|
Imaging field of view	1.5° x 1.5° csc|δ|	7.7° x 7.7° csc|δ|
UV coverage	Fully sampled	
T_{sys}	< 50K	< 150K
System noise (1σ) 12 hr: 8 min:	11 μJy/beam 100 μJy/beam	33 μJy/beam 300 μJy/beam
Polarisation	Dual Linear	
Correlator	I and Q (Full Stokes at 125 MHz BW)	
Frequency resolution	120–1 kHz (FXF mode: 240 Hz)	
Independent fanbeam	1.3′ x 1.5°	6.2′ x 7.7°
Indep. fanbeam offset	±6°	±27°
Sky accessible in < 1 s	180 deg²	1000 deg²

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 'signal path' diagram shows how these technologies fit together - more details of the individual components are given in two companion posters. Important features of the telescope include:

- Multibeaming
- Wide instantaneous field of view
- Digital Beamforming
- FX Correlators
- Frequency and Pointing Agility
- Wideband linefeeds and LNAs
- Cylindrical Antenna Prototype – in particular addressing
  - Polarisation purity
  - Beam variability/stability
  - Inter-antenna patch coupling
- Adaptive Null steering and Adaptive Noise cancellation

Signal Path



Observing Modes

The telescope will have several modes of operation - making it possible, for example, to carry out deep spectral-line observations with integration times of hours or days, while simultaneously monitoring the continuum emission of other sources well outside the main beam.

Wide Field Imaging
- Full integration over 12 hours or multiple snapshots.

Spectral Line Observations
- FX mode 2048 channels, each 1 - 120 kHz (0.2 - 25 km/s).
- FXF mode 1 or 2 channels with 768 complex lags.

Independent Fanbeam Observations
An independent fanbeam can be formed within ±6° (1420 MHz) or ±27° (300 MHz) of the imaging beam. This could be used for pulsar timing or flux monitoring.

Optional digital beamformer with 64 fanbeams
- Pulsar and SETI search observing.

Interleaved Observing
The electronic beamforming enables rapid changes (< 1 s) in observing frequency and meridian distance. The frequency agility allows for spectral index determination using interleaved frequencies. The meridian angle agility makes 10,000 deg² of sky accessible during routine 12h observations allowing for, for example, source monitoring or calibration.

Science Goals

The science goals listed below take advantage of several unique features of the Molonglo telescope - its large collecting area, wide field of view and fully-sampled uv coverage (i.e. excellent sensitivity to diffuse and extended radio sources with complex structure). 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.

Low-frequency radio spectrometry (300-1420 MHz)
- Selection of objects via their radio spectral shape, e.g. candidate high-redshift (z>3) galaxies with ultra-steep radio spectra (de Breuck et al. 2000), which allow us to study the formation of galaxies and massive black holes.

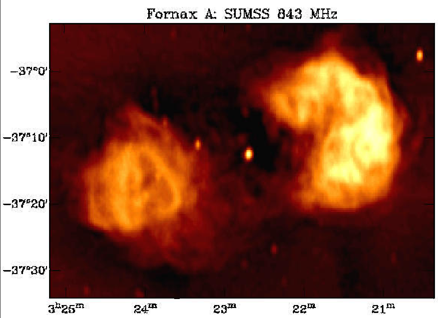
Redshifted HI (300-1420 MHz)
- HI in absorption against bright continuum sources over a wide redshift range (z=0 to 3).
- HI in emission - evolution of the HI mass function from z=0 to 0.5. Will be able to detect a bright spiral galaxy (2.5 x 10^{10} solar masses of HI, ΔV=200 km/s) at z=0.1 in 12 hours (see figure opposite).

Low-frequency Galactic recombination lines
- Recombination lines of carbon and hydrogen can be used to probe the partially-ionized ISM and constrain the physical conditions (Anantharamaiah & Kantharia 1999).

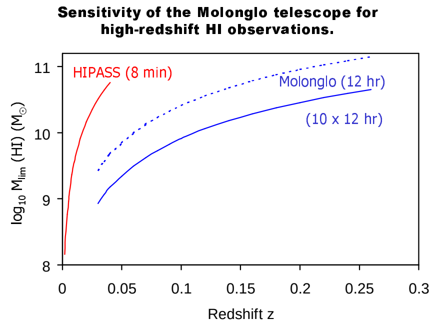
Gamma Ray Bursters
- Electronic beam steering gives 5% chance of monitoring instantaneously on alert.

Concurrent Pulsars and Source Flux Monitoring
- 18 to 400 square deg² accessible around main beam.
- Real time dedispersion.

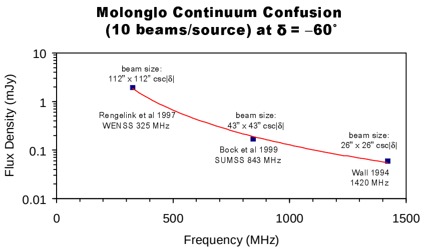
Pulsar and SETI Searches (optional 64 fanbeam system)
- Fast high sensitivity search.



The nearby radio galaxy Fornax A at 843 MHz, showing the excellent image quality made possible by the continuous *uv* coverage of the Molonglo telescope.

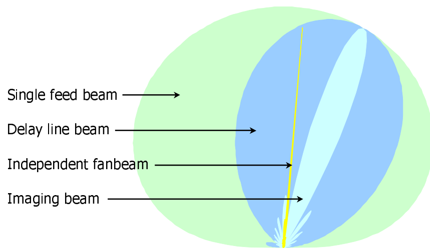


The red line shows the HI mass limit (for H_0 = 50 km/s/Mpc, q_0 = 0.5) reached by the HI Parkes All-Sky Survey (HIPASS; Barnes et al. 2001) for a galaxy with velocity width ΔV = 200 km/s in a 500 s observation. Molonglo will be able to reach similar mass limits over the redshift range z=0.03 to 0.26 with integration times of ~120 hours per 1.7 deg² field, allowing a direct measure of the evolution of the HI mass function over this redshift range.



The scientific and technological goals of this project focus on radio spectrometry of mJy-level continuum sources and wide-field spectral-line observations, which are unaffected by confusion in the Molonglo beam. We note however, that images from the high-frequency end of the bandpass (where the angular resolution is highest) will help deconfuse lower-frequency images, so that the effective continuum confusion limit should be well below 0.1 mJy (a full 12 hr synthesis observation will reach a 5 sigma detection limit of ~0.17 mJy in a 30 MHz continuum band near 1400 MHz).

Antenna Pattern



The analog delay line beamformer reduces the meridian distance range (dark blue). The imaging beam (light blue) is formed in the middle of this range. The independent fanbeam (yellow) can be placed anywhere within this range. Optionally, 64 fanbeams can be formed within the imaging beam.

References

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D. G. Barnes et. al. (2001) MNRAS **322** 486.

D. C.-J. Bock, M. I. Large and E. M. Sadler (1999). AJ **117** 1578.

C. de Breuck, W. van Breugel, H. Rottgering and G. Miley (2000). A & AS **143,** 303

R. B. Rengelink, Y. Tang, A. G. de Bruyn, G. K. Miley, M. N. Bremer, H. J. A. Röttgering and M. A. R. Bremer (1997). Astron. Astrophys. Suppl. Ser. **124** 259.

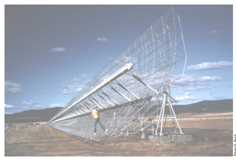
J. V. Wall (1994). Aust. J. Phys. **47** 625.

Further Information

www.physics.usyd.edu.au/astrop
www.atnf.csiro.au/ska

Prototype SKA Technologies at Molonglo:

2. Antenna and Front End



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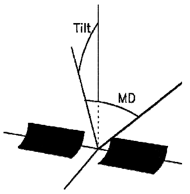
Abstract

We propose to prototype SKA technologies on the Molonglo radio telescope, enabling the telescope to operate over the frequency range 300-1420 MHz. The telescope collector consists of two 778 m x 12 m cylindrical parabolic reflectors, currently operating at 843 MHz. The front end of the instrument will demonstrate wide band line-feed and low noise amplifier technologies. These are discussed along with the collector performance at 1420 MHz, the synthesised beam shape for a promising configuration of line-feed patches, and the radio-frequency interference environment at Molonglo.

Collector

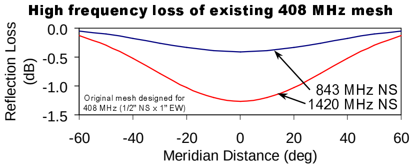
The telescope's collector consists of two cylindrical paraboloids, 778m x 12m, separated by 15m and aligned east-west (total area 18,000 m^2). The telescope is steered by mechanical rotation of the cylindrical paraboloids about their long axis, and by electronic delays of the feed elements along the arms. The resulting 'alt-alt' system can follow fields south of declination -30° for ±6 hours.

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 need to be replaced for operation above ~1 GHz.

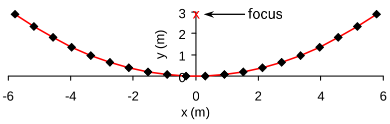


Beam Steering Geometry
MD: Meridian Distance.

High frequency loss of existing 408 MHz mesh



Piecewise linear fit to parabola shape

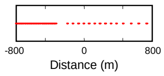


Mesh supported at 0.6 m (2 ft) intervals in x direction.
Each section gives the same error for a linear fit to a parabola.
Gives a total of 0.1 dB loss at 1420 MHz.

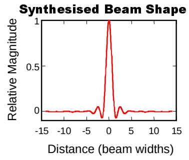
Beam Shape

The synthesised beam shape for a possible configuration of antenna patches on the telescope is shown. This configuration has a contiguous patch covering a third of the telescope area for forming 1.3' beams for pulsar or SETI searches. The remaining part of the telescope is more sparsely covered (with positions calculated from a simple grading function) to give good imaging resolution.

Patch positions on reflectors



Synthesised Beam Shape



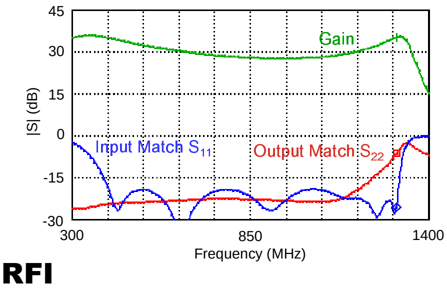
Feeds

A wideband feed is required to cover the complete 300-1420 MHz band, with optimum performance required at the higher frequencies. A linear array of Vivaldi antennas, such as the 750-1500 MHz array used in the ASTRON THEA project, may be suitable for this purpose. At lower frequencies, increased sky noise and continuum confusion allow for more tolerance in the feed performance.

LNA

Shown below is the simulated performance of a wide band (400-1200 MHz) ambient temperature low noise amplifier (LNA), based on the 50Ω two-stage HEMT 843 MHz LNA used on the existing telescope. The anticipated noise temperature of the LNA is ~20K. It is likely that the frequency range can be extended to cover 300-1420 MHz, with design simplifications possible for higher input impedance. This discrete component based LNA provides a useful starting point for migration to MMIC design for mass production.

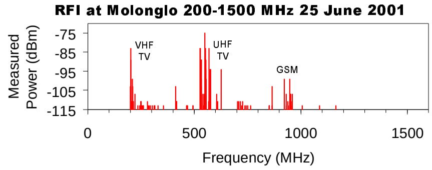
Performance of 400-1200 MHz LNA



RFI

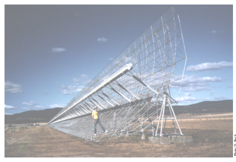
The telescope is located in the Molonglo valley, about 40 km from Canberra (population ~300,000). The figure below shows the low level of radio frequency interference (RFI) at the site, particularly above ~1 GHz. RFI mitigation techniques are discussed further in the poster: Satellite Signal Decorrelation in an Interferometer, Mitchell et. al.

RFI at Molonglo 200-1500 MHz 25 June 2001



Prototype SKA Technologies at Molonglo:

3. Beamformer and Correlator



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Abstract

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 1m 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.

In imaging mode the FX correlator proposed is ideally suited to handle the large number (>3,000) of baselines. 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.

Beamformer

Cost constraints prevent the use of a full digital system for the ~6000 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 ±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 IF, 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 A/D clocks, polyphase filters or using additional small analog delay elements. Fan beam delays will be implemented digitally at as large a bandwidth as possible.

Correlator

The digital filterbanks use the same technology as the the ATNF 2 GHz filterbanks. It is estimated that one XC2V6000 field programmable gate array (FPGA) is needed per filterbank. See 'A 2 GHz Digital Filterbank Correlator' (this meeting) for more details.

The correlator cross-multiply-accumulate units (XMACS) are also implemented in FPGAs and operate at 125 MHz. At this speed each FPGA implements 36 XMACS, each with 1024 complex 36-bit accumulators. Two 125 MHz banks of XMACS are used to process the full 250 MHz bandwidth. About 100 FPGAs are needed to implement a full correlator for each Stokes parameter.

Spectral line observation will be implemented using decimation in the filterbank and FXF techniques. For this system 768-lag XF correlations can be implemented in each bank of the XMACs. This allows for a further 500 fold increase in resolution beyond that provided by the digital filterbank.

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. For a 64-beam system groups of 8 to 10 adjacent filterbank outputs are used to form 8 broad fanbeams. Corresponding broad fanbeams are then combined to form 8 fine fanbeams for a total of 64 fine fanbeams. This can be implemented in a total of 64 FPGAs. FFT beamforming is also being investigated.

Beamforming and Digital Filterbanks for one of 44 bays