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The Australia Telescope Millimetre-Wave Upgrade

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Abstract

The Australia Telescope National Facility has begun a new project aimed at upgrading the AT Compact Array (ATCA) to mm-wave operation. The upgrade, to cost $6M and scheduled for completion in 2002, means that the ATCA will be the first operational Southern-Hemisphere mm-wave aperture synthesis telescope. Despite limitations flowing from a low-elevation site, the large collecting area of the ATCA gives it a sensitivity equal to the best existing northern mm-wave synthesis arrays. The multi-wavelength capability of the upgraded Australian telescope (λ = 20 cm to 3 mm), its frequency agility, the use of new receiver and LO technology, the incorporation of an atmospheric phase correction system, and its southern location, will ensure that the ATCA will continue to make major scientific contributions. Importantly, it will also be a test-bed for next-generation, large-area arrays to be located in prime mm-wave observing sites in Chile.

Introduction

The six-antenna ATCA, located near Narrabri in NSW, was completed in 1988 as an Australian bicentenial project. Scheduled astronomical observing began in 1990. The Telescope, shown in Fig. 1 and described in [1], features state-of-the-art antenna, receiver and signal processing technology for cm-wave radio observations in the range 1-10 GHz. With leading-edge technology, an unmatched view of the southern sky (including the Galactic centre and Magellanic Clouds), and advanced observational techniques, the instrument has already made important contributions to astronomy [2]. Scientific imperatives, such as the need for higher angular resolution and access to the line (quasi-CW) signature emission from abundant cosmic molecules, have led to a push for ATCA observation frequencies as high as 100 GHz (λ = 3 mm). Although the antennas were originally designed to have useable performance at these frequencies, there was concern that excessive atmospheric attenuation and instability at the low-altitude (200 m) site would prevent useful scientific observations from being made. However, following favourable technical feasibility (including site) studies and user consultative programs, funding for a comprehensive mm-wave extension was approved by the Commonwealth Government in 1995 under the auspices of the Major National Research Facilities upgrade scheme.

The Project

The upgrade project is split into the following major tasks:

- re-surfacing of the ATCA antennas to extend the high-frequency (>50 GHz) reflecting surface of five of the six dishes from the present 15 m to the full 22 m antenna diameter;
- modification of the present rail track arrangement to give a 150 m north-south "spur" track, together with new stations on the existing 3 km east-west track; this will give an improved spatial frequency response in the aperture synthesis process and correspondingly better imaging, especially with the shorter-duration observations likely to forced upon mm-wave programs by atmospheric stability limitations;
- provision of a new high-frequency HEMT receiver suite packaged in a single cryostat and covering the 12 mm (16-26 GHz), 3.5 mm (85-100 GHz) and, most likely, the 2.6 mm (115 GHz) bands;

- installation of an improved local oscillator distribution system, using a star topology and a single-mode optical fibre transmission medium, specified to give < 5° rms phase jitter at 100 GHz;
- provision of an atmospheric phase correction system based on radiometric phase correction or one of its variants;
- development and installation of new antenna control computers and telescope on-line observing software.

Project status and highlights are available via the Internet at http://www.atnf.csiro.au.

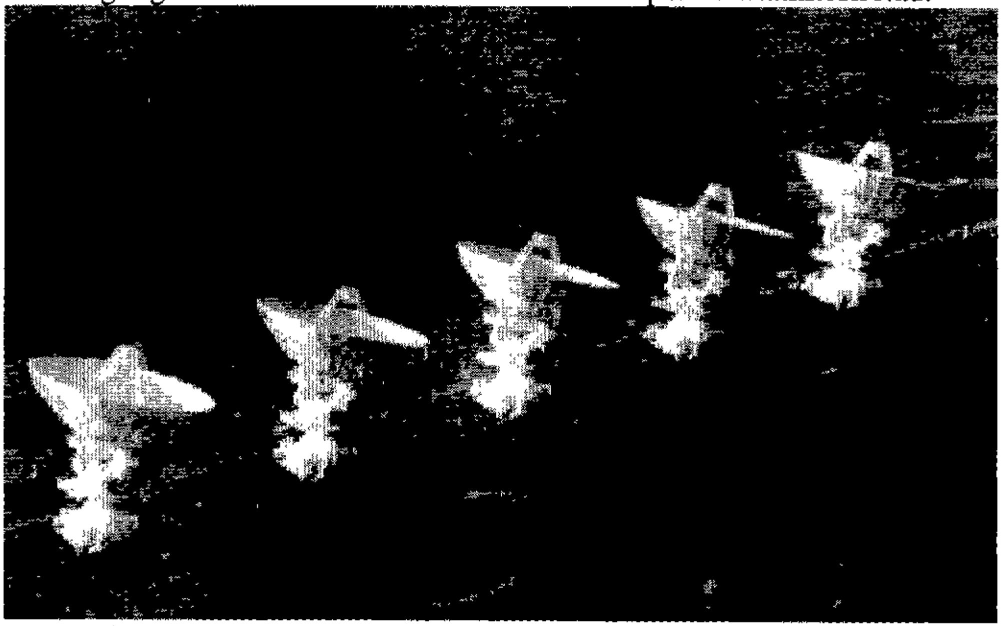

Figure 1 - General view of five of the six ATCA 22 m antennas.

Projected Performance

The preliminary specifications of the upgraded array are summarised in Appendix 1. The summary is intended as a guide; none of the material included should be regarded as definitive at this early stage of the project. At present, only the 12 mm (16-26 GHz) and 3.5 mm (85-100 GHz) bands are funded but technology developments in the MMIC low-noise amplifier area will probably allow coverage to 115 GHz in the production receivers. Provision has also been made within the mm-wave receiver cryostat for a future 7 mm (40-50 GHz) band option.

The receiver performances are indicative only and have been derived from ATNF Receiver Group projections and measurements at the ATNF Mopra mm-wave radio telescope, a very similar antenna to those of the ATCA. In particular, the 85-115 GHz receiver performance is extrapolated from that of a model (cooled) GaAs MMIC LNA (designed by Dr. John Archer, CSIRO Telecommunications and Industrial Physics).

In computing the array sensitivities, no degradation factor has been included for antenna-to-antenna de-correlation caused by LO phase jitter or atmospheric phase instability . The degradation factor is $\eta_{LO}\,\eta_{AT} = \exp[-(\sigma_{LO}^2 + \sigma_{AT}^2)/2]$, where the σ terms are rms phase errors (radians). The preliminary MNRF upgrade specification calls for 100 GHz LO instabilities of <5° rms and a projected clear-sky phase correction error <10° rms giving, in the best estimate, minimal de-correlation.

The ATCA backend (cross-correlation spectrometer) will remain largely unchanged in the initial

upgrade. Assuming dual-polarization, single-frequency observing, a maximum correlator bandwidth of 128 MHz per polarization product (32 channel resolution, 2-bit sampling) will be available in continuum mode; a best spectral line mode resolution of 2 MHz will be offered. Wider total bandwidths are desirable in mm-wave astronomy and two options are being considered as ways of increasing band coverage. First, the existing AT correlator incorporates a 256 MHz/1-bit option and it may be possible to provide associated antenna hardware economically. If successful, 128 independent channels per baseline (to be divided by the number of polarizations and observing frequencies) will be offered. An alternative, equally sensitive, option involves fast frequency stepping already-implemented 128 MHz bands. Finally, the provision of a tied-array mode (with a currently-projected maximum bandwidth of 64 MHz) is also envisaged, giving the equivalent of a mm-wave single-dish antenna 50 m in diameter.

Project Highlights

Antenna Resurfacing

This operation involves replacing the existing outer perforated panels (which are effective only to 50 GHz) with new solid panels, giving 22 m reflectors useable to beyond 100 GHz. The existing "shaped" reflector profile will be retained and the Cassegrain sub-reflector will remain unchanged. A likely upgrade strategy involves fitting one set of new panels to an antenna of the ATCA; the removed panels will be re-manufactured with a solid surface, then re-fitted to a second antenna. Each antenna can thus be upgraded progressively. Antenna surface adjustment will be done in conjunction with coherent radio holographic measurements using 30 GHz satellite beacons as test signals. The goal, after final adjustment, is a surface error not exceeding ~150 µm rms, giving aperture efficiencies of 40% at 100 GHz. Panel manufacture will be contracted to industry and will most likely use vacuum forming techniques pioneered during the construction of the ATCA.

Rail-track Modifications

There are two major components to this sub-project. MNRF upgrade funding will be used to provide three additional stations (for locating and connecting antennas) on the east-west track, while an additional $1.25M of CSIRO capital funds will provide a new north-south spur track approximately 150 m long. The N-S spur will run to the north from the centre of the E-W track and will contain either three or four new stations, depending on the outcome of final array configuration studies. Connell Wagner P/L, consultants and project managers, are assisting CSIRO to design the track modifications, additions, and antenna turning arrangements. They will also assist in producing tender documentation and in supervising civil works.

Receivers

The ATCA mm-wave receivers will be the first astronomy receivers to use cooled (20 K) MMIC technology for low-noise amplifiers and conversion components. No final decision on the source of MMIC amplifiers has yet been taken; commercial (e.g. Lockheed Martin) or CSIRO GaAs or InP devices may be used ; InP devices could give T_{rx} ~ 120 K at 100 GHz. All ATNF mm-wave receivers will be dual-polarization types, and will be mounted in a common dewar assembly occupying one position on the ATCA receiver positioning turret; Fig. 2 is a sketch showing one possible arrangement using a wire grid polarizer and a cooled 100 GHz feed. The position of the future 40-50 GHz feed is also shown. Provision of a simultaneous 12/3.5 mm observing capability is currently being canvassed. Australian industry will be invited to participate in the construction of the new receivers, especially in the supply of components for the 22 GHz system.

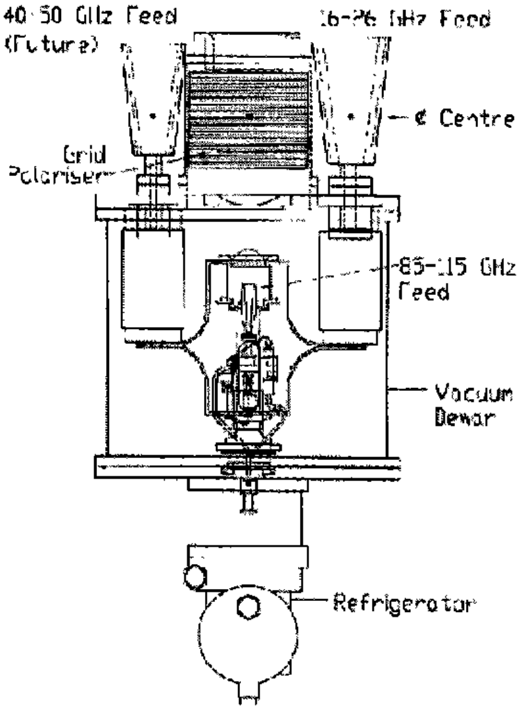

Figure 2 - Sketch of a possible arrangement for the new ATCA mm-wave receivers.

Atmospheric Phase Correction

Water-vapour inhomogeneities (blobs) moving in the troposphere cause differential electrical path fluctuations between antennas in the array, resulting in imaging degradation. The effect is severe at mm-wavelengths and research at the ATNF [3] and other radio astronomy institutions seeks to correct the atmospheric distortion by using remote-sensing techniques to measure the integrated water-vapour content along the line of sight of individual antennas. At this stage, it is most likely that the ATCA system will be based on channelized measurements of emission from the 22 GHz water-vapour resonance line, although broadband measurements at 225 GHz are a possibility.

Local Oscillator

The quality of the distributed local oscillator is a crucial factor in maintaining array coherence and hence in determining the imaging quality of a synthesis radio telescope. For good imaging, the LO jitter should not exceed 5° rms at the observing frequency. The existing ATCA local oscillator is adequate for cm-wave observations but, with a measured jitter of 0.25° per GHz, a replacement system is necessary for mm-wave observing. Furthermore, the present "daisy-chain" method of distributing the main LO reference signal has proved troublesome; the new "star" topology, using some 40 km of single-mode optical fibre to transport signals to individual stations, should substantially increase reliability.

Conclusion

The ATCA mm-wave upgrade will allow Australian astronomers to view the universe through a window of unparalleled clarity for a wide range of astronomical observations. The new window is an important one, hitherto unopened in the Southern Hemisphere, despite an otherwise-impressive collection of telescopes with operational wavelengths extending from the optical to metre-wave radio. The unique capabilities of the new ATCA will ensure it remains a leading-edge telescope while its advanced technology requirements provide excellent opportunities for Australian industry. The completed instrument will be an invaluable test-bed for even more ambitious millimetre- and

submillimetre-wave arrays.

Acknowledgements

We thank our colleagues within the ATNF and its user community who have helped make the mm-wave upgrade project a reality. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

References

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APPENDIX 1 - ATCA MILLIMETRE-WAVE PERFORMANCE PROJECTION

Band (mm)	12			7		3.5		2.6
Frequency (GHz)	16	22	25	40	50	85	100	115
Number of Antennas	6			6		5		
Antenna Diameter (m)	22							
Antenna Efficiency (150 μm rms surface error)	0.59	0.59	0.59	0.56	0.54	0.45	0.40	0.36
Antenna Sensitivity (Jy K^{-1})	12.2	12.2	12.2	12.9	13.4	16.0	18.0	20.0
Array Physical Area (m^2)	2280			2280		1900		
Maximum Baseline (km)	6			6		3		
Minimum Baseline (m)	30							
Field of View (arcsec.)	211	153	135	84	68	40	34	29
Best Synthesized Resolution (arcsec.)	0.77	0.54	0.49	0.31	0.25	0.29	0.25	0.21
Receiver Type (SSB, Dual-polarization)	GaAs HEMT			GaAs HEMT (MMIC?)		GaAs HEMT (MMIC)[#]		
T_{rx} (K)	50	50	50	70	70	190	200	300
$T_{atmosphere}$ (K), zenith, 10 mm precipitable water vapour (PWV)	4	25	12	15	53	36	41	108
T_{sys} (K), zenith, 10 mm PWV	54	75	62	85	123	226	241	408
Zenith Opacity τ_0 - (5 mm PWV)	0.01	0.05	0.03	0.04	0.18	0.09	0.09	0.31
Zenith Opacity τ_0 - (10 mm PWV)	0.01	0.08	0.04	0.05	0.20	0.13	0.15	0.47
Above Atmosphere System Equivalent (1-Antenna) S_0^* (Jy) - 5 mm PWV	653	828	728	1096	1903	3745	4409	9627
Above Atmosphere System Equivalent (1-Antenna) S_0^* (Jy) - 10 mm PWV	670	1013	800	1148	1996	4140	5045	11024
Continuum Flux Sensitivity ΔS_0^* (mJy/beam, 2 IF, 10 mm PWV, BW = 128 MHz, 2-bit correlation, t = 1 min., *t = 12 hr.*)	1.12 *0.04*	1.70 *0.06*	1.34 *0.05*	1.92 *0.07*	3.34 *0.12*	8.49 *0.32*	10.35 *0.39*	22.61 *0.84*
Line Flux Sensitivity ΔS_0^* (mJy/beam, 2 IF, 10 mm PWV, $\Delta V = 1\ kms^{-1}$, 2-bit correlation, t = 1 min., *t = 12 hr.*)	55.0 *2.1*	70.8 *2.6*	52.5 *2.0*	59.6 *2.2*	92.6 *3.5*	180.4 *6.7*	202.7 *7.6*	413.1 *15.4*
Continuum Brightness Sensitivity ΔT_b^* at best angular resolution (K, 2 IF, 10 mm PWV, BW= 128 MHz, 2-bit correlation, dec. = -45°, t = 1 min., *t = 12 hr.*)	6.59 *0.25*	9.95 *0.37*	7.86 *0.29*	11.28 *0.42*	19.62 *0.73*	12.49 *0.47*	15.18 *0.57*	33.17 *1.24*
Line Brightness Sensitivity ΔT_b^* at best angular resolution (K, 2 IF, 10 mm PWV, $\Delta V = 1\ kms^{-1}$, 2-bit correlation, dec. = -45°, t = 1 min., *t = 12 hr.*)	322.6 *12.0*	415.9 *15.5*	308.1 *11.5*	349.5 *13.0*	543.6 *20.3*	264.8 *9.9*	297.5 *11.1*	606.2 *22.6*

[#] Preliminary. InP MMIC devices may be used if available, giving T_{rx} ~ 120K at 100 GHz.