Australia Telescope Compact Array Centimetre Receiver Upgrade Science Case

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Introduction

The current receiver system for the Australia Telescope Compact Array (ATCA) consists of separate receivers covering the 20 cm (1.25 – 1.8 GHz) and 13 cm (2.2 – 2.5 GHz) bands and the 6 cm (4 .4 – 6.9 GHz) and 3 cm (8.0 – 9.2 GHz) bands. The maximum instantaneous bandwidth is 128 MHz, limited by the current correlator, though the feedhorns and dual linear OMTs are capable of receiving the full 20/13cm and 6/3cm frequency ranges. In 2007 the correlator will be upgraded to a 2 GHz maximum bandwidth, which far exceeds the current receiver bandwidths. Here we propose to upgrade the centimetre receiver systems to take advantage of the increased correlator bandwidth. This proposal will remove the diplexers, replace the current LNAs with wide bandwidth LNAs, and replace the current polarisers with wideband polarisers. The replacement of the polarisers will solve a long-standing problem with the polarization performance of the receivers at 13 cm. This project will greatly extend the frequency coverage of the ATCA at centimetre wavelengths, improve the continuum sensitivity, and enable a number of new scientific opportunities. The proposed upgrade to the ATCA frontend is designed to complement the Compact Array Broadband Backend (CABB) upgrade by allowing gigahertz bandwidths at centimetre frequencies.

Scientific Motivation

This project is motivated by the desire to provide more continuously sampled frequency coverage from 1 to 12 GHz, improve the continuum sensitivity, improve the polarization response at 13 cm, and expand the spectral line flexibility. Increasing the instantaneous frequency coverage to the 2 GHz bandwidth of the CABB will provide a factor of ~ 4 increase in continuum sensitivity and reduce the observing time for deep continuum observations by more than a factor of ten. The improvements in the 13 cm polarization capabilities will correct a longstanding problem preventing widefield polarimetry at 13 cm and thereby enable polarimetric studies of the interstellar medium, supernova remnants and radio galaxies at this wavelength. The upgrade will also expand the spectral line capabilities of the ATCA, improving in particular the sensitivity at the important 6.6 GHz methanol line. Here we broadly outline three specific science projects: tomography of the Galactic magnetoionic medium, improved spectral line coverage, and lunar Cherenkov measurements. Future incarnations of this document will expand on these scientific goals and outline the full system requirements.

Magnetoionic Tomography

In recent years radio polarization imaging techniques have improved significantly. Gaensler et al. (2001) and Haverkorn et al. (2004) have shown that interferometric imaging of the rotation measure against the diffuse Galactic synchrotron background is a powerful tool for probing magnetohydrodynamic turbulence in the ISM. However, rotation measure images of the Galactic plane at a given frequency only probe to a specific "Faraday depth" or distance into the ISM, beyond which the signal is too depolarised to reveal structure. Rotation measure images at a range of frequencies, *spectropolarimetry*, provide a means for slicing the ISM three-dimensionally. A new technique called rotation measure synthesis offers an even more powerful method for probing the magnetized ISM (Ramkumar & Deshpande 1999). Rotation measure synthesis continuously dissects the ISM along the line of sight. By resampling the data with wavelength squared (λ^2) and taking the Fourier transform of the polarization position angles as a function of λ^2 we can directly measure the polarized signal as a function of depth into the ISM. This technique provides an extremely powerful way of probing the ionised and magnetised ISM.

To make use of this technique requires several technical capabilities. Firstly, we require a large instantaneous bandwidth. The maximum bandwidth determines the largest polarized intensity scale sampled. Secondly, we require excellent polarization properties across the band. The ATCA already has good polarization properties in the 20 cm system, which combined with its compact configurations, has made it the best interferometer in the world for studying Faraday rotation as a probe of the magnetoionic ISM. Improving the polarization at 13 cm would enable Faraday tomography across the entirety of the current 20 and 13 cm bands. The proposed upgrade will increase the maximum instantaneous bandwidth by more than an order of magnitude and standardise the polarization properties of the receivers from 1 GHz to 3 GHz, enabling rotation measure synthesis of the Milky Way and external galaxies.

Spectral Line Capabilities

Another powerful probe of the ISM and star formation are spectral line studies. A fundamental limitation of the current 6 cm receiver is the 6.8 GHz lower frequency limit, which raises the system temperature at the 6.6 GHz methanol (CH_3OH) line a factor of 2.5 higher than the centre of the 6 cm band. With the construction of the Parkes methanol receiver, a matched ability to receive the methanol line at the ATCA is increasingly important. In particular, the methanol multibeam survey will detect sources throughout the Galactic plane whose positions must be checked with the higher angular resolution of the ATCA. An important component of methanol studies is VLBI imaging. In this capacity the sensitivity of the LBA could be significantly improved by decreasing the system temperature of the ATCA at 6.6 GHz. Reducing the system temperature at the frequency of the methanol line will speed the follow-up detections by about a factor of five. If the upper frequency limit of the 3cm system could be raised to ~12.4 GHz, it would allow observations of another methanol spectral line with a rest frequency of 12.2 GHz, which is an excellent probe of high density regions in the ISM and is sensitive to kinetic temperature. Simultaneous fits to both the 6.6 GHz and 12.2 GHz methanol lines would allow for derivation of both the density and temperature distribution of gas in dense regions. Traditionally ammonia (NH_3) in the 12mm band has been used in this respect but recent improvements in the methanol collisional rates coefficient means that methanol can also be used as a probe of the physical conditions in dense star forming regions (Leurini et al. 2004). This capability provides a nice method for comparison with work done with the ATCA at 22 GHz on ammonia in star-forming regions.

Lunar Cherenkov Radiation

Detection of high-energy neutrinos is one of the most significant challenges in modern high-energy physics. Large volume detectors, such as Kamiokande have been used for optical detections of Cherenkov radiation from neutrino interactions with hadrionic matter. However, these detections are few and have only provided a rough upper limit to the neutrino mass and provided very little information on the spectrum of high-energy neutrinos. It may also be possible to detect radio emission from Cherenkov cascades from neutrino interactions with the Moon's surface. This has the distinct advantage that the Moon provides a much larger volume detector than any on Earth. Dagkasamensky & Zheleneznykh (1992) estimate that these Cherenkov cascades should result in very brief (<microsecond), strong (~ 4000 Jy at 1420 MHz) pulses which peak in the 1 – 3 GHz range. These brief pulses should be detectable by radio telescopes with sufficiently high time resolution. In fact, the best limits on the neutrino flux and energy have been placed by an experiment conducted at Parkes by Hankins, Ekers & O'Sullivan (1996) searching for the Lunar Cherenkov radiation at 1175 – 1675 MHz. However, the chance of detection is maximised if the primary beam of the telescope is matched to the size of the moon (~30 arcmin). The ATCA primary beam at 20cm is well matched to the moon size and detection Lunar Cherenkov radiation might be possible given sufficient time resolution. The time resolution achieved is limited by the maximum instantaneous bandwidth of the receiver, however gigahertz bandwidths would enable nanosecond time resolution. Ekers proposes to take advantage of the increased sensitivity and bandwidth of the proposed frontend upgrade of the 20/13cm system to search for high energy neutrinos from the lunar surface.

The main technical requirement for this project is a large instantaneous bandwidth, preferably the covering full 1 – 3 GHz extent of the 20/13cm feedhorn. An additional requirement is a flat polarimetric response across the band. The polarization of the detected emission can provide positional information about the detected pulses.

Additional Benefits

The improved instantaneous frequency coverage will offer a significant improvement to centrimetre wave continuum imaging experiments. This improvement is two-fold: a factor of ~ 4 increase in sensitivity and improved *u-v* coverage through multi-frequency synthesis techniques. For future deep continuum imaging projects, like the recently completed Hubble Deep Field South survey, the improvement in sensitivity could reduce the observing time by more than a factor of ten. In addition, the increase in frequency coverage should allow far superior *u-v* coverage through multi-frequency synthesis techniques. It should be noted, however, that algorithmic work will be required to enable large bandwidth multi-frequency synthesis in interferometric imaging software.

By extending the upper frequency limit of the 3 cm receivers towards the lower limit of the 12 mm receivers (~16 GHz) it would allow almost continuous frequency coverage from 1.2 GHz to 22 GHz, which would be very useful for spectral index studies of continuum sources, such as radio galaxies and supernova remnants. This capacity would allow the ATCA to remain competitive with the VLA as it will acquire continuous frequency coverage as part of the EVLA upgrade. Finally, increasing the frequency coverage of the ATCA would complement the eVLBI project, which seeks to establish 2 GHz bandwidths across the entire Australia LBA.

Technical Requirements

The technical requirements for the proposed upgrade are:

- Continuous frequency coverage from 1 to 3 GHz for the 20/13 cm feeds
- Continuous frequency coverage from 4 to 12 (preferably 12.5) GHz for the 6/3cm feeds
- Polarization purity to ~1-2% across the entire 20/13 and 6/3cm bands
- No system temperature increase and with a desired reduction to ~ 25 K
- Designs and mitigation techniques to reduce the impact of RFI (may include pre-amplification notch filters)

Technical Considerations

The technical feasibility of this upgrade is constrained by several considerations. First, the current feedhorns are incapable of bridging much of the frequency gap from 3 to 4 GHz and the current 6/3cm feedhorns cannot extend much beyond 12 GHz. New broadband feedhorns may be feasible if deemed scientifically necessary, but this would dramatically increase the scope of this project. In addition, the focus of broadband feedhorns may be limited by the range of movement of the subreflector. Second, there is a tradeoff between broad bandwidth and the noise floor of the LNAs. Therefore the new LNAs will have a higher noise floor than the current LNAs. However, removing the diplexers will counteract this effect and there should be no increase in the overall system temperature. To further extend the frequency coverage would likely increase the system temperature beyond what it is now and worsen the polarization capabilities. Third, RFI will likely be a significant factor in the operation of this system. At present we do not know enough about the RFI environment outside the current ATCA bands, but efforts are being organised to explore this issue. While notch filters can be inserted before the LNAs, these will increase the overall system temperature of the system. The best solution would be to avoid the worst RFI by carefully choosing the frequency bands. As an example, the 1-3 GHz band could be shifted up from the specified 1 GHz lower limit if this would avoid strong RFI.

Summary

We propose an upgrade to the current centimetre wave receivers on the ATCA to take advantage of the 2 GHz bandwidths available via the CABB. This upgrade will extend the observable frequency ranges to 1-3 GHz and 4 – 12 GHz, offering, in conjunction with the CABB, a four-fold increase in continuum sensitivity. The dramatic improvement in frequency coverage, as well as the improvement in polarisation properties at 13 cm will enable a variety of new scientific studies, such as Magnetoionic tomography, Lunar-Cherenkov radiation, and deep continuum sky surveys. The proposed upgrade will allow the ATCA to continue to compete in the era of the EVLA, which will have continuous frequency coverage from 1 – 50 GHz by 2012. The proposed ATCA upgrade timeline, aiming for completion in late 2007, will bring the dramatically enhanced ATCA online several years in advance of the EVLA.

References

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