The Murchison Widefield Array in search of 'the dreamtime'

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Raman Research Institute, Bangalore is a partner in a large-scale multinational project for the development of a sensitive radio telescope called the Murchison Widefield Array (MWA), which will be deployed in the land of ancient aboriginal tribes in the Western Australia Outback. According to their mythology, 'the dreamtime' is a sacred epoch in the distant past when ancestral spirit beings created the world and laid down the laws and patterns for life. MWA will detect faint signals coming from the time when the first structures in the universe were formed – 'the dreamtime' in modern astronomy.

Keywords: Astronomy, Murchison Widefield Array, radio telescope.

ASTRONOMY was born and is nourished by our internal necessity and intellectual effort to make sense of and explain our natural surroundings. The questions astronomy seeks answers to are profound and fundamental in nature, attempting to shed light on the origin, evolution and structure of the vast universe. The essence of such questions far transcends any national, social or ideological boundaries, and sets the path for the emergence of large multinational research activities whose participating institutions are often scattered on different continents. This process is further strengthened by the current increasing demand for diverse scientific and engineering expertise, and the advances in global communication technologies. The scientific goals set for international projects of such scale place them at the forefront of scientific research, whereas the extensive interactions across international groups with diversified skills provide a unique environment for knowledge expansion and a breeding ground for new and innovative ideas.

Researchers at the Raman Research Institute (RRI), Bangalore have recognized the value and importance of being a partner in such global endeavours. Having a long history and expertise in low-frequency radio astronomy, RRI has joined a number of renowned institutions from USA and Australia, in an effort to design and build a novel radio telescope to explore astronomical phenomena in the low-frequency portion of the radio spectrum. The project is called the Murchison Widefield Array (MWA) and the consortium of institutions include the MIT Haystack Observatory, MIT Kavli Institute, Harvard-Smithsonian Center for Astrophysics, Australian National University, Melbourne University, Curtin University, Australia Telescope National Facility of CSIRO and RRI (http://www.wmatelescope.org).

'There were a lot of scientific and instrumentation activities related to MWA which were a natural extension of what we had already worked on at RRI', said Udayashankar (RRI), one of the coordinators for the MWA project. 'Two of the major scientific goals of MWA align with our interests and strengths, so we were quite happy to join the project and they were quite keen on getting us on their team', he added.

MWA is a novel radio telescope that utilizes 512 subarrays, referred to as tiles, distributed in a quasi-random fashion, to form an aperture array with large collecting area. The frequency range of operation for the MWA antennas is 80–300 MHz. Using modern computational power, the antenna outputs will be: (i) combined to form a single beam, and (ii) cross-correlated to form real-time wide-field synthesis images of the sky with unprecedented sensitivity. The MWA telescope operates in a frequency band that is highly cluttered with man-made radio frequency interference (RFI) which severely deteriorates the telescope sensitivity. To escape the strong RFI generated in thickly populated areas, MWA is being deployed in the remarkably radio-quiet Murchison region in the outback of the Western Australian desert (Figure 1).

The design of the MWA telescope is focused on achieving three key scientific objectives concerning: (i) the epoch of reionization; (ii) solar, heliospherics and ionospheric studies, and (iii) transient radio events. Researchers from RRI have aligning interests with their American and Australian colleagues in two of these three topics. The first one is the detection of the 3D brightness temperature fluctuations in the 21 cm line of neutral hydrogen during the epoch of reionization (EoR)[1]. 'The epoch of reionization is what a large section of the radio astronomy community nowadays is looking into, and

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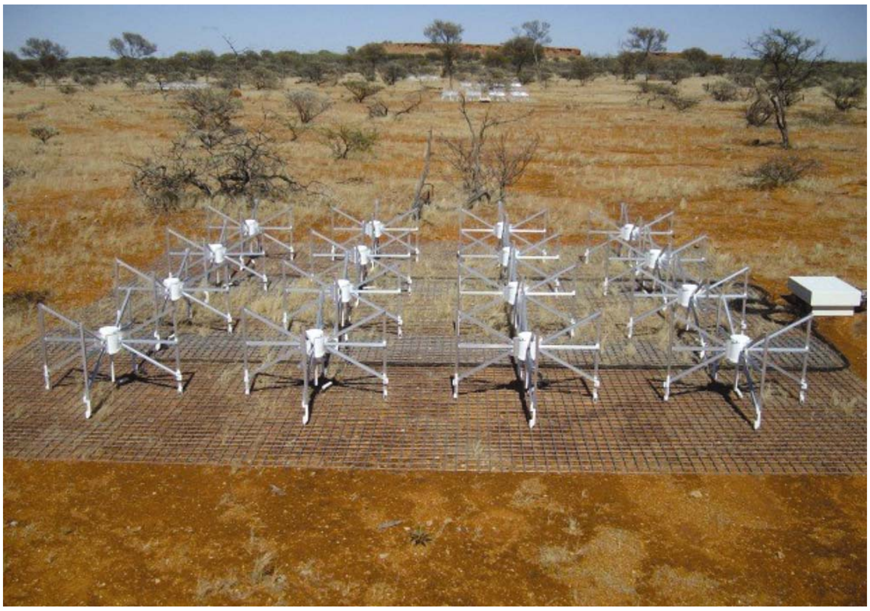

Figure 1. One of the 32 Murchison Widefield Array (MWA) tiles deployed on site in the Western Australian desert. Image credit: MWA Consortium.

therefore, it is the most exciting science related to the MWA project', commented Udayashankar. The largely uniform thermal glow from a time before the universe expanded and cooled to form neutral hydrogen is what we observe today as the cosmic microwave background (CMB). Then came the Dark Ages, devoid of luminous sources, an era of cold neutral hydrogen. Slowly, irregularities in the density of matter caused gravitational collapse in certain regions, heating the gas and creating the first luminous sources. The radiation emitted by these initial sources ionized the neutral gas creating expanding bubbles of plasma around them, which eventually re-ionized the bulk of hydrogen in the universe. This process was completed around a billion years after the creation of the universe. Since the 21 cm emission is the hallmark of neutral, and not ionized hydrogen, it can be used as a tracer of this reionization process – one of the unexplored frontiers in our theory of cosmic evolution. To probe deep into EoR, MWA will search to detect the faint signals of emission and absorption of the 21 cm hyperfine transition line in neutral hydrogen redshifted to frequencies around 200 MHz (http://www.wmatelescope.org). Such observations will provide information about the density, temperature and velocity of the matter during the EoR, from which important conclusions about the early history of structure formation and origin of the luminous sources can be deduced.

The required sensitivity for direct imaging of the extremely weak EoR signal demands a physical collecting area that is currently unfeasible. Therefore, MWA uses statistical detection approaches within a large effective field-of-view (1000 deg^2 at 200 MHz). Increasing the area of the sky that is observed (equivalent to increasing the number of independent samples), effectively leads to improved MWA sensitivity to the power spectrum (intensity versus wavenumber) of EoR signal fluctuations. To acquire 3D information in EoR signal, MWA will measure signal intensities across its field-of-view over a range of frequencies corresponding to different redshifts.

The second scientific objective of MWA which coincides with the interests of researchers at RRI aims at generating a survey of the dynamic sky with a sensitivity to transient radio events, which is six orders of magnitude better than the currently existing surveys. Despite the significant progress in our understanding of steady-state astrophysical phenomena, the difficulties associated with observations of transient events have left the physics of the dynamic universe a largely unexplored area until now. 'There is very exciting science with MWA about transient events. It is also a new branch in which radio astronomers have started to look into recently', said Udayashankar. Current advances in the software and hardware needed for transient radio observations were described by Morales *et al.* and serve as the basis for the proposed radio survey with MWA (http://www.wmatelescope.org). The primary advantage of MWA for transient event observations includes its wide field-of-view, excellent point-spread function, high sensitivity and varying time resolution (http://www.wmatelescope.org)[2]. To customize and optimize the MWA response to transient events, specialized software analysis tools will manipulate the cross-correlation as well as the voltage-sum sample streams of the 512 tiles[1]. These include analysis and observing routines for transient source observations on the timescales of 0.5 s to months[2]. Radio observations of the dynamic sky can provide information about the magnetic fields and non-thermal processes that drive many transient events. The MWA telescope will look at potential sources of radio transient emission like gamma-ray bursts, stellar, planetary and compact objects. The observing frequency band of the MWA telescope falls in the lower frequency range of non-thermal magnetohydrodynamic processes and the upper range of coherent radio source emissions, making it a powerful tool for studies of the non-equilibrium processes in dynamic astronomical phenomena.

The ambitious science goals of MWA have placed an exacting demand on the scale and quality of instrumentation. 'MWA is a new-generation radio telescope. No one in the past has designed and developed a system with such large number of elements', mentioned Udayashankar. The MWA telescope array is based on the so-called large-N design where hundreds of small, wide-beam antennas are spread over a large area and their signals are captured independently. Since the number of cross-correlation products for *N* antennas go as *N* squared, large *N* designs are riddled with gigantic data rates. Fortunately, the low-frequency range of operation, and tradeoffs in the number of tiles and field-of-view give a formidable, yet manageable data rate of 300 Gbit/s for MWA. Several such trade-off studies have helped in arriving at specifications for the key instrumental components, viz. antennas, digital receiver, correlator and real-time system.

Custom-designed, dual-polarization, active bow-tie dipole antennas are used for MWA. Sixteen such antennas are attached to a 5 × 5 m steel mesh to form a 4 × 4 array. This array forms one of the 512 MWA tiles. An analog RF beamformer located close to each tile receives the 32 signals (16 dipoles × 2 polarizations) and uses a true delay steering to form a tile beam (15–50° depending on the frequency) at a particular direction in the sky.

Researchers and engineers from RRI have contributed significantly to the design and development of the next step in the MWA signal chain – the digital receiver. The receiver digitizes, spectrally filters and formats 16 RF signals (coming from eight tiles for the two polarizations), before it sends the output through fibre optic cables to the correlator unit located about 2 km away. The receiver consists of: (i) an analogue signal conditioning board, for adjusting the power levels and bandwidth of the incoming RF signals; (ii) analogue to digital converters sampling the RF signal at 655.36 MHz; (iii) FPGA hardware, where the digital signals are divided into 24 coarse channels (of 1.28 MHz bandwidth), yielding an instantaneous, processed bandwidth for MWA of 30.72 MHz; (iv) hardware to accumulate and reformat the data before sending them to the correlator via three fibre optic cables; (v) a single-board computer to monitor and control the receiver node, and (vi) a sampling clock generation module. The digital circuitry of the receiver is located close to the eight tiles and housed in an air-conditioned and RF-shielded enclosure. Sixty-four digital receiver nodes are needed for the 512-tile configuration of MWA. Commenting on her experience while developing the receiver, K. S. Srivani (RRI) said: 'The FPGA board for the receiver arrived from CSIRO, but the FPGA programming and functionality was implemented by engineers at RRI. After collaborating with people with such expertise, we have learned a lot and acquired the skills to build our own boards in future.'

The digital data-streams from the 64 receivers are carried over 192 fibre optic cables to the correlator subsystem that performs spectral filtering and cross-multiplication using two FPGA-based boards called the polyphase filter bank board (PFB) and the correlator board (CBD). The PFB board splits each coarse channel into 128 fine channels (each of 10 kHz bandwidth) with the resulting number of data streams exceeding 3 million. The overwhelming task of cross-correlating these data streams is accomplished in the CBD, where correlation products (visibilities) are integrated for a period of 0.5 s and sent to the real-time system.

The real-time system (RTS) of MWA is implemented on a GPU-enhanced cluster and consists of: (i) a visibility integrator; (ii) a calibrator measurement loop; (iii) all-sky ionospheric and instrumentation calibration systems, and (iv) imaging software applications that produce real-time images of the sky (http://www.wmatelescope.org)[3]. The visibility integrator reduces the data resolution to 8 s. This time interval is considered an optimal choice taking into account the confusion limits and sensitivity of the array, as well as the timescales of the ionospheric variability. The calibrator measurement loop uses 100 calibration sources to create models, updated every 8 s, of both the ionospheric distortions and the MWA antenna beam. The all-sky ionospheric and instrumentation calibration systems are responsible for determining the ionospheric and instrument calibration for MWA. A major challenge in MWA calibration is achieving an accurate estimation of the full polarization response of the instrument, which is determined by the individual responses of the 512 tiles. This requires a precise measurement of the instrumental complex gain in a particular direction as a function of time, frequency and polarization for each of the 512 tiles. The imaging application of RTS produces calibrated images of the sky in both instrumental and Stokes coordinates, with an integration time of 8 s.

Despite the distant geographical locations of the participating institutions, members of MWA Consortium conduct teleconferences on a regular basis and assemble twice a year for week-long project meetings. During that time, the progress of the different groups is presented, existing or new problems and their possible solutions are discussed, and future directions for the project are identified. The last project meeting was held in Sydney, Australia at the beginning of July 2010. The latest developments during the 13th expedition to the MWA site and the progress made by various project groups were summarized.

'During our expeditions many system and scientific experiments have been carried out to prove and understand the concept of MWA', said Udayashankar. 'Currently, there is a 32 tile test-bed system set up on the site. Results of the fully operational 32 tile system that were presented in Sydney showed a satisfactory system performance with the expected dynamic range and sensitivity. These are very encouraging results for the MWA', he added.

The test-bed system which is operating in Murchison, Australia is a critical step in the development of the 512 tile system. Systematic errors in the instrument hardware and software have been addressed and successfully resolved during the expeditions to the deployment site. This has given the MWA consortium enough confidence to proceed with the mass manufacturing of the 512 tile-system components in the near future. Data collected during the recently completed X14 mission are also expected to provide insight into the challenging issues of foreground subtraction, calibration and imaging. A number of different groups involved in the MWA project, including researchers at RRI, are working in parallel testing different techniques and methods to tackle these problems. 'It is still debatable as to what is the best way to do foreground subtraction in MWA because of its novel design and the unknowns associated with the detection of the EoR signal', explained Harish Vedantham (RRI). 'At this point, the MWA team has achieved the desired level of foreground subtraction in simulations, which is a very promising result', he added.

At present, the calibration and imaging are carried out offline by various research groups from USA, Australia and RRI. 'We're refining the necessary pipelines and algorithms which will eventually be used in the real-time system', commented Vedantham. 'The very wide-field of view of the MWA causes the calibration and imaging techniques to be rather complex and involved. Our current processing pipelines have already produced good quality images', he added.

It is worth mentioning the enormous practical and logistical planning related to deploying the MWA telescope in the remote desert site in the Western Australia outback. The 32 tile system is deployed 30 km from Boolardy homestead that provides basic accommodation to the researchers on site. Perth, which is ~ 700 km away from the site, is the only place that provides sophisticated laboratory equipment for measurements, characterization and repairs. Safety regulations restrict the number of people allowed on site and require them to vacate the site before sunset, leaving little room for mistakes to be corrected during night-time observations. Temperatures in the desert (reaching 50°C in the summer) are harsh throughout the year, presenting serious challenges for the MWA cooling systems, as well as the researchers and engineers on site. The large number of cables that carry signals from each antenna are open and accessible to the abundant wildlife in the area. Stringent requirements apply to all equipment carried on site to preserve the RFI quiet environment.

In a video titled 'MWA: from the Outback to the Cosmos', Colin Lonsdale, the MWA project leader from MIT Haystack Observatory summarized the excitement and expectations associated with the project: 'The MWA is orders of magnitude more sensitive than anything that's done before in a number of different ways. And the sky in these frequencies is chock full of interesting things. There is no shortage of things to look at. It is just that up till now, it is been very difficult to get a clear view of these things. With the new technologies that we have in MWA, all of these remarkable phenomena will snap into focus. Furthermore, as these things come into focus many others which we never knew about will become visible to us (http://www.wmatelescope.org). Regarding what all this means to researchers in India, Udayashankar said: 'First of all, to the best of my knowledge, this is the first time that India is participating in an international consortium to built a telescope jointly. The amount of things we have learned while working step by step along with our collaborators spread across different continents has been and will continue to be an excellent working experience. EoR and transient science are two scientific topics which are very current and any participation in investigations of these two topics would be a very rewarding exercise for engineers, astronomers and all the Ph D students involved in the project from India.'

The 512 tile MWA telescope is anticipated in the Western Australia outback in the year 2012.

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ACKNOWLEDGEMENT. I thank Dr Udayashankar, K. S. Srivani and Harish Vedantham, RRI, Bangalore for their remarks and willingness to share the excitements of their research with me.

Received and accepted 13 January 2011