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The Murchison Widefield Array comes to fruition

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Abstract. The Murchison Widefield Array has now completed its construction phase (late 2012), its science commissioning phase (first half 2013) and has entered its full science operations phase since mid-2013. I will review the current status of the MWA instrumentation and the first scientific results from this exciting new facility for low frequency astronomy in the Southern Hemisphere. I will also discuss the MWA role in the SKA pre-construction program.

Keywords : instrumentation: interferometers – techniques: interferometric – techniques: radio astronomy – radio continuum: general – radio lines: general

1. Introduction

The field of low frequency radio astronomy is undergoing a resurgence in importance, fuelled by developments in technology (mainly computing and signal processing) and motivated by some of the most interesting outstanding questions in astrophysics and cosmology. Among the motivating questions, the nature of the transition from a neutral Universe to a fully ionised Universe as the first stars and galaxies forming during the first billion years of the Universe - the so-called Epoch of Reionisation (EoR) - looms large. Probes of the EoR uniquely require low frequency radio telescopes, ~50 - 250 MHz, as do a number of other areas of astrophysics (Bowman et al. 2013).

The conference to which this paper belongs, “The Metrewavelength Sky”, has illustrated these points well. During the conference we heard updates on the refurbishment of existing telescopes, such as the GMRT (contribution by Gupta), as well as efforts to establish new low frequency instruments, such as PAPER (contribution by Aguiree), LOFAR (contribution by Brentjens), and the Murchison Widefield Array (MWA: this contribution). The conference celebrated ten years of operation of the GMRT, but the new projects have only recently come to fruition - LOFAR had

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been operating for approximately 12 months and the MWA had been operating for approximately 6 months, at the time of the conference.

The MWA is the only Square Kilometre Array (SKA: Dewdney et al. (2010)) Precursor telescope at low radio frequencies. An SKA Precursor is a recognised SKA technology demonstrator located at one of the two sites that will host the SKA, the Murchison Radio-astronomy Observatory (MRO) in the Murchison region of Western Australia and the Karoo region of South Africa's Northern Cape. The MWA is sited at the MRO, along with a second SKA Precursor, the Australian SKA Pathfinder (ASKAP: Johnston et al. (2008); Johnston et al. (2007)). The MeerKAT SKA Precursor will be located at the South African site[1]. The MWA is sited at the MRO due to the extremely low levels of human-made radio frequency interference in this area of Western Australia, particularly within the FM band (87 - 108 MHz) encompassed by the MWA at the low end of its operating frequency range (80 - 300 MHz).

In this paper I will briefly re-cap the recent phases of the MWA project: construction (2012); commissioning (2012 - 2013); and operations (2013 - present), highlighting the science thus far undertaken and the significant science that is ongoing through operations. I will also briefly outline the role the MWA plays in the critical pre-construction phase for the SKA project, to be executed over the next few years.

2. Phases of the MWA project

The MWA system is fully described by Tingay et al. (2013a) and Lonsdale et al. (2009) and the overall science case for the MWA is described by Bowman et al. (2013).

For the MWA, a 32 tile (aperture arrays consisting of 4×4 grids of closely spaced dipole antennas) test array (32T) operated for two years from 2009, allowing the deployment of a number of generations of prototype hardware as well as system integration investigations, in advance of construction for the final instrument.

The 32T array also supported science-quality astronomical observations, in order to demonstrate on-sky performance. A number of science results have been, or will soon be, reported from 32T data. Williams et al. (2012) performed the first survey of the EoR fields, taking initial steps toward testing the imaging and calibration performance of the MWA system, detecting 655 radio sources with high significance in the 110 - 200 MHz band. The data of Williams et al. (2012) were used by Dillon et al. (2014) to explore real-world challenges in EoR signal detection and to place initial upper limits on the signal from the 32T data. Oberoi et al. (2011) published 32T observations of solar activity that unexpectedly showed a wide range of low level emission components, both narrow band and of short duration during quiet solar periods. Recently, Bell et al. (2014) published the first large scale search for transient and

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[1] http://public.ska.ac.za/meerkat

variable radio sources performed with 32T at 154 MHz, finding two variable objects, likely due to refractive scintillation or intrinsic variability. Bell et al. (2014) derive an upper limit on the surface density of sources $< 7.5 \times 10^{-5} deg^{-2}$ for flux densities >5.5 Jy, and characteristic time-scales of both 26 min and 1 yr. **?** demonstrated the ability of the MWA system to reproduce objects with extended emission with 32T by imaging the entirety of Centaurus A. And **?** showed initial promising results in terms of the polarisation capabilities of the MWA system from 32T data, detecting Faraday rotation for both point sources and galactic diffuse synchrotron emission.

As readers can see, 32T was a very useful scientific instrument in its own right. This phase of the project allowed the exploration of some interesting science, allowed the engineering team to prototype hardware and software in the field, allowed the management team to accurately schedule and cost the construction phase for the full instrument, and (perhaps most importantly) provided training for a large number of young and enthusiastic students and postdoctoral researchers at the MWA institutions. These people became familiar with the instrument, the challenges of working with MWA data, and managing a large-scale data flow. This was invaluable experience in prosecuting the commissioning and operational phases of the MWA project efficiently (which is what has transpired). Operation of 32T ceased in late 2011, in preparation for the start of construction for the final MWA instrument in early 2012.

Construction of the final MWA took place within calendar year 2012 and proceeded very quickly and efficiently, from the deployment of the supporting infrastructure (trenching for reticulation of power and data transport, power systems, and rack space within the central building provided by CSIRO), to the deployment of the antennas and in-field electronics systems, to the central signal processing systems and software systems. Rather than go into details of the construction schedule here, it is rather more instructive and interesting to see the story in pictures, recorded on the MWA Facebook page (http://www.facebook.com/Murchison.Widefield.Array).

By the middle of 2012, enough end-to-end hardware was deployed to the field, supported by the infrastructure, that engineering and science commissioning could commence. The plan was to alternate between commissioning activities and construction activities in the second half of 2012, building increments of 32 tiles, commissioning those increments as 32 tile arrays individually, and finally commissioning the full 128 tile array during the first half of 2013. This approach allowed the project team to verify the hardware in manageable increments and allowed the science and engineering teams to alternate responsibility for the instrument, breaking up the workload on individuals and sub-teams (important when working on an instrument at a site as remote as the MRO). This approach also allowed the science commissioning team to collect data for scientific purposes, as well as instrumental verification. With instruments such as the MWA, with very wide fields of view, it is difficult to devise verification tests for the instrument that do not go close to observations and data processing of science quality.

The most important scientific product from the commissioning phase will be the Commissioning Sky Survey, described in a paper currently under MWA collaboration review and due to be published in the first half of 2014 (Hurley-Walker et al. 2014, in preparation). This survey, based on two meridian drift scans at declinations of -26.7 and -47.5 degrees, covers 12 hours of right ascension and approximately 4300 square degrees of sky (more than 10% of the celestial sphere). The survey detected approximately 14,000 objects in this area in Stokes I. Thus far there has been one published paper using commissioning data, a study exploring the potential for the MWA to detect and monitor space debris, using the technique of passive, bi-static radar with FM radio stations acting as non-cooperative transmitters (Tingay et al. 2013b).

The MWA was fully commissioned by June 2013 and was officially launched into its operations phase by the then Australian Minister for Innovation, Senator Kim Carr on July 10, 2013. The MWA is operated under an Open Skies policy and observing time is allocated under Guaranteed Time (for MWA members only) and Open Access (for non-members) categories. Proposals are accepted for six month semesters and are evaluated by an independent and international Time Allocation Committee. As of writing, the first observing semester (2013B: July - December 2013) has been completed and time has been awarded for the second observing semester (2014A: January - June 2014). The allocations of time to individual projects can be found on the MWA web page (http://www.mwatelescope.org); substantial time has been allocated to all MWA science themes: EoR; transients; solar and heliospheric science; and galactic and extragalactic science. The MWA EoR collaboration has accumulated 350 hours of data in semester 2013B and has been awarded another 350 hours in semester 2014A and are keeping up with the data flow and processing very well. One of the most interesting and efficient programs is GLEAM, the GaLactic and Extragalactic MWA Survey. GLEAM will support a very wide array of different science goals and will prove to be a goldmine of information on the low frequency sky. GLEAM was awarded 114 hours in 2013B and another 140 hours in 2014A. Already publications from the operations phase are making their way to MWA internal collaboration review and a flood of papers from the prototype, commissioning and operations phases are expected to be in press by the end of 2014 and beyond.

Extension modes of MWA operations are currently being commissioning, with a goal of being available in the second half of 2014 (semester 2014B). These modes will most significantly consist of high time resolution and voltage capture modes, aimed at pulsar science, Fast Radio Bursts (FRBs), high time resolution solar studies, and other non-standard applications (space debris tracking, RFI studies etc).

3. The MWA and SKA pre-construction

As an official SKA Precursor, the MWA has certain obligations to the international SKA project. For instance, MWA technical and science expertise was used at the Concept Design Review (CoDR) stage for the low frequency component of the SKA.

Over the next few years, the MWA will serve a central role in the development of the low frequency SKA. During the construction phase of the MWA, the project decided to deploy more infrastructure than was required to support the 128 tile MWA. At the MRO, the MWA maintains significant reserves of power and data network in the field, excess rack space in the CSIRO central building on site, and excess capacity (with an ability to expand) on the long haul data transport network from the MRO to the $80m Pawsey supercomputing centre in Perth where MWA data are archived. This was a purposeful move to allow future expansion of the MWA or additions to the instrument.

A key use for this excess infrastructure has emerged as part of the SKA pre-construction phase. The Low Frequency Aperture Array (LFAA) consortium of the SKA project will seek to use the infrastructure to build and operate a series of low frequency verification systems. Undertaking LFAA prototyping and verification at the MWA site is highly efficient and cost effective for the SKA, as it will be possible to correlate SKA antennas against well-understood MWA antennas and process the data through the signal path and data analysis pipeline already in place and operational for the MWA. First steps in this direction have seen the establishment of the Aperture Array Verification System 0.5 (AAVS0.5) at the MWA and successful co-operation with the MWA. This work has taken place under the MWA External Instrument Policy and has already yielded valuable information regarding the performance of SKA candidate low frequency antennas. Over the next few years, leading up to the commencement of SKA construction at the MRO, it is hoped that larger verification systems will be deployed.

4. Final comments

The MWA project has been a long haul and at times has been a very challenging project. There have been a variety of reasons for this, but broadly speaking it has been challenging at a technical level, at an organisational level, and because we chose the best location on Earth for low frequency astronomy to build the instrument. This last point has meant that we have developed the instrument at a site where, up until a couple of years ago, no infrastructure existed. The MWA is greatly indebted to CSIRO for providing the magnificent facility that is the Murchison Radio-astronomy Observatory and for allowing us to build the MWA on the site, with ready access to base infrastructure. Even with this base, the MWA project has been hard work. But now that the MWA has been successfully constructed and commissioned, and is now robustly operational, we are reaping the rewards of our choice of location. The MRO is virtually RFI free. Tingay et al. (2013b) shows that for significant parts of the time, the strongest signals present in the FM band are those that have been transmitted from near Perth and bounce off objects in Earth orbit such as the International Space Station. Now that is a radio quiet observatory!

The MWA project has built up a wonderful team of operational staff, PhD students and postdoctoral staff across its 13 institutions. These people have largely learned their low frequency craft on the job, getting their hands dirty with the instrument, software and science. As a group, they are well placed to tackle what comes next, the low frequency SKA. As an engineering effort, a science program, and training ground for young scientists, it is already clear that the MWA is a great success.

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