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Results from the MWA EoR Experiment

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Abstract. The MWA EoR is one of a small handful of experiments designed to detect the statistical signal from the Epoch of Reionisation. Each of these experiments has reached a level of maturity, where the challenges, in particular of foreground removal, are being more fully understood. Over the past decade, the MWA EoR Collaboration has developed expertise and an understanding of the elements of the telescope array, the end-to-end pipelines, ionospheric conditions, and and the foreground emissions. Sufficient data has been collected to detect the theoretically predicted EoR signal. Limits have been published regularly, however we still several orders of magnitude from a possible detection. This paper outlines recent progress and indicates directions for future efforts.

Keywords. Epoch of Reionisation, MWA

1. Introduction

The primary science case for the design and construction of the Murchison Widefield Array (MWA) was the detection of the Epoch of Reionisation (EoR) signal from intergalactic neutral Hydrogen at redshifts in the range 7-11 (Tingay *et al.* (2013), Bowman *et al.* (2013)). The theoretical predictions of both the epoch and angular scale of fluctuations in the HI emission underpinned the architecture of small-D-large-N for the array, developing an experiment with a sensitivity tuned to the theoretically expected EoR signal. While the array has the theoretical sensitivity to detect the EoR signal, it is buried under about four orders of magnitude of signal from foreground sources, including the Milky Way (Morales & Wyithe (2013)). The expectation that the spectral smoothness of the foregrounds will enable removal has underpinned the design of the data analysis pipelines. However, after the first detailed analyses, the complexity of the task has now been re-calibrated, and new approaches are being tested. The current status of the MWA EoR experiment will be described, as well as some of the new directions being explored in the ongoing analysis. While the collaboration has several thousand hours of observations, at the present time, a noise floor is reached after a few tens of hours). The current focus is to identify the key contributors to this noise floor and establish whether these effects can be mitigated in software, or whether a re-design of the signal path is required.

Recent directions for the MWA EoR experiment include development of rigourous quality assurance metrics, exploration of the beam shapes, and its potential variation across the array, detailed end-to-end modelling of the analysis pipeline, and more careful modelling of the sources that are peeled from the images.

2. MWA Phase II

The original MWA array, now termed Phase I, comprised 128 tiles, each with 16 'bowtie' dipoles, randomly distributed over a core of about 2 square kilometers, with the longest baselines of about 3 kilometers. The concentration of tiles in a relatively small area

Figure 1. Southern Hexagonal array in the foreground with the core of the Phase I array in the top right corner of the image. Credit: Curtin University 2017.

provided excellent sensitivity to the EoR signal. It also allowed detailed characterisation of the large-scale signal from the galaxy. In Phase II, a further 128 tiles have been constructed, providing two new Hexagonal redundant arrays, each comprising 36 tiles, in an equilateral configuration with the Phase I core, plus new long baselines reaching up to 5 kilometers. Fig. 1 an image of the southern Hexagonal array, with the Phase 1 core also visible.

At the present time, the number of receivers for the array has not been increased, and so it is not possible to observe with all 256 tiles simultaneously. Thus two configurations have been designated, a compact configuration and an extended configuration, and the receivers are moved approximately once per year to enable different observational opportunities.

The compact array was specifically designed to enhance the detection of the EoR signal with two redundant cores, enabling direct comparisons between the calibration of a redundant array and a random array, while the extended array allows for a higher resolution image, enabling more precise quantification of the foreground emission.

3. Quality Assurance Metrics

At least three factors affect the quality of the data collected by the MWA. These are RFI, ionospheric variations and variations in the beam due to either tile-to-tile variations or missing dipoles. The latter will be more fully discussed in the following section. RFI mitigation is achieved using software developed by André Offinga, and is incorporated into the early stages of the EoR analysis pipeline using the program 'Cotter' (Offringa *et al.* (2015)). This effectively removes intermittent RFI above a threshold, though the Murchison Radio Observatory (MRO), where the MWA is located is relatively free of RFI.

All EoR data has been collected during nighttime, when the ionosphere is more stable. However there are still significant variations in he ionosphere above the MRO, which can be partially accounted for in the data analysis pipeline. Adam Beardsley (ref)

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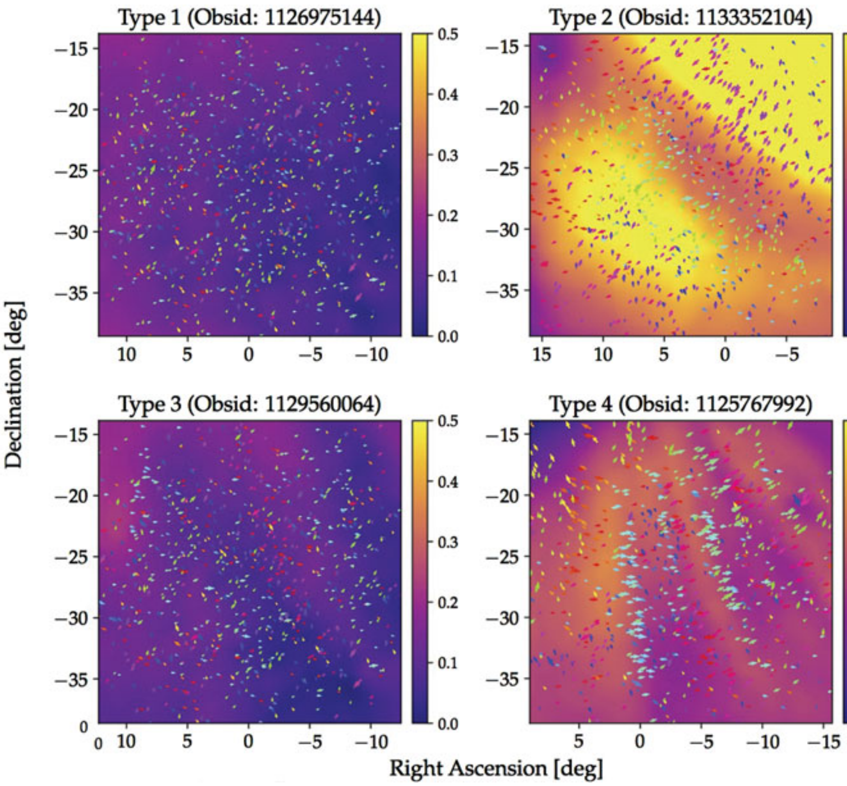

Figure 2. Examples of four different types of ionospheric activity characterised by the magnitude of the angular offset and the degree of correlation of the offsets (Figure 2 (Jordan *et al.* (2017))).

demonstrated that significantly stronger limits could be obtained by filtering the most affected data (check this). Subsequently, Chris Jordan has developed an algorithm to filter data taken when the atmosphere is most active (Jordan *et al.* (2017)). Fig. 2 shows four different manifestations of the ionospheric effects on EoR images. In this study, The Real Time System pipeline (RTS) was used to measure the positions of the 1000 brightest sources in the EoR0 field over 19 nights. The small tick marks show the ionospheric positional variation for each source, colour-coded by size. The background colour scale shows the reconstructed Total Electron Count (TEC) scalar field. The metrics developed by Jordan *et al.* (2017) measure the median magnitude of the ionospheric offsets and the degree of correlation, measured by the dominant normalised PCA eigenvalue. Four different 'types' of ionospheric activity were then charaterised, with either small or large magnitude offsets, and either weak or highly correlated offset directions, as depicted in Fig. 2. Fig. 3 shows a scatter plot of these two metrics for each data image in the sample. The fractional size of each population is approximately 74, 15, 2.3 and 8.4% respectively, with contours plotted on the diagram enclosing 90, 60 and 30 % of the density.

4. Beam Model

In order to peel sources from either the image or the visibilities, an accurate model of the beam is required. Early pipelines used an analytic beam model, but an early experiment of a test tile based at Greenbank Observatory demonstrated differences between the

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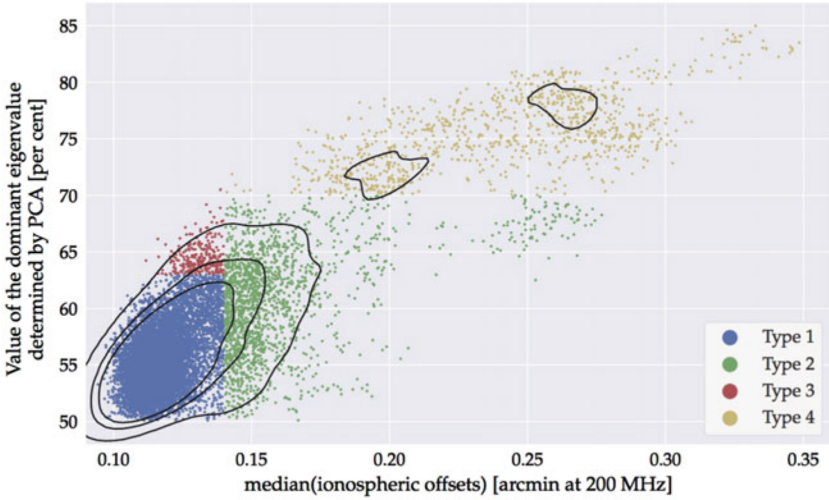

Figure 3. Scatter plot of the dominant PCA eigenvalue against the median ionospheric offset for each of the 4 types of ionospheric activity (Figure 1 (Jordan *et al.* (2017))).

theoretical and a measured beam (Neben, *et al.* (2015)). The measured beam used the signals from the ORBCOMM satellites at 137MHz, which provided both a strong signal and frequent passages of a satellite over the tile location. Differences were found between the theoretical and measured beam, in the sidelobes, at the few dB level. Motivated by this study, and using the same technique, Jack Line, Ben McKinley and collaborators have measured the beams of 8 tiles onsite at the MWA. Fig. fig4 shows the early results from these measurements, with a slice through a single beam, compared to the analytic model.

From the data collected to date, there are differences in the measured beam from tile to tile, and there are also differences between the theoretical beam and the measured beam at the few dB level in the sidelobes. However a number of questions remain: how great are the tile-to-tile differences; how can the beam shape at 137MHz (where it can be measured) be extrapolated to 170MHz where the observations are made; how does the true beam shape change off-zenith; does the dipole construction affect the measured polarisation; and finally how does the beam shape change if one dipole on the tile is dead. Further measurements will be required to flesh out each of these issues.

5. Modelling Foreground Sources

Removal the signal from foreground sources is crucial to detecting the EoR signal. A critical assumption enabling the detection of the EoR signal, is that foreground sources have smooth spectral energy distributions. A detailed sky model is then constructed, and the brightest sources are peeled from the image. For the statistical detection of the EoR signal, ideally any residual emission either from mis-subtracted sources or faint sources, will be confined to the 'wedge'. The wedge is the region in the 2D power spectrum, caused by the chromatic PSF of the instrument at low $k_{\|}$ and high $k_{\perp}$. Unfortunately signal from these foreground sources bleeds out of the wedge contaminating the region where the signal from the EoR can be measured. Thus considerable effort is being made to understand

A study of the EoR1 field imaged by the MWA shows that approximately 13% of sources are partially resolved with the MWA, including some of the brightest sources

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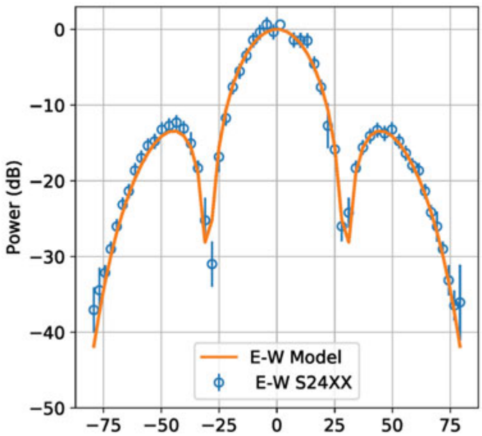

Figure 4. Single slice through a beam, showing both the theoretical model and the measured data points.

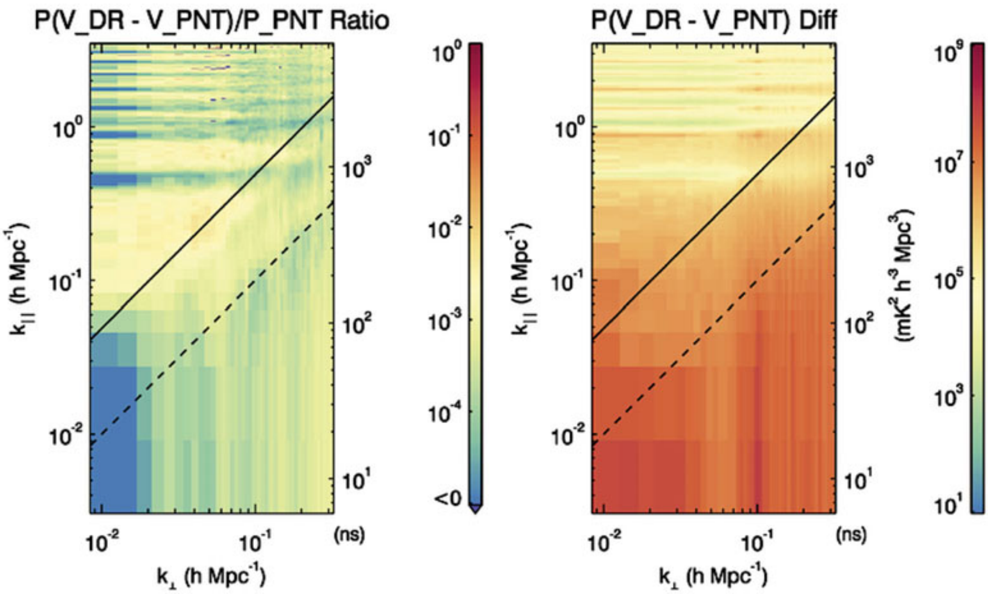

Figure 5. Left: ratio of the residual power in the PS when closely-spaced doubles are subtracted relative to when they are subtracted as point sources; Right: difference in power from peeling non-point sources correctly and as point sources (Fig. 5 Procopio *et al.* (2017)).

(Procopio *et al.* (2017)). The detailed sky model was built cross-matching sources from the GLEAM catalogue from the MWA (Hurley-Walker *et al.* (2017)) with the higher resolution TGSS (TIFR GNRT Sky Survey) (Intema *et al.* (2017)) using the PUMA cross-matching algorithm (Line *et al.* (2017)). The majority of sources resolved by TGSS are doubles, which were modelled as double point sources. Complex sources were modelled as multiple Gaussians based on the TGSS data.

Interestingly, there is little change in the calibration solution, with the new sky model. However the improvement in the location of signal in the 2D power spectrum is shown in Fig. fig5. This figure shows both the ratio and difference in the 2D power spectrum when closely-spaced doubles are modelled as point sources versus double point sources.

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Further analysis of the effect of detailed modelling of the complex sources is shown in Procopio *et al.* (2017). The challenge for a particular EoR dataset is to determine the optimal resolution and modelling for the sky model to be peeled from the image.

6. Final Comments

The best published limits from the MWA EoR collaboration were obtained by Adam Beardsley (Beardsley *et al.* (2016)). However since the publication of those limits significant progress has been made in understanding the ionosphere and data quality, the telescope beam, and modelling foreground sources. With all these improvements to the MWA EoR pipelines, we expect to publish signficant new limits during 2018.

Two final issues are worth remarking on. The analysis pipelines for the detection of the EoR signal are complex, and consideration needs to be given to verification of limits, and of course the potential detection of a signal. Within the MWA EoR Collaboration we have demonstrated that two independent pipelines are necessary to have confidence in any published limit (Jacobs *et al.* (2016)). As further limits are published, the MWA EoR collaboration will ensure that each analysis is cross-checked. Finally, as more detailed effects are filtered from our datasets, we need both understand which issues are most significant, and whether the mitigation strategies implemented are also affecting the EoR signal. Therefore it is crucial that hand-in hand with data analysis, full end-to-end simulations are undertaken to verify the pipelines.

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