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Self-calibration of highly-redundant low-frequency arrays – initial results with HERA

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Abstract

HERA is a highly-redundant transit interferometer with 14 m-diameter parabolic dish elements. We exploit the fact that the Galactic centre transits through the main beam of the telescope to attempt a conventional self-calibration approach to imaging and calibration. The Galactic centre provides a bright source which, we show, can be approximated as a point source sufficiently well to initialise the self-calibration loop and derive initial delays and antenna frequency-independent phases. Subsequent iteration using a more complex sky model derived from the data itself then converges to a reasonable bandpass calibration. The calibration solutions have good stability properties. We show therefore that the conventional self-calibration is a feasible parallel approach in addition to the redundant calibration already planned for HERA. The conventional imaging and calibration is useful as a cross-check to the alternatives being pursued in the HERA project, as a way of quantifying the performance of the hardware on the ground (and potentially identifying problems) and as a route to imaging and removing brighter continuum sources before power spectrum analysis.

1 Introduction

The Hydrogen Epoch of Reionization Array (HERA, DeBoer et al., 2016) is an experiment to measure the large-angular-scale redshifted H I 21 cm line signal from the Epoch of Reionisation (EoR, $12 \lesssim z \lesssim 6$). HERA is located at the Karoo Radio Astronomy Reserve in South Africa and as a scientific pathfinder for the SKA situated on an SKA site it has been designated as a SKA Precursor instrument.

The full HERA instrument will consist of up to 350 elements each of which is a 14 m-diameter parabolic antenna fixed in the transit direction. Of these, 320 elements will be arranged in a dense-packed hexagonal configuration and 30 will be arranged as outrigger elements on baselines up to 800 m. The instrument is being deployed in stages: in this paper we present measurements with the first 19 antennas; at the time of writing there are 37 antennas on the site and it is expected by the end of the 2017 calendar year there will be 128 operational antennas on the site.

HERA is designed to have highly redundant baselines to provide high sensitivity for the delay-spectrum analysis strategy (Parsons et al., 2012) as well as to enable redundant baseline calibration (Liu et al., 2010). These two techniques form the primary strategy for scientific data analysis for HERA. In this summary paper we show initial results of calibrating HERA with the conventional imaging and self-calibration approach with a view of investigating if this is a feasible parallel data reduction route.

2 Observations

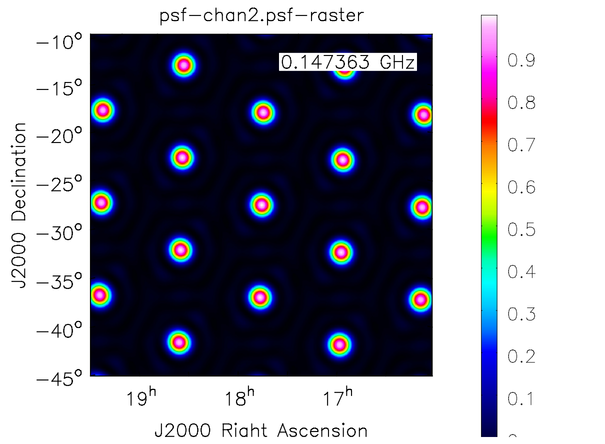
HERA observes continuously during the night hours. The observations we selected for analysis were made during June 2016 with 19 elements at the Karoo site. All of the elements were in a closed-packed hexagonal configuration. Observations from this time were chosen because the Galactic centre transits through the telescope main beam during this time. The observations consist of 1024 channels covering 100 MHz to 200 MHz and have an integration time of 10.7 s.

3 Calibration

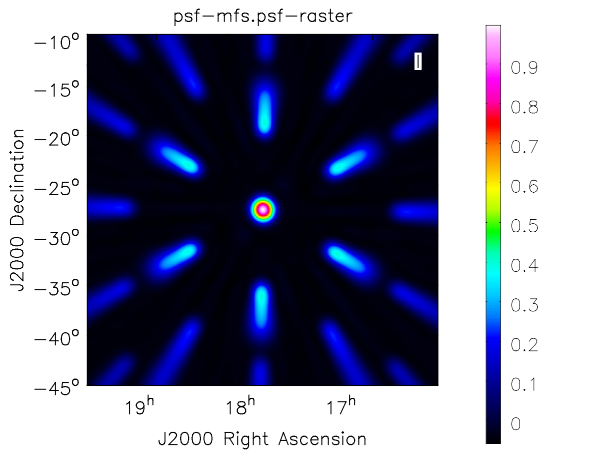
The strategy we employed was to derive the delays and initial frequency-averaged gain phase solutions from an initial sky-model consisting simply of a point source at the Galactic centre, then make an initial image of the sky which then was used for solving for the full-resolution band-pass calibration. All of the processing was done in the NRAO CASA package.

The calibrations steps for a dataset with the Galactic centre in the main beam were:

1. Carry out initial visual flagging of bad antennas (2) and channels affected with RFI
2. Insert a (flat-spectrum) continuum point source model for the Galactic centre
3. Use this point-source model for solve for the antenna delays and the mean antenna phase (i.e., phase averaged over the whole band)
4. Apply the delay and phase corrections and make an image of the sky using the MultiFrequency Synthesis (MFS) mode of CASA (Rau and Cornwell, 2011). The CLEAN components were constrained to be inside a



(a) PSF for a single channel (close to the middle of the observing band) map



(b) PSF for a multi-frequency synthesis map of the whole observed band (100 MHz – 200 MHz)

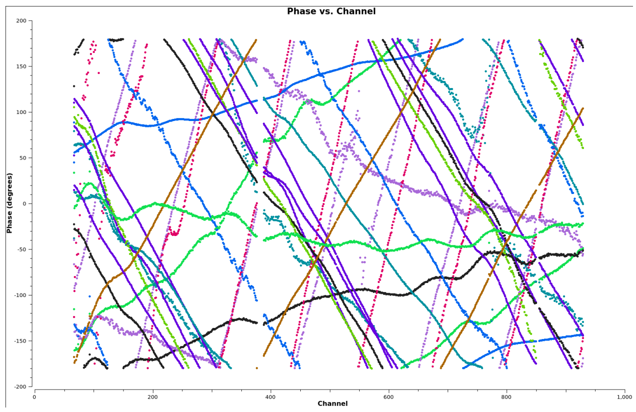
Figure 1. Illustration of the contrast between (a) a single-channel PSF and (b) multi-frequency synthesis PSF. The PSF was computed from a synthesis of about 20 minutes of data.

region corresponding to the nominal primary beam of HERA

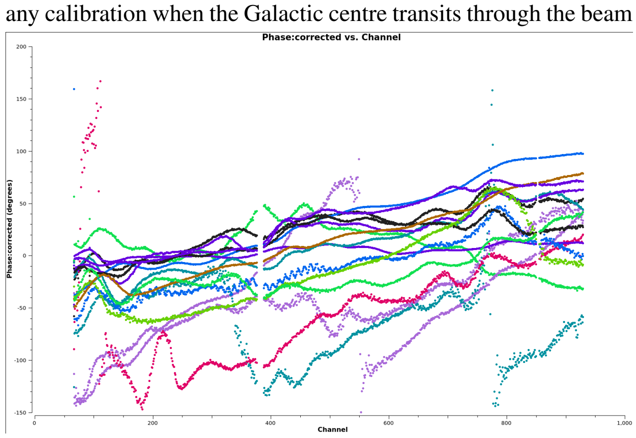
5. Using the CLEAN model derived in previous step, solve for the bandpass amplitude and phase at full spectral resolution

6. Apply the bandpass solution and repeat the imaging step for a visual check. Optionally repeat the cycle of bandpass calibration and imaging

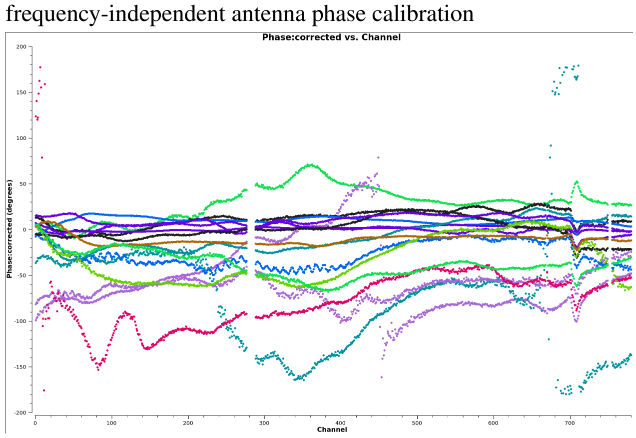
We found that use of MFS is essential for this process to converge both to decrease the point spread functions side-lobes (which are very pronounced due to the highly redundant configuration of HERA, see Figure 1) and to improve the signal to noise ratio.



(a) Fringes for all baselines to one of the HERA antennas before any calibration when the Galactic centre transits through the beam



(b) The same fringes as in (a) but after the initial delay and frequency-independent antenna phase calibration



(c) The same fringes as in (b) but after additionally correcting the band-pass response using the calibration based on the sky model derived from the data themselves

Figure 2. Illustration of the effect of calibration on the observed fringes when the Galactic centre is transiting.

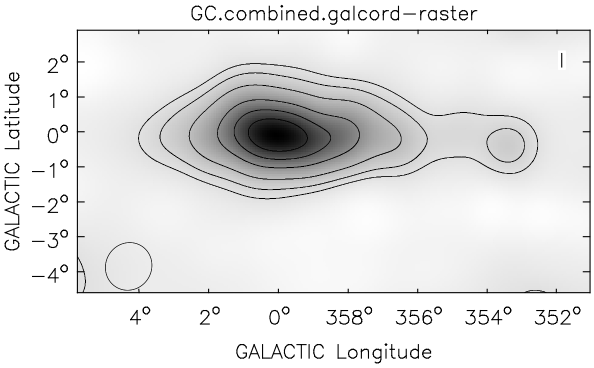


Figure 3. Final image of the Galactic Centre with HERA-19 using 20 minutes of data. The whole observing band was imaged as a continuum using multi-frequency synthesis. Contours are shown at $0.05, 0.1, 0.2, 0.4, 0.6, 0.8 \times$peak. The data have not been placed on an absolute flux scale.

4 Results

For the present analysis we've concentrated on datasets which have the Galactic centre transiting through the main beam. We find that the above procedure results in good calibration solutions as judged by:

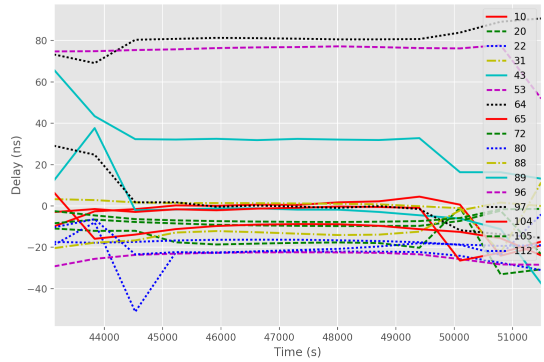
1. Feedback from CASA about the signal-to-noise ratio of the calibration solutions (few solutions are flagged due to insufficient S/N)
2. The fringe pattern after calibration, shown in Figure 2, is consistent with observations of a point-source dominated region of the sky
3. The resulting image of the sky, shown in Figure 3, is consistent with known structure in the Galactic centre

We have investigated the stability of the delay solutions when analysing datasets just before and just after the transit of the Galactic centre. The results are shown in Figure 4, where it can be seen that the good solutions are found for an hour-long period around the transit of the Galactic centres. During this time the delays are highly stable. As expected, when the Galactic centre is outside the main beam (the first few and last few points in Figure 4) it is not possible to solve for the delays using the Galactic centre point source model.

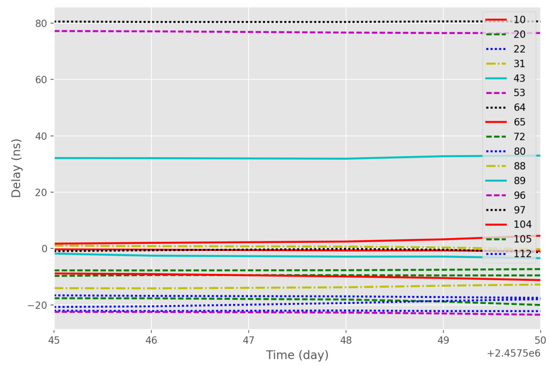
In the lower panel of Figure 4 we show the variation of the delay solutions for observations made at same local time over five consecutive days. The delays can be seen to have good stability over this period.

5 Discussion

We show that it possible to do a reliable calibration of a highly redundant array such HERA using the conventional self-calibration technique. Our calibration is initialised using a point source model for the Galactic centre and is then



(a) Antenna delay solutions derived from a sequence of 13 observations around the time of the transit of the Galactic centre. The fluctuations at the beginning and end are due to the Galactic centre being outside the main beam of the telescope at these times.



(b) Antenna delay solutions derived from a sequence 10 minute-long observations around the time of the transit of the Galactic centre on five consecutive days.

Figure 4. Illustration of the stability of the delay solutions made with observations of the Galactic centre during a day (top panel) and across different days (lower panel).

refined by making a map from the data itself and using that to solve for the frequency dependent structure of the antenna gains. The stability of the solutions is sufficient that it can be transferred in time to other fields, allowing these fields to be imaged and potentially making these other fields also useful for calibration.

This conventional imaging and calibration is useful as a cross-check to the redundant-calibration alternative also being pursued in the HERA project, as a way of quantifying the performance of the hardware on the ground (and potentially identifying problems) and as a route to imaging and removing brighter continuum sources before power spectrum analysis.

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References

DeBoer, D. R. et al.: Hydrogen Epoch of Reionization Array (HERA), ArXiv e-prints, 2016.

Liu, A., Tegmark, M., Morrison, S., Lutomirski, A., and Zaldarriaga, M.: Precision calibration of radio interferometers using redundant baselines, MNRAS, 408, 1029–1050, doi:10.1111/j.1365-2966.2010.17174.x, 2010.

Parsons, A., Pober, J., McQuinn, M., Jacobs, D., and Aguirre, J.: A Sensitivity and Array-configuration Study for Measuring the Power Spectrum of 21 cm Emission from Reionization, ApJ, 753, 81, doi:10.1088/0004-637X/753/1/81, 2012.

Rau, U. and Cornwell, T. J.: A multi-scale multi-frequency deconvolution algorithm for synthesis imaging in radio interferometry, A&A, 532, A71, doi:10.1051/0004-6361/201117104, 2011.