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PSA-64 POWER SPECTRUM

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ABSTRACT

Subject headings:

1. INTRODUCTION

The Donald C. Backer Precision Array for Probing the Epoch of Reionization (PAPER) is a dedicated experiment to measure the power spectrum of highly redshifted 21 cm emission from the Epoch of Reionization.

2. OBSERVATIONS

Here, we describe the features of the data set used in this analysis. We used the maximally redundant configuration of the PAPER array (see Figure 1 for this analysis, relying on all of the redundant baselines for the calibration procedure, but only using a subset of the baselines for the power spectrum analysis. For the power spectrum analysis we are using the baselines that correspond to the width between two columns (e.g. 49-41) as well as those that correspond to over and up and down one antenna (e.g. 10-41 and 10-58, respectively). These 154 baselines are used in the power spectrum analysis because they are instantaneously redundant and therefore they measure the same Fourier modes on the sky. The sensitivity of the array is mostly captured by these baselines.

The observation of the 64 antenna data set spanned a 135 day period that commenced on 2012 November 8 (JD62456240) and ended 2013 March 23 (JD62456375). Each baseline instantaneously measured the 100-200 MHz band which was divided into 1024 frequency channels of resolution 97.66 kHz and integrated for 10.7 seconds.

2.1. *Compressing the Data*

The raw described above constitue XX TB of data which can be cumbersome and time consuming to do meaningful science. Therefore, the raw data was reprocessed through a compression algorithm that comprised of chopping bits of data out that correspondend to parts of the sky that was not relavant to our science objectives. By applying fourier filters in the delay (Fourier dual of frequency) and fringe rate (Fourier dual of time) spaces, we are able disregard

3. SUMMARY OF IMPROVEMENTS FROM PSA32

In comparison to the previous PAPER pipeline (see Parsonsi, 2014), this analysis took a slightly different approach which included some important steps to improve our bottom line. In short, the improvements included using a new, refined redundant calibration method (Zheng 2014), increasing the width of the wideband delay filter that removes smothe spectrum foregrounds, weighting the lst binned data sets, and optimal fringe rate filtering.

Figure **??** shows the power spectra when each of the steps mentioned above are turned off and for the one where all of them are turned on.

4. ANALYSIS

Describe the overall flow of the data through of the pipeline.

4.1. *Calibrations*

4.2. *General*

The calibration pipeline included a rough calibration based on logarithmic and linear redundant calibration, as well as self calibration. A rough pass of log cal was first applied to the data on the basis of redundancy to match up baselines of the same separation. This included a gain calibration that set the flux scale to PictorA (Jacobs, 2013).

4.3. *Gain Calibration*

Gain calibration was derived on the basis of redundancy and self calibration.

4.4. *A First Pass*

Phase calibration was c

4.5. *Omnical*

The new element to our calibration pipeline was the use of the omnical package developed at MIT by Jeff Zheng (Zheng 2014).

4.6. *lstbinning*

After calibration, we then average and bin data in lst bins of

4.7. *WB delay filtering*

Galactic synchrotron and extragalactic point sources, generally foregrounds, greatly contaminate the EOR signal. They are roughly 9 orders of magnitude (Pober 2013a) above the expected level and EOR and can hide low order RFI events and cross-talk. Therefore, its removal is completeley necessary and required in order to obtain the desired EOR signal. In addition to dominating the EOR signal, foregrounds can corrupt higher-order k modes in the power spectrum measurement from the

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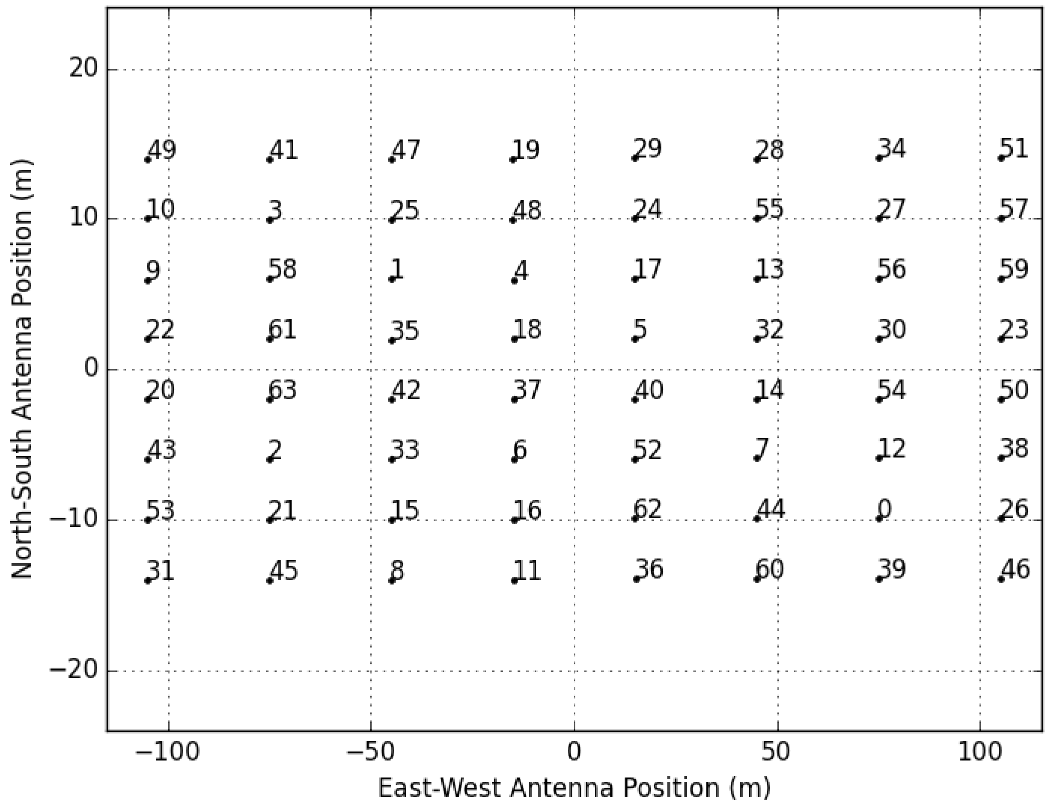

FIG. 1.— Antenna positions for the PAPER 64 observation run.

sidelobes arising from RFI flagging and the finite bandwidth used in the line of sight Fourier transform (corresponding to $k_{\|}$).

PAPER uses the delay filtering technique described in Parsons 2012b to remove smooth spectrum foregrounds that mask EOR. Followeing the technique described there, we first take the delay transform of every baseline for every integration, as per

$$\tilde{V} = \int W(\nu)S(\nu)V(\nu)e^{-2\pi i\tau\nu}d\nu, \tag{1}$$

where $V(\nu)$ is the visibility measured, $W(\nu)$ is a blackman-harris windowing function and $S(\nu)$ is the weighting function that encodes the flags for he data. Following the method in (Parsons Backer 2009), we use a CLEAN algorithm to deconvolve out the effects of RFI flags and band edge effects. FRI flags and the band edges have the effect of scattering foreground emission to higher order delay modes which would otherwise be uncontaminated. The implementation of CLEAN is such that it treats the RFI flags as a sampling function in frequency and iteratively fits to the highest point in delay space, and therefore trying to fill in the flagged data in frequency. We restrict these CLEAN components to fall within 100 ns of the horizon limit for a given baseline.

For the 30m baseline used, the cutoff corresponds

4.8. *optimal Fringe-rate filter*

Before forming power spectra we need to time average visibilities that measure the same k mode on the sky. This is the best way to combine data because we get a $\sqrt{N}$, where N is the number of samples, gain in sensitivity. This is in oppostion to weighting after forming power spectra, where noise beats down as the $\sqrt{N}$. Rather than a straight averaging in time, we can do better by using a weighted averge. Specifically, we want to upweight samples that have higher signal-to-noise.

This is acheived by applying a carefully crafted filter in fringe rate domain, the fourier dual to time. Different patches on the sky correspond to different fringe rates, for a given baseline and frequency. Maximum fringe rates are found along the equatorial plane where zero fringe rates are found around the poles (sources at the poles do not move through the fringes of a baselines). Sources on the other side of the pole, corresponds to negative fringe rates, because they move through the fringe pattern in the opposite direction. By weighing the fringe rates sampled by a baseline by the beam response of the baseline, gives us the optimal fringe rate filer to use for time averaging. See Parsons/Liu 2014 for a detailed discussion.

We implement the optimal fringe rate filter by first calculating the fringe rate of everypoint on the sky and weighting it the beam of a given baseline, summing along constant fringe rate contours, This is then squared to get the effective sensitivity of each fring rate bin (squaringe the power beam). That is we are upweighting fringe rate bins that have greater signal-to-noise. We then fit a gaussian to the optimal filter to have a smooth function, along with tanh function for to have a smooth cut off

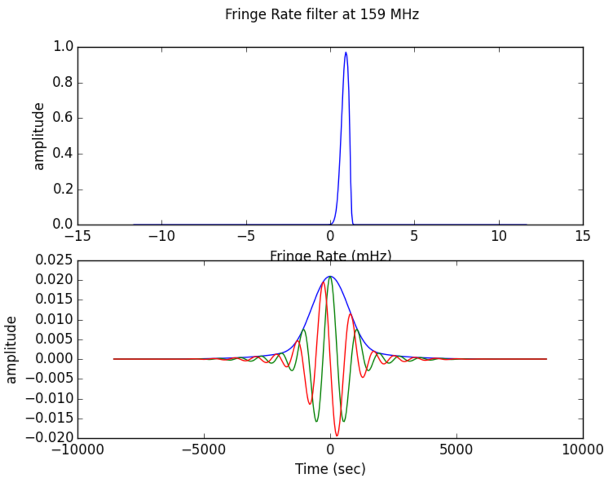

FIG. 2.— slice of a fringe rate filter at a frequency of 159MHz

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at the maximum fringe rate for the given baseline and frequency. Note that this only calculated for a given frequency and scaled to other frequencies, due to the fact that fringe rate scales linearly with frequency via

$$f_{max} = \frac{|\mathbf{b}_{eq}|}{c} \omega_{\oplus} \nu \quad (2)$$

To minimize edge effects in time we fourier transform the optimal fringe rate filter to get the time domain convolution kernel and apply it to each visibility for a given channel and baseline.

The exact implementation of the optimal fringe rate filter, uses a convolution kernel of 400 integrations. This has the effect of denoising the data as if it averaged over 4.75 hours with a weigthing function that is the beam weighted fringe rate. For each of the baseline types used (30 m baselines of different orientations).

Since the PAPER beam is 45 degrees, and the array is located at a declination of $-30°$ the fringe rates associated with the low signal to noise (down in the beam) correspond to very high and very low/negative fringe rates. Figure **??** shows a cut of the optimal fringe rate at MHz for a 30 m east west baseline. Therfore, the implemented fringe rate filter removes some sky signal, signal associated with fringe rates outside of the ranges shown in Figure **??**. Figure **??** shows that the applied filter removes sky associated with negative fringe rates and very high fringe rates.

5. RESULTS

6. SCIENCE

7. CONCLUSIONS

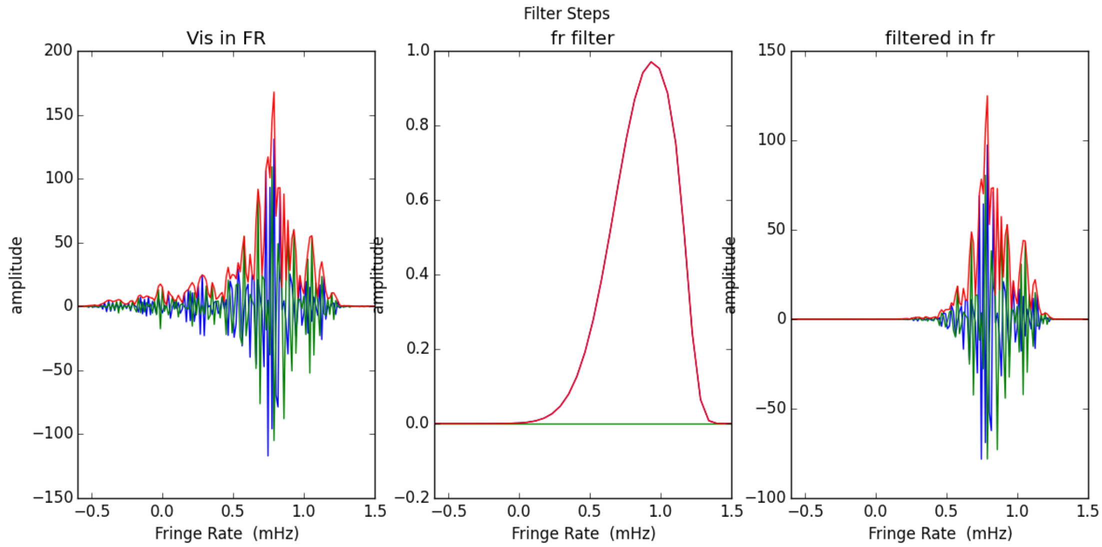

Fig. 3.— slice of a fringe rate filter at a frequency of 159MHz

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