Imaging sensitivity estimates for HERA

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June 11, 2013

Introduction

Here I estimate[1] the imaging sensitivity of the proposed HERA 576 antenna array by simulating the response to a reionization simulation. HERA576 is a 24 x 24 grid configuration of 10m dishes operating in 2m radio band. Adopting the more conservative foreground avoidance strategy, we would image "above the wedge" by limiting the bandwidth over which we might average. Here I choose 1MHz, which selects a window just above the highest delay bin at the longest baseline of 240m.

The punchline is the SNR map in Figure 4 which shows that in one season of observing, even under conservative assumptions, we clearly see localized HI emission at SNR$\gtrsim$3.

As input I use a simulation by M. Mcquinn with an apparent resolution of $25''$and size of $6°$. This simulation combines output from simulations at different redshifts to generate a simulation in "observer" units of sky position and redshift. To generate a suitable image from this simulation I extract a slice corresponding at 154MHz $\pm$ 1MHz, smooth to $2'$, and average in frequency. The image is then used as input to a visibility simulation. The simulation volume is formed from the provided ionization field I and density field D using the relation

$$T_b = \frac{26}{1+z}(1+D)(1-I)$$

Array Simulation

Input

The visibilities are simulated in CASA using the simobserve/simanalyze tasks. The primary beam is an Airy disk corresponding to a 10m dish at 2λ. A single 10 minute drift scan is simulated at 10s intervals, fitting within the 40 minute-wide FWHM primary beam. The flux conversion is set such that the output flux scale is consistent with the model smoothed to 25 $'$. The peak brightness in the raw simulation is 31mK. Smoothing to $2'$and

[1] including a few intermediate steps so the reader might follow along and perhaps spot any errors.

Observing Frequency	155MHz
Bandwidth	1MHz
z	8.16
Δz	0.119
λ	1.934m
dish size	10m
K	35mK/Jy
SEFD	21084 Jy
Antenna count	576
center spacing	20m
Nights	136
Time/night	45minutes
Total time	100 hrs
Theoretical noise limit/night	22μ K
after 100 hours	1.7 μK
sim size	1000Mpc/h
sim resolution	0.9Mpc/h
resolution	$25''$
peak flux (post smoothing)	12mK

Table 1: System and Observation Parameters .

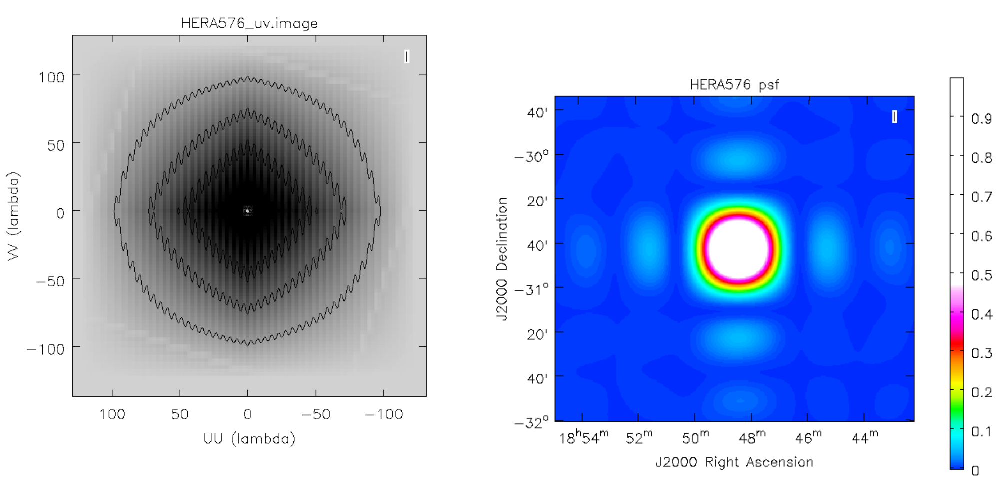

Fig. 1.— HERA576 uv coverage (left) and psf (right). The dynamic range of the psf peak to first side lobe is 22.

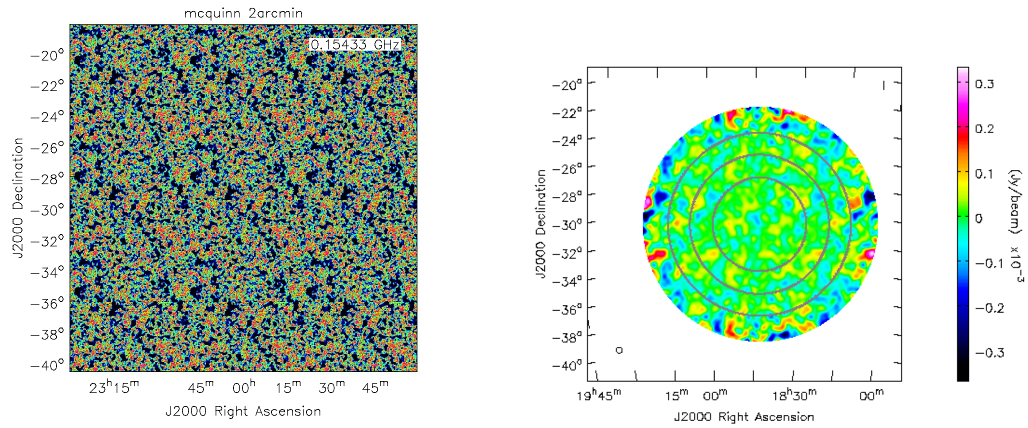

Fig. 2.— Left: Surface brightness model from M. Mcquinn centered at z=8, smoothed to 2′, averaged over 1MHz and tiled in a 3x3 pattern to cover 18°. Right: The simulated HERA response with primary beam response overlain in black.

averaging over 1MHz, the peak is 12mK this is the input to the simulation. As a comparison with the full simulation we further smooth to 25′, which reduces the peak to 7mK. Using Eq 9-25 of Taylor et al,

$$F = T_b \frac{2k_B\nu^2}{c^2} * S$$

(where S is the synthesized beam area) we can convert to flux. At 2′the flux is 1.8e-6Jy/bm, at 25′it is 2.3e-4Jy/bm. As we increase in psf size, the surface brightness sensitivity increases faster than the rms decreases due to the smoothing by the psf.

Noise

- The HERA conversion from surface brightness to per-baseline flux is

  $$\frac{\lambda^2}{2k_b\Omega} = 0.035K/Jy$$

  for a primary beam covering $\Omega = 0.04$ steradians.

- I simulated without noise and then did two noise simulations, injecting noise equivalent to 1 night and 100 hours

- Assume a conservative 600K system temperature for a per-baseline noise of

$$T_{rms} = \frac{600K}{\sqrt{1\text{MHz}40\text{min}}} = 13mK = 360mJy/bl \tag{1}$$

$$T_{rms} = \frac{600K}{\sqrt{1\text{MHz}100\text{h}}} = 1mK = 28mJy/bl \tag{2}$$

- Comparing predicted and simulated image noise (Table 2) suggests my noise simulations are basically coming out right.

- Noise contaminated images start to look reasonable after ∼100 hours Fig 3

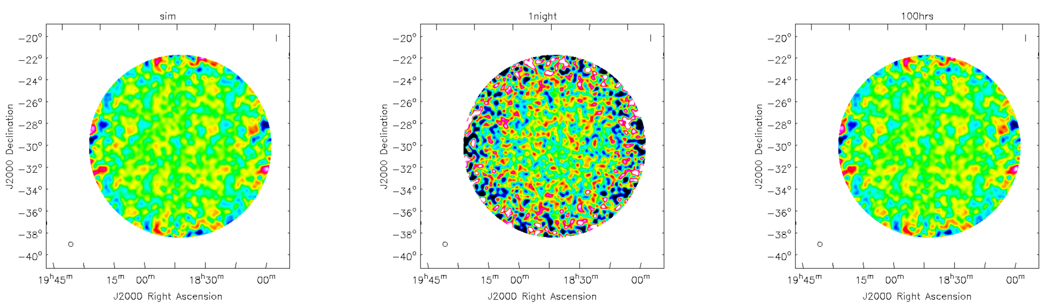

Fig. 3.— left to right: Dirty images simulated EoR as seen by HERA576 with no noise, 1 night and 100 hours worth of noise.

- SNR after 100 hours is typically 2 to 4. Large regions should be easily detectable.

Conclusion

Imaging that avoids foregrounds completely (above the "wedge") requires that only a very narrow bandwidth may be used. This limits imaging fidelity and sensitivity. However, the very dense uv sampling of the grid configuration, combined with the high sensitivity of the dishes offsets these costs to enable direct imaging of HI regions at z=8 and above. This limit is conservative as I assume a fairly high system temp, ignore any possibility of foreground subtraction and don't apply any optimal filtration, all of which could dramatically increase the SNR on individual regions.

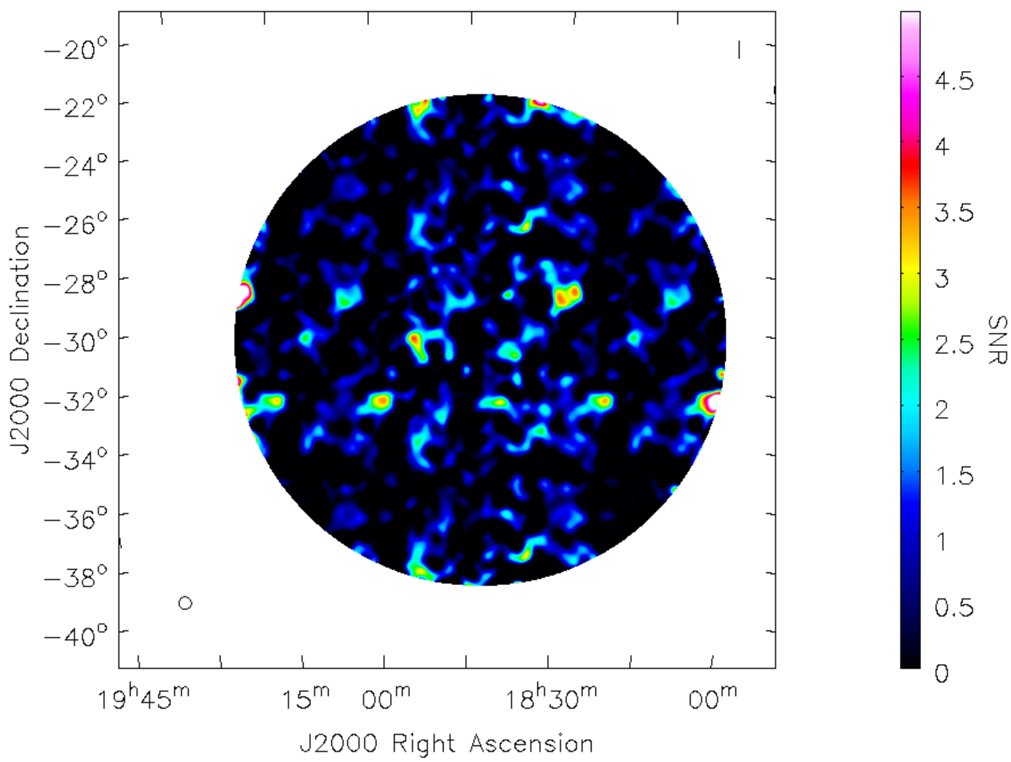

Fig. 4.— SNR of the 1MHz bandwidth field at z=8 after 100 hours (166 nights) of observing. Most of the HI features have SNR>2, many with SNR>3.

Simulation peak ($2'$)	12mK (1.8e-6Jy/bm)
Simulation peak ($25'$)	7mK (2.3e-4 Jy/bm)
Theoretical noise (1 night)	0.9mJy/bm
Theoretical peak SNR	0.32
Simulation rms (1 night)	0.277
Simulation peak SNR	0.85
Theoretical noise (100 hours)	0.07 mJy/bm
Theoretical peak SNR	3.3
Simulation rms	0.08 mJy/bm
Simulation peak SNR	**3.7**

Table 2: noise simulation parameters. The intention here is to double check that my simulated noise is coming out at about predicted amplitude. The residual rms differs from the theoretical noise rms by a factor $\sim \pi$. This is most likely a CASA peculiarity. Investigations ongoing... . However, when I smooth the noise map to make the SNR map, that level comes out as predicted. I suspect a conspiracy between competing normalization conventions. This is a fairly minor problem, but noted here for the good of Science.