HERA Imaging: Mock Observations using CASA
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C.L. Carilli[1,2], P. Sims[2]

ccarilli@aoc.nrao.edu

ABSTRACT

We present mock line and continuum imaging observations for HERA using the CASA simulator and imager. We adopt the HERA-350 'split-core' configuration of Dillon & Parsons. The sky line model involves a very wide field (45^o) line cube of the HI 21cm emission from the neutral IGM at $z = 10$ generated by 21cmFAST over 8MHz bandwidth. Two continuum models are explored: (i) a higher latitude continuum model extrapolated from existing observations of the diffuse Galactic emission plus a realistic approximation of the Extragalactic synchrotron emission, and (ii) a scaled version of the Effelsberg 1.4GHz continuum survey of the Galactic plane in the Galactic Center region. For the line imaging, we investigate the simple quetion: does HERA have the sensitivity and image fidelity at the given resolution to perform direct imaging of the neutral IGM in a reasonable integration time? The answer is clearly yes, with three-dimensional imaging of IGM structures with brightness fluctuations up to $\pm$13mK on tens of arcmin scales at 8σ. Of course, these results are highly idealized by assuming complete removal of the much stronger foreground continuum emission. For the mock observations of the continuum foregrounds, one interesting result arises from the natural high pass spatial filtering of the interferometer. The interferometer is not sensitive to the very large scale, mean continuum surface brightness, which dominates the sky brightness (400K for the adopted higher latitude model). Only fluctuations on the mean are detected by the interferometer, at the level of $\pm$10K. Hence, the dynamic range in the interferometric image of the continuum relative to the HI 21cm line fluctuations would be only $\sim 10^3$.

[1]National Radio Astronomy Observatory, P. O. Box 0, Socorro, NM 87801

[2]Cavendish laboratory, Cambridge University, UK

1. Introduction

We have performed mock observations for HERA-350 of both the cosmological HI 21cm line emission, and of the continuum emission at high Galactic latitude and toward the Galactic Center, which passes within 2^o of transit at the HERA site. We are well aware that the crux of the 21cm cosmology problem is dynamic range and continuum removal. However, extensive efforts are underway to address this problem. In this memo we consider the idealized case of sensitivity limited imaging for the line observations. We also consider the response of the interfermeter to large scale, diffuse continuum emission.

2. Sky models, mock observations, and imaging

We have generated models of the low frequency sky including both the HI 21cm signal and the continuum signal.

The HI 21cm signal was generated using 21cmFAST (Mesinger et al. 2007; 2011). In order to investigate very wide field effects, the input model is 45^o across, generated by tiling a series of line cubes with structure based on the excursion set analysis for the IGM during cosmic reionization (Sims et al. 2016; Furlanetto et al. Mesigner et al.). A very wide-band cube was generated, from roughly 100MHz to 200MHz, with 0.21MHz channels. From this, we selected an 8MHz band at $z = 10$, or 130MHz for the HI line, and for which the IGM in the model has a mean neutral fraction of 0.5.

The input sky model is in FITS image cube format, in units of Jy pixel^{-1}, with a pixel size of 85" (converted from the original Kelvin brightness unit). The model is folded through the CASA simulator, SIMOBSERVE, using the Dillon-Parsons (2016) 'split core' array for HERA-350. Thermal noise is added per visibility per channel. We assume a total integration time of 100 hours and 210kHz channels. We adopt a system temperature appropriate for the coldest region of the sky, and nominal array performance as given in de Boer et al. (2016). The theoretical noise per channel in the final image is then $\sim 50\mu$Jy beam^{-1}.

We then generate an image cube using CASA CLEAN. Natural weighting of the visibilities is assumed, and hence the results are heavily weighted toward the core 331 array. No CLEANing was employed, since there are no bright structures in the input model that require deconvolution. The primary beam is applied assuming an 'Airy disk' model for a 14m antenna. The field of view set by the primary beam at 130MHz has FWHM = 10^o, which transits in 40min. Hence, this observation would take 150 days.

We also 'observe' two continuum models. The first corresponds to a higher Galactic latiture field ($b = -78^o$). This model is also very wide field (45^o), and includes models for both the Extragalactic point sources, and the Galactic diffuse synchrotron emission based on existing low frequency observations but extrapolated to smaller scales in a statistically defensible manner (Sims et al. 2016). Again, noise is added per visibility, but now for a bandwidth of 8MHz. The thermal noise in the image would be $\sim 10\mu$Jy, however, at $10'$ resolution and 130MHz, the array is completely in-beam confusion limited at a level of order 1 Jy beam^{-1} (Sims et al. 2016). In this case, we employ Briggs weighting of the visibilities with Robust $= -2$ (close to Uniform weighting). The resulting synthesized beam FWHM = $10'$. The image is deconvolved using a multi-scale CLEAN with zeroth order multi-frequency synthesis. The HERA-350 array has a maximum out-rigger baseline length of 570m.

The second continuum model is based on the Effelsberg 1.4GHz continuum the Galactic Plane at $\sim 10'$ resolution and a pixel size of $4'$ (Reich et al. 1990). The model image is adjusted to 130MHz assuming a spectral index of -0.8. Visibilities are generated using SIMOBSERVE and thermal noise added for an 8MHz bandwidth and a high system noise expected for the Galactic Center (although, again, confusion dominates). We use Briggs weighting of the visibilities with robust parameter = 0, leading to a synthesized beam FWHM = $12'$, and again, we employ a multiscale clean. We image out to the 10% point of the primary beam. Note that the input model from the Effelsberg survey only goes to -32^o declination, hence the Galactic plane south of the Galactic Center is truncated (the Galactic center is at -29.0^o, while HERA is at a latitude of -30.8^o).

3. Results

3.1. Synthesized beams

Figure 1a shows the synthesized beam for Briggs weighting with Robust = 2 (Natural weighting). The synthesized beam FWHM = $25'$. The peak near-in negative sidelobe is -0.3% at a radius of $35'$. The peak near-in positive sidelobe is +2% at a radius of $74'$. For a grid array, the synthesized beam has serious grating lobes well outside the primary beam. Secondary 'triple' grating lobes, caused presumably by the split-core, are at 11^o radius, with a peak of 25%. The main grating lobes are at 19^o radius and approach unit response. Note that the HWHM of the primary beam is 5^o, so these grating responses are highly attenuated by the primary beam (roughly near the first and second null in the primary beam, respectively).

Figure 1b shows the synthesized beam for Briggs weighting with Robust = 0 of HERA. The synthesized beam FWHM = $12'$. The peak near-in negative sidelobe is -4% at a radius of 15′. The peak near-in positive sidelobe is +5% at a radius of 20′. In this case, the main grating lobes are again almost unity, at 19^o radius.

Grating lobes may be a problem if the primary beam has significant diffraction lobe response (> few percent), at very large distances from zenith (HERA is a transit telescope), and if there are bright sources that pass through these sidelobes.

3.2. Line imaging

Figure 2 shows two channels of 0.21MHz each (484 km/s at 130MHz). The color-scale is the input model smoothed with a Gaussian of FWHM= 25′, while the contours show the mock HERA observation. The HI signal on 25′ scales has peak to peak variations of about ± 0.4mJy beam^{-1} ($\sim$ 13mK), or roughly $\pm 8\sigma$, where $\sigma = 50\mu$Jy beam^{-1} = thermal noise per channel in 100 hours.

Figure 3 shows two example spectra through the 8MHz cube. Again, both the mock observation spectra and the smoothed (noise free) input model spectra are shown. Clearly, HERA has the raw sensitivity to image the three-dimensional structure of the HI 21cm emission from the neutral IGM, if the continuum can be removed.

3.3. Continuum imaging

Figure 4 shows the results on the higher Galactic latitude field. Fig 4a shows the input continuum model image scaled to 130MHz (color-scale), smoothed with a 10′ Gaussian and truncated at the 30% point of the primary beam. Fig. 4b shows the HERA mock observation.

Evident in Figure 4 is the natural behaviour of an interferometer as a high-pass spatial filter. The basic features are there, but gradients are greatly enhanced, and point sources are very much more prominent. Essentially, the input model brightness is dominated by very broad structures, with a mean brightess temperature of about 400K, and gradual gradients and fluctuations over the full field at from 350K to 450K. The interferometer is only sensitive to the gradients, ie. the mean is filtered-out, and the resulting brightness temperature fluctuations in the interferometric image are about ± 10K. This spatial filtering of the bright mean implies that the dynamic range of the continuum in the interferometric image relative to the HI 21cm line fluctuations is only $\sim 10^3$.

Figure 5 shows the results for the Galactic Center field. Shown is an overlay of the input Effelsberg image scaled to 130MHz (color-scale), and the HERA mock observation

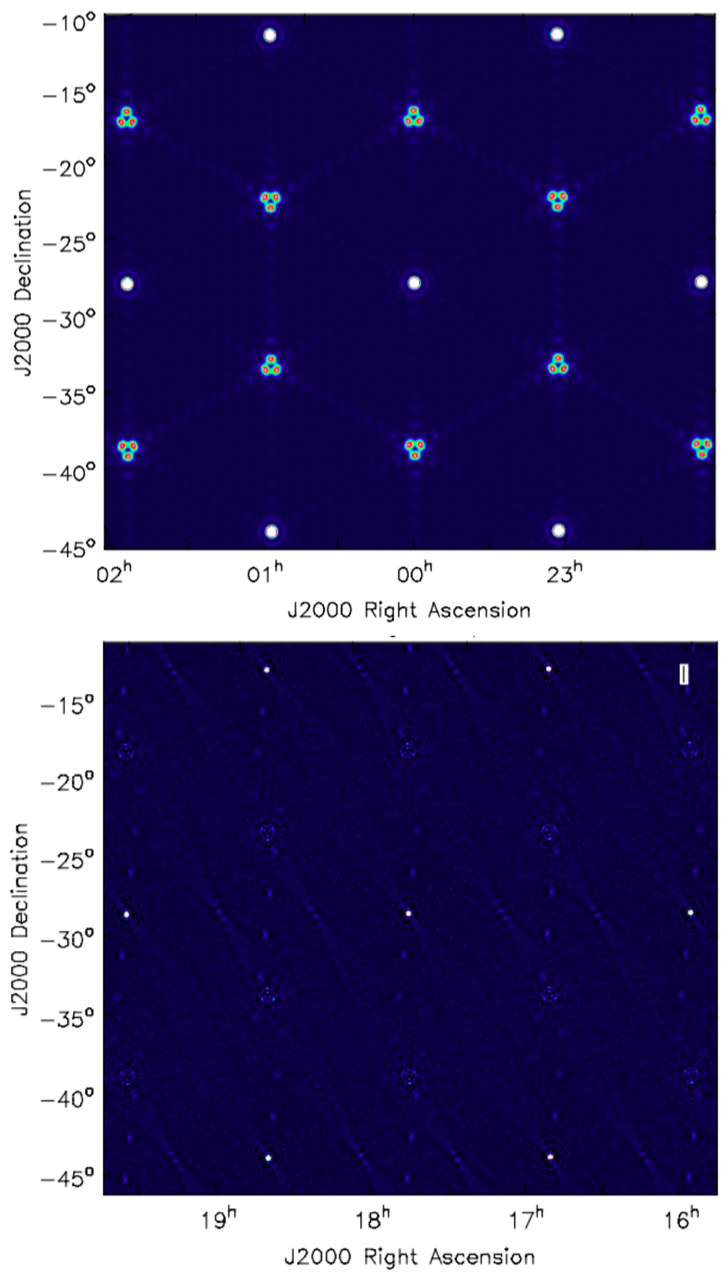

Fig. 1.— Images of the synthesized beam. Top shows the beam using Natural weighting. Bottom shows the beam with Robust=0 weighting.

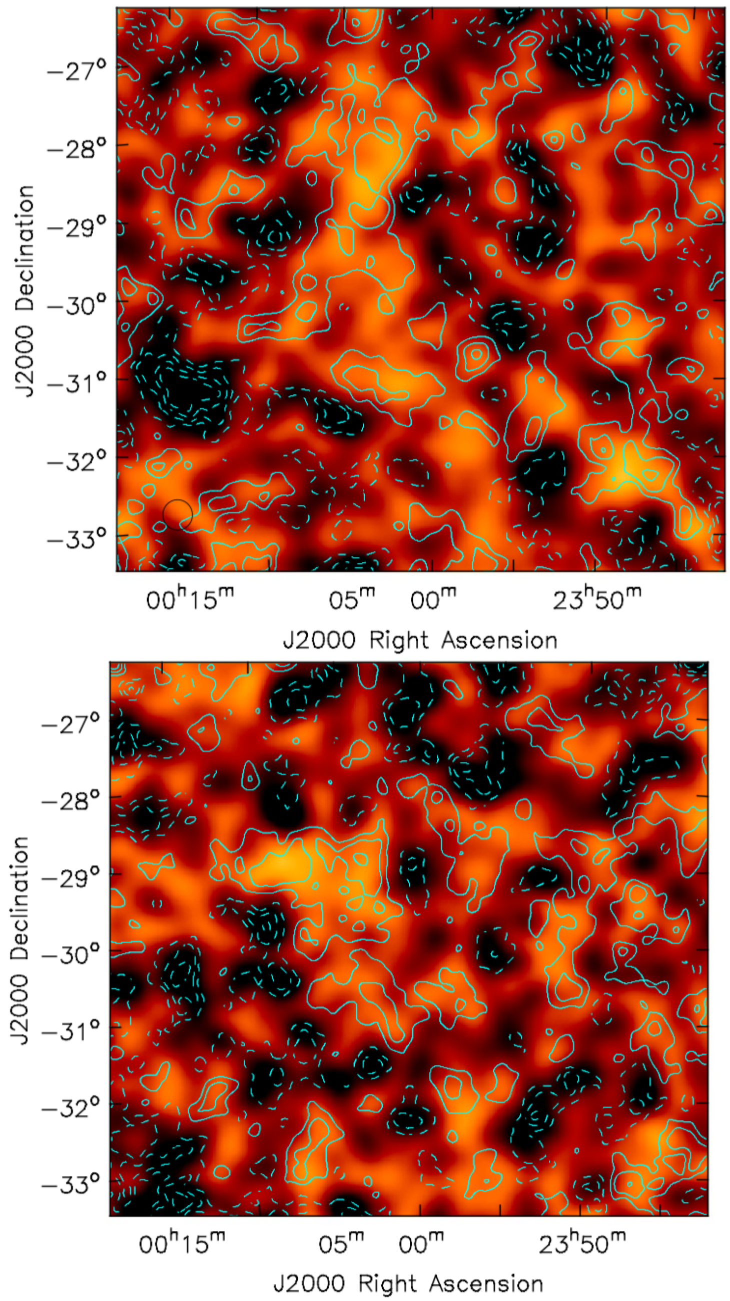

Fig. 2.— The color scale shows an input model image of the HI 21cm emission from the IGM at $z = 10$ (130MHz; Sims et al. 2016), smoothed with a $25'$ Gaussian. The contours show the mock HERA observation assuming 100 hours integration, with a resolution of $25'$. Two representative channels are shown from the 8MHz cube, and the channel width is 0.21MHz. The thermal noise per channel is $\sim 50\mu$Jy beam^{-1}. The contours are: -0.4, -0.3, -0.2, -0.1, 0.1, 0.2, 0.3, 0.4 mJy beam^{-1}. A primary beam correction has been applied, with a FWHM $= 10^o$.

(contours). The peak surface brightness on the HERA image is 2330 Jy beam^{-1}. Again, without total power measurements, the interferometer is not sensitive to the very large scale emission from the full Galactic plane, ie. scales of a few degrees set by the shortest spacings. Hence the plane sits in a elongated 'hole' in the interferometric image, leading to the sharp edges in the contours. Estimating roughly from the images, it appears structures larger than about 3^o are poorly restored by the interferometer.

4. Conclusions

We again emphasize that the line imaging herein is highly idealized, assuming full subtraction of the continuum emission, in order to address the basic question of thermal noise limited performance when imaging of the HI 21cm signal. HERA will have excellent spectral imaging capabilities, easily delineating IGM structures on tens of arcmin scales in three dimensions, if, somehow, the continuum emission can be removed. Such removal is a difficult task, due to the chromatic wide-field response of the interferometer coupled to the strong continuum foregrounds. Such coupling sets stringent demands on continuum subtraction and calibration requirements, as shown by Datta et al. (2009, 2010). Standard smooth-curve spectral fitting and removal to either the visibility spectra (UVLIN) or the resulting image cube (IMLIN), fails for these types of observations.

The continuum imaging analysis of the Galactic plane shows the capability of HERA to study large scale, diffuse Galactic emission. Of particular interest will be regions of thermal absorption in the plane, as well as large supernova remnants (Nord et al. 2006; Brogan et al. 2006). The broad band continuum spectra will be a powerful diagnostic in this regard.

One interesting result from these mock observations arises from the natural spatial filtering of the interferometer. The interferometer is not sensitive to the very large scale, mean continuum surface brightness which dominates the sky brightness at higher latitudes (400K, in this model). Only fluctuations on the mean are detected at the level of $\pm$10K for modeling. Hence, the dynamic range in the interferometric image of the continuum relative to the HI 21cm line fluctuations is only $\sim 10^3$.

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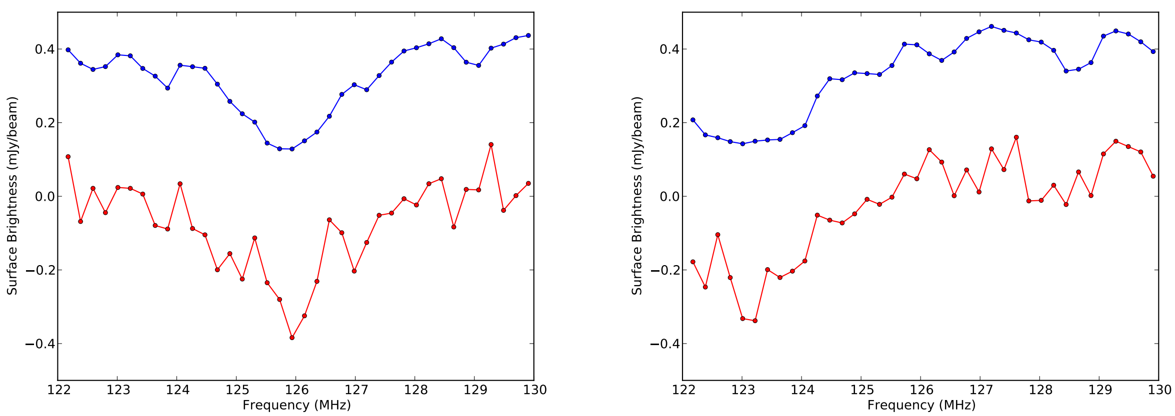

Fig. 3.— Two representative spectra through the mock HERA observed line cube. The red curves show the mock HERA spectra, and the blue curves show the spectra of the noise-free model smoothed to 25′ resolution. Note that the input model is positive-definite, while the interferometer without total power leads to a zero mean in the images.

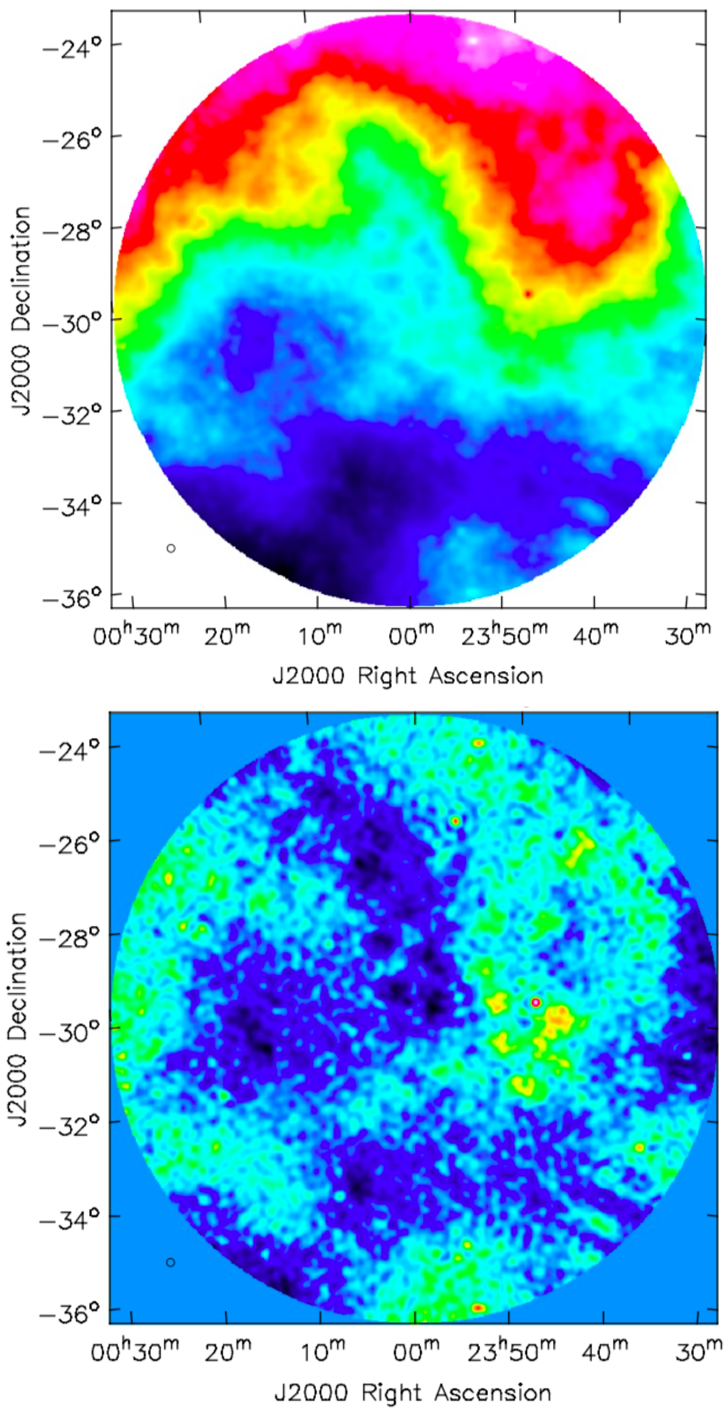

Fig. 4.— Continuum images of the high Galactic field at 130MHz. The smoothed input model is on top. The mock HERA observation with a resolution of $10'$ is on the bottom. A primary beam correction has been applied, with a FWHM $= 10^o$, and truncated at the 30% point. The input model has a mean brightness of 400K and large scale gradients from 350K to 450K, while the HERA mock observation has zero mean (as expected for an interferometer), brightness fluctuations at the level of ± 10K.

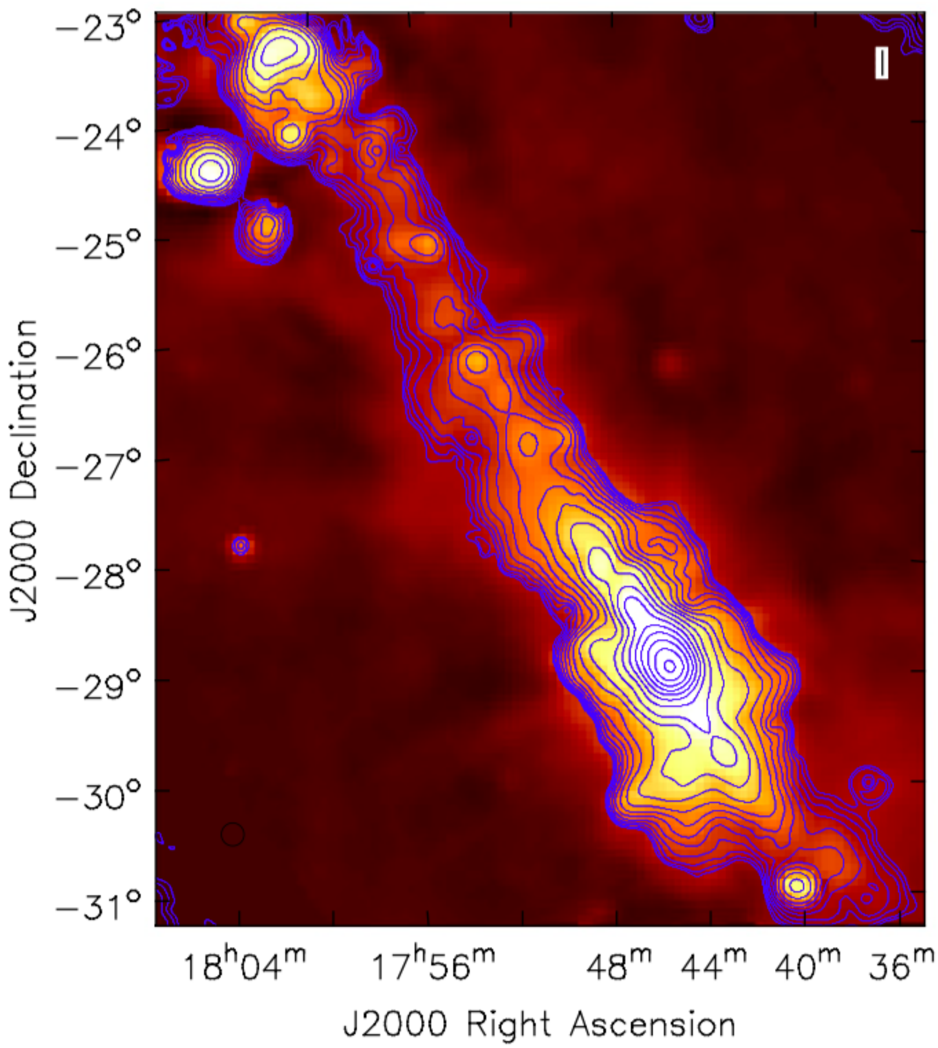

Fig. 5.— The color-scale shows an input model image of the Galactic center region based on the Effelsberg 21cm continuum survey (Reich, W. Reich, P., Fuerst, E. 1990). The contours show the mock HERA observation at 130MHz with a resolution of 12′. Contour levels are a geometric progression in square root 2, starting at 5 Jy beam^{-1}. The peak surface brightness on the HERA image is 2330 Jy beam^{-1}. A primary beam correction has been applied, with a FWHM = 10^o, and truncated at the 10% point.