HERA Mock Observations: Temporal Variations of Visibilities for a Transit Array
HERA Memorandum Number 14
June 15, 2016

C.L. Carilli[1,2], P. Sims[2]

ccarilli@aoc.nrao.edu

ABSTRACT

We investigate temporal variations in visibility amplitudes and phases for a transit interferometer such as HERA using the continuum and HI 21cm line models from Sims et al. (2016). We employ the CASA simulator and adopt the HERA37 configuration to generate a series of uv measurement sets, as the sky moves through the primary beam with time. We do not assume phase tracking – each measurement set is as if the phase tracking center was the zenith at a given time. The question addressed is whether the temporal variations of the complex visibilities for the continuum might be demonstrably different than for the line, and hence act as a further means for removing, at least in part, the strong continuum emission from HI 21cm cosmological observations. The answer is clearly not: the continuum and line observations show similar temporal structure, in terms of fractional variation in amplitude and phase as a function of time. The time variations in phase at a given frequency are a few degrees per minute for the shortest baseline, and 10% to 20% per minute in fractional amplitude. For completeness, we also model visibility spectra (amplitude vs. frequency) for the line and continuum separately. The continuum spectra show much smoother fractional structure in frequency that the line, by construction. While removing a first order polynomial as a function of frequency to the continuum visibilities removes 99% of the continuum, the spectral residuals are still an order of magnitude, or more, larger than the line signal. This is just another way of visualizing the 'wedge'.

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

[2]Cavendish laboratory, Cambridge University, UK

1. Introduction

This is the third in a series of memos investigating the response of the HERA array to the HI 21cm cosmological line signal, and the strong foreground continuum signal. We employ wide field continuum and line sky models from Sims et al. (2016), as described in HERA memos 12 and 13 (Carilli & Sims 2016). The mock visibility data sets were generated using the CASA simulator, again as described in Memos 12 and 13.

In this memo, we consider, primarily, the temporal behaviour of the visibilities at a fixed frequency due to the transit nature of the array. For a single point source, this drift would cause a systematic phase shift with time of the interferometric phase relative to the zenith, and the amplitude will rise and fall as the point source passes through the beam. For a complex sky, the behaviour is obviously more complex due to the multiplication of the drifting sky by the beam power pattern. It is not simple, *a priori*, to predict these changes, but easily calculated through mock observations (although tedious).

The question addressed is whether there is a difference between the temporal variations of the complex visibilities for the HI 21cm line signal vs. the continuum. The line signal shows essentially stochastic structure over a broad range of scales. The continuum is a mixture of diffuse Galactic synchrotron emission and extragalactic non-thermal point sources. On the short baselines in question (14m to 42m), the Galactic emission dominates (90% or more). Hence, it is possible that, if the continuum structure is much smoother spatially that the line, the temporal behaviour of the visibilities will also be smoother for a transit array.

2. Models and Modeling

The HI 21cm model was derived using 21cmFAST, as described in previous memos. The total field of view of $48^o \times 48^o$ was generated using tiling of smaller fields (see Sims et al. 2016).

The continuum model is comprised of three components: Galactic diffuse synchrotron emission, Galactic free-free emission, and extragalatic synchrotron point sources.

The spatial structure of the Galactic diffuse synchrotron emission was derived from the diffuse synchrotron component of a power spectral decomposition of a $48^o \times 48^o$ subsection of Remazeilles et al. (2015) bright-source-removed and destriped Haslam 408 MHz all-sky map, centred on (RA=0 degrees, Dec=-30 degrees). Power on smaller spatial scales than those measured in the Haslam 408 MHz survey is added to the map by estimating and extending the local power spectrum of the region of the map under consideration with zero-mean

Hermitian Gaussian random noise.

The spatial structure of the Galactic free-free emission model uses a model of Galactic diuse interstellar dust (Finkbeiner, Davis & Schlegel 1999) as an emission tracer with intensity equal to 1% of Galactic diffuse synchrotron intensity at 130 MHz.

The point source model is based on the Square Kilometre Array (SKA) Simulated Skies Simulation of Extragalactic Sources (Wilman et al. 2008). This is a simulation of extragalactic radio continuum sources out to a redshift of $z = 20$. The model includes contributions from radio-quiet active galactic nuclei (AGN), radio-loud AGN of the Fanaroff–Riley type I and type II structural classes, and star-forming galaxies. The latter population consists of quiescent and starbursting galaxies. The simulation method is 'semi-empirical', meaning sources were drawn from observed (or extrapolated) luminosity functions and grafted onto an underlying dark matter density field with biases parametrised by a double power law angular correlation function which reflect their measured large scale clustering.

For generation of the measurement sets, we start with the very wide field (48^o) line and continuum models described above. We then create a series of square sub-images of $40^o \times 40^o$ each, shifted by 2.5min (in time). We create 18 model images, corresponding to 42.5min total. This is roughly the transit time across the 10^o field of view FWHM of a HERA 14m antenna at 127MHz.

Mock observed visibility data sets were made for each time using the CASA simulator. We use the HERA37 configuration. We then analyze the temporal variation at a given frequency of the visibility amplitudes and phases. We do not add noise.

3. Results

3.1. Time variations of complex visibilities

Figure 1 shows the motion of the sky through the Field of View of the HERA antenna over 40min. The white circle is the FWHM of the primary beam power pattern at 127MHz. The model is a high latitude field from Sims et al. (2016). Figure 2 shows the same series, but now for the HI 21cm line model. It is clear that over 40min, the array sees a very different sky from start to finish.

Figure 3 shows the time variations of amplitude and phase for channel 22 (126.77MHz) for the continuum model. The baselines shown are: blue = shortest = 14m, red = mid = 28m, green = long = 42m. The amplitudes vary from a few Jy on the longest baseline, to 100Jy on the shortest baseline. Again, no phase tracking is applied, ie. these correspond the complex visibilities as if the zenith were the phase center for each time.

Figure 4 shows the time variations of amplitude and phase for channel 22 of the line model. The amplitudes are a few mJy.

Looking at the phase variations, the variations with time for the line and continuum models are of similar magnitude. On the shortest baselines, the fastest variations are $\sim 4^o$ per minute, while on the longest baselines the variations can be faster, up to $\sim 30^o$ per minute. The dominant effect is likely caused by the largest structures shifting through the primary beam.

The temporal behaviour of the visibility amplitudes for both line and continuum are also of similar magnitude, showing fractional variations up to $\sim$ 10% to 20% per minute. The rate is not strongly dependent on baseline length.

The obvious implication of these results is that the qualitative behaviour with time of the complex visibilities is not significantly different for the line vs. the continuum signal. Hence, temporal variation is not a potential method for removing some fraction of the continuum through eg. smooth curve fitting in time.

A second implications is that, when averaging visbilities in the compression stage, the averaging time needs to be shorter for longer baselines in order to maintain coherence. For example, to avoid phase changes by $> 30^o$, the averaging time for the 42m baselines should be < 1 minute . Fringe stopping might slow this down (I think), but that is not the nature of the measurements being considered for HERA as a transit instrument.

Of course, the results clearly depend on the input assumptions for structure in the models.

3.2. Visibility spectra

For completeness, we plot some visibility spectra, ie. amplitude vs. frequency, for one of the temporal models. Figure 5 shows the continuum spectra for the three baselines. Figure 6 shows the HI 21cm line spectra. In this case, three 30sec 'records' are shown at each frequency point, corresponding to a fringe-stopped observation over 90sec. This provides some indication of how quickly the visibilities vary if fringe tracking is applied.

As expected, the line signal shows a 'stochastic' behaviour with frequency, with amplitudes up to $\sim$ 4 mJy. The continuum shows very smooth structure in frequency, with amplitudes up to 100 Jy on the shortest baseline, and a few Jy for the longest.

As a test of continuum subtraction, a linear baseline in frequency was fit and subtracted from the continuum UV spectra using UVCONTSUB in CASA. The residuals are shown in Figure 6. The residuals show variations of about 1 Jy for the short baselines, and about 50mJy for the longest. While these residuals are only 1% of the amplitudes before baseline removal, they are still more than an order of magnitude larger than the line signal. This is just another way of visualizing the 'wedge'.

References

Carilli, C. & Sims, P. 2016, HERA Memo. No. 12

Carilli, C. & Sims, P. 2016, HERA Memo. No. 13

Finkbeiner, D., Davis, M., Schlegel, S. 1999, ApJ, 524, 867

O'Dea, C. 1998, PASP, 110, 493

Remazeilles, M. et al. 2015, MNRAS, 451, 4311

Rogers, A & Bowman, J. 2008, AJ, 136, 641

Sims, P. et al. 2016, MNRAS, submitted.

Wilman, G. et al. 2008, MNRAS, 388, 1335

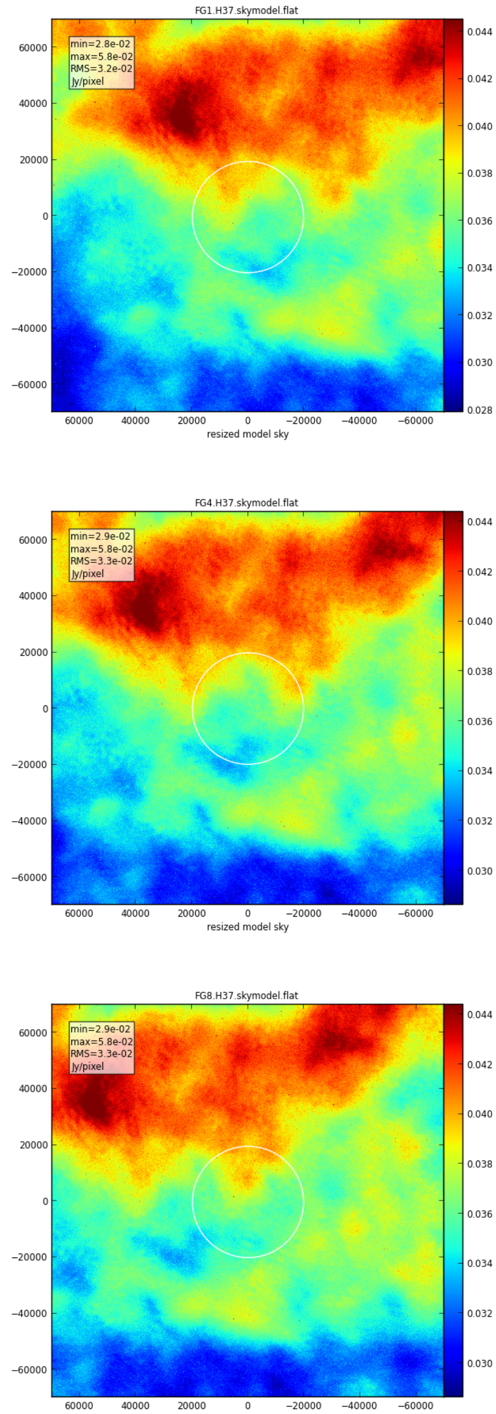

Fig. 1.— Movement of the sky through the primary beam of HERA over 40min. The white circle shows the HERA primary beam FWHM at 127MHz. The model is the synchrotron continuum for a high Galactic latitude field from Sims et al. 2016.

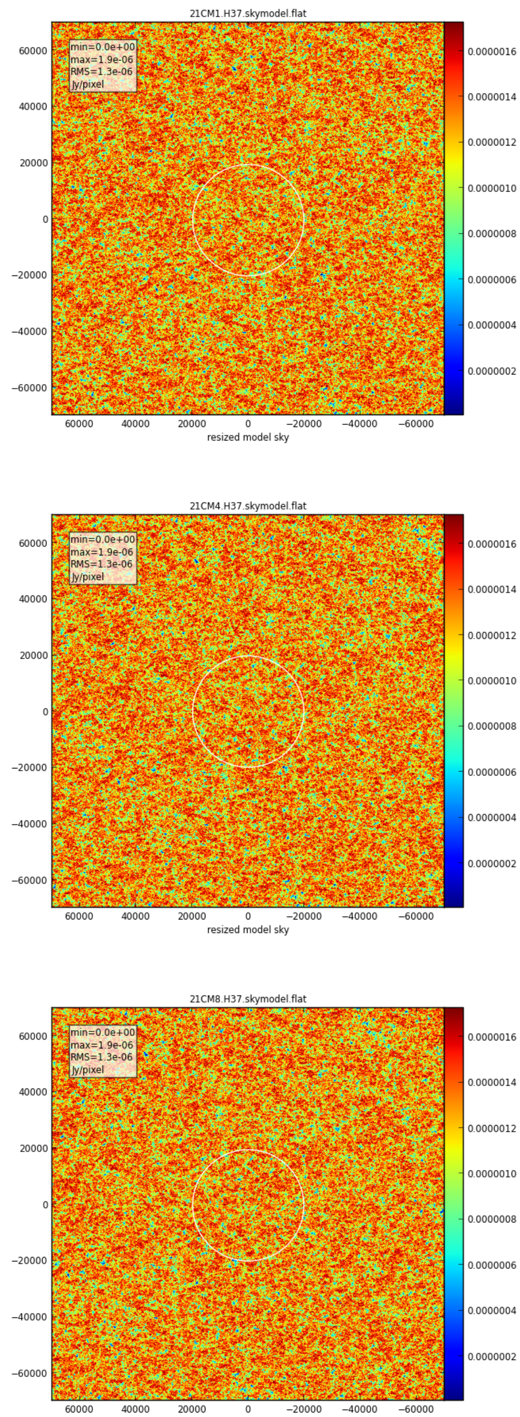

Fig. 2.— Movement of the sky through the primary beam of HERA over 40min. The white circle shows the HERA FWHM at 127MHz. The model is the HI 21cm line signal from Sims et al. 2016.

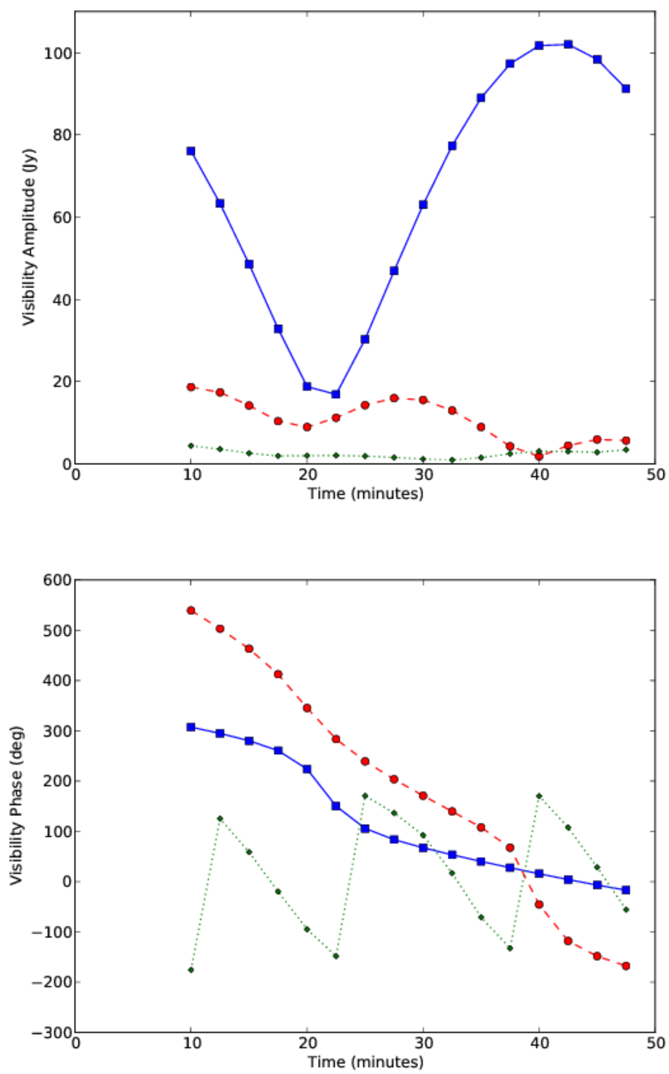

Fig. 3.— Visibility amplitude and phase for the continuum emission for channel 22 (126.77 MHz) versus time for a transit array such as HERA. No fringe stopping (delay tracking) is applied. Each measurement is averaged over 30sec. The blue is the shortest baseline of 14m (Ant 0 and 1). Red Antenna 0 and 2, baeline = 28m. Green is antenna 0 and 3, baseline = 42m. Note that for the phase curves, the phase is ambiguous by 360^o. These ambiguities have been 'unwrapped' for the blue and red curves, but not for the green curve.

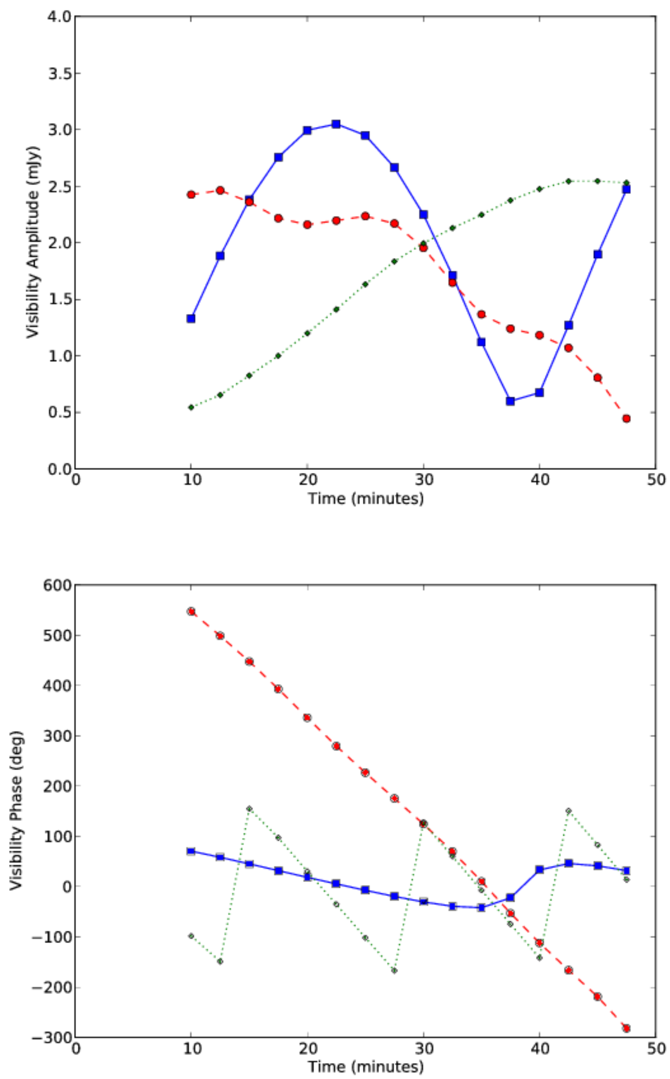

Fig. 4.— Visibility amplitude and phase for the line emission for channel 22 (126.77 MHz) versus time for a transit array such as HERA. No fringe stopping (delay tracking) is applied. Each measurement is averaged over 30sec. The blue is the shortest baseline of 14m (Ant 0 and 1). Red Antenna 0 and 2, baeline = 28m. Green is antenna 0 and 3, baseline = 42m. Note that for the phase curves, the phase is ambiguous by 360^o. These ambiguities have been 'unwrapped' for the blue and red curves, but not for the green curve.

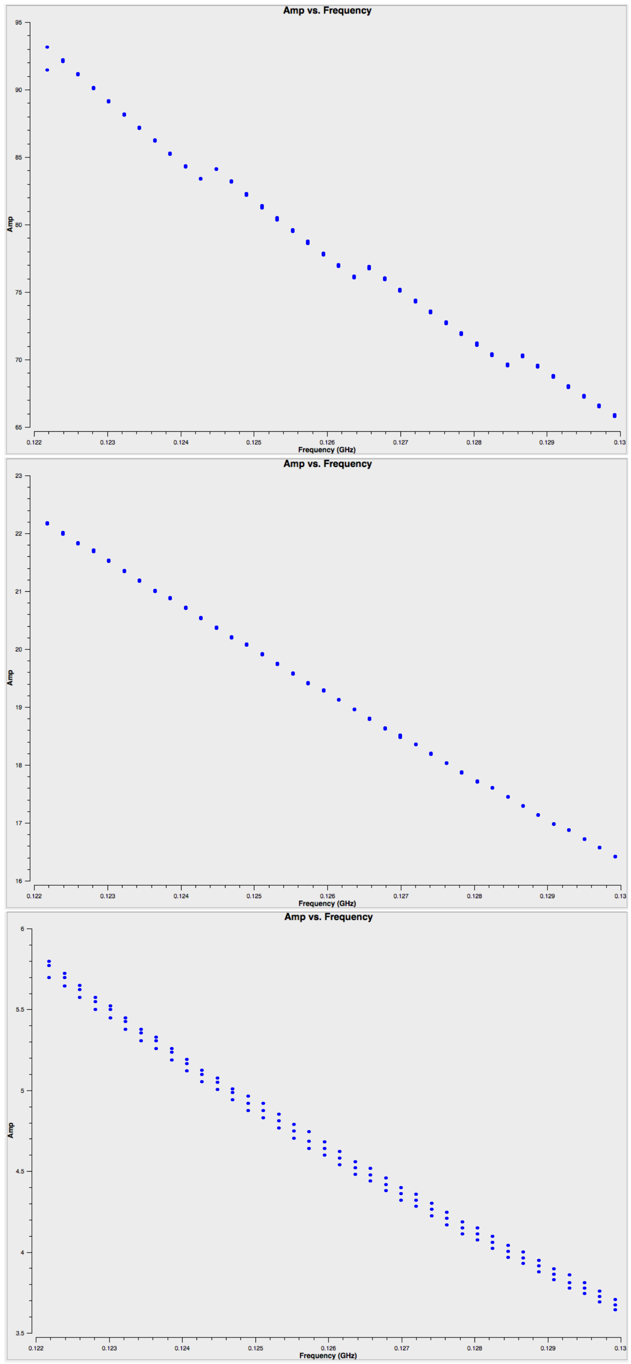

Fig. 5.— Continuum model visibility amplitude versus frequency for baselines 0-1 (top), 0-2 (middle), 0-3 (bottom) for one time step in the modeling. The amplitudes are in Jy. Note that three 'records' of 30sec each are plotted per point, hence the verticle extension in some cases.

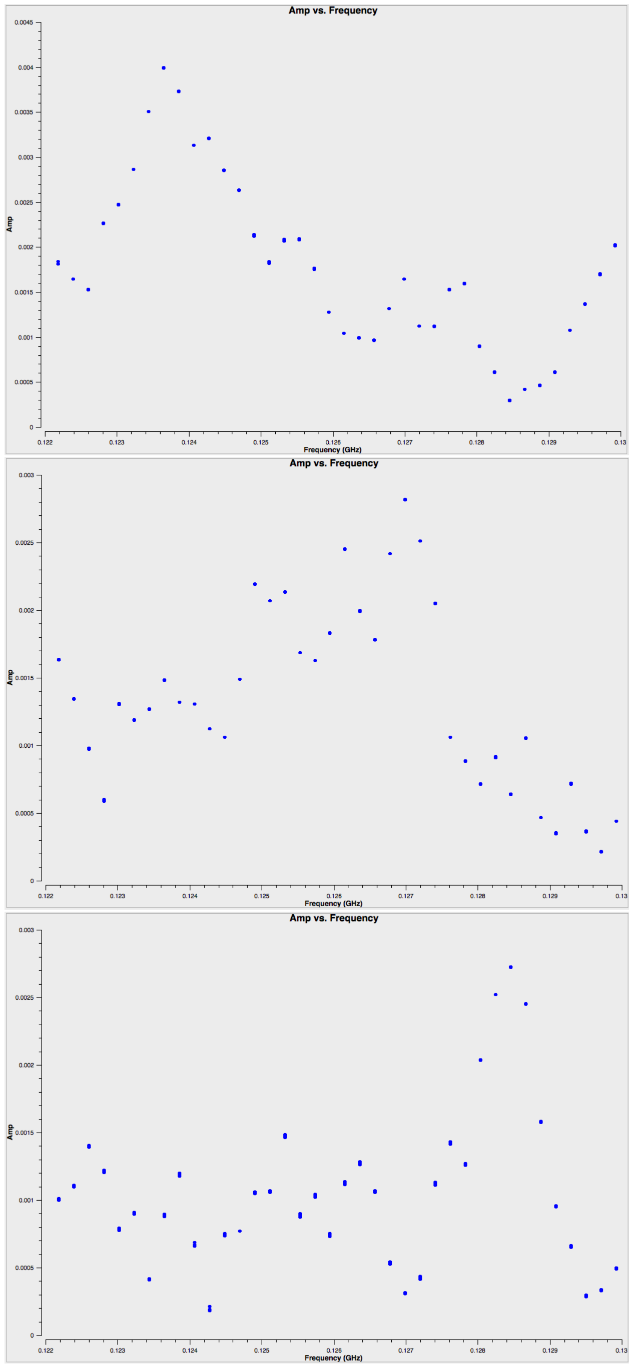

Fig. 6.— HI 21cm line model visibility amplitude versus frequency for baselines 0-1 (top), 0-2 (middle), 0-3 (bottom) for one time step in the modeling. The amplitudes are in Jy. Note that three 'records' of 30sec each are plotted per point, hence the verticle extension in some cases.

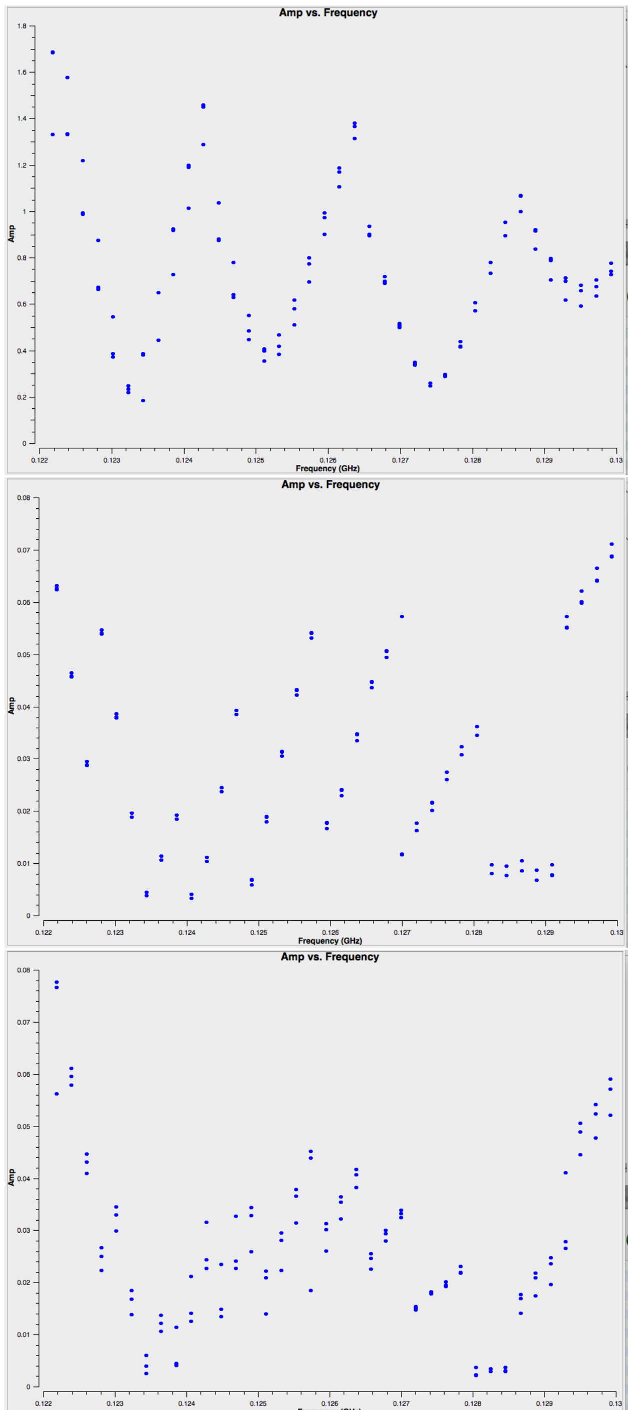

Fig. 7.— Continuum model visibility amplitude versus frequency for baselines 0-1 (top), 0-2 (middle), 0-3 (bottom) for one time step in the modeling. In this case, a first order polynomial has been fit and subtracted from the complex visibility. The amplitudes are in Jy. Note that three 'records' of 30sec each are plotted per point, hence the verticle extension in some cases.