HERA Memo 60: System Noise from LST Differencing
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ABSTRACT

I derive the visibility noise values (in Jy), and the system temperature for HERA, using differencing of visibility spectra for sky-calibrated data for a given LST on two consecutive days. The system temperatures are: 481 K, 360 K, and 296 K, at frequencies of 125 MHz, 150 MHz, and 175 MHz, respectively, with a scatter of about 30%. The derived values are grossly consistent with a receiver temperature of about 260 K that is constant with frequency, plus the expected antenna temperature as a function of frequency due to the sky radio emission in a colder region of the sky. However, the measured system temperatures appear to increase more rapidly with decreasing frequency than implied by this simple model. Regardless, the relevant quantity for generating model visibilities is the visibility noise, in Jy, as a function of LST, which can be derived from the data themselves using LST differencing.

1. Data and Process

The data analyzed were during the transit of Fornax A (J0322-3712). The data were from the IDR2.1 sky-calibrated reduction (Kern et al. 2018). The two datasets employed were:

zen.2458106.33430.yy.HH.uvOCRS

zen.2458105.33429.yy.HH.uvOCRS

The process involved identifying visibility spectra at the same LST on each day on 4 selected baselines, and two polarizations. The record length is 10.7 seconds. The UTC for

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the time stamp on Day105 was 20:09:58.4, while that on Day106 was 20:06:02.4 (separation of 3.94min). Longer baselines were chosen to minimize the continuum level. The main challenge to calculating the noise occurs due to any frequency dependent gain variations from day to day that might couple the strong continuum into the noise calculation.

The Fornax A region is located in a colder part of the radio sky, well outside the Galactic plane. Fornax A itself is intrinsically about 700 Jy, but it is 7^o from zenith at transit, and the apparent flux density is 70Jy.

The visibility spectra for each LST and each polarization were differenced between days. The standard deviations (STD) of the residual spectral fluctuations were then calculated over ranges of 100 to 150 channels centered at 125MHz, 150MHz, and 175MHz.

2. Analysis and Results

The resulting difference spectra are shown in Figures 1 and 2. The baselines are listed in the figure. The XX polarization difference spectra show systematic offsets from zero, and broad frequency structure. These structures appear broad enough that, over the limited frequency ranges in which the noise is calculated, they do not dominate the STD calculation. Broad structure in the difference spectra at matching LSTs is likely due to variation of the bandpass that is not corrected in the calibration process.

The YY polarization difference spectra are more noise-like, meaning centered at zero, with no significant residual broad structures in frequency.

The values for the STD in the difference spectra for the three spectral regions are given in Table 1, in Jy units. Note that the STD values for 11-123.XX are significantly larger than those derived for the other baselines. The 11-123.XX difference spectrum shows the most systematic structure of all the data analyzed, and we do not include these data in the subsequent analysis.

We then calculate the implied system temperature using the standard radiometry equation (eg. Thomson, Moran, Swenson 2018), appropriate for a single polarization:

$$\mathrm{STD} = 1.414 \times 1.414 \times (\mathrm{T_{sys}/A_{eff}}) \times [\mathrm{d}\nu \times \mathrm{t_{int}} \times \mathrm{N(N-1)}]^{-0.5}\ \mathrm{Jy} \quad (1)$$

where the first root two is for difference spectra, and the second for one polarization. T_{sys} is in K, A_{eff} is in m^2, $d\nu$ is in kHz = 97.7 kHz, t_{int} is in hours = (10.7sec/3600.0), and N=2. The effective area is the physical area for a 14.7m diamete antenna, times the aperture efficiency. We adopt an aperture efficiency of 66% across the band, as derived by Fagnoni et al. (2018, figure 10). This value is roughly constant across the band, to within 10%. The resulting system temperature values are also listed in Table 1.

I then assume the system temperature is a sum of the receiver temperature, T_{rx}, and the antenna temperature, T_A due to the sky. For the latter, we adopt the equation for the sky temperature from the the HERA MSIP proposal Table 2:

$$\mathrm{T_{sky}} = 120 \times (\nu/150\mathrm{MHz})^{-2.55}\ \mathrm{K} \quad (2)$$

where it is reasonable to assume the antenna and sky temperature are the same, since the sky fills the aperture. We then fit a model assuming a constant T_{rx} with frequency, plus the frequency dependent sky temperature above. The results are shown in Figure 3. We find that the best fit is for a receiver temperature of about 260 K.

While the scatter in the data is significant, it appears that the frequency dependence of the adopted model is too shallow relative to the measurements. This steepness implies either the sky spectrum is steeper than assumed, or there is also a frequency dependence for increasing receiver temperature with decreasing frequency, as was also found by Beardsley (2017).

Note that, if the sky temperature has been underestimated, then the receiver temperature would be lower. However, the system temperture, as determined by the difference-noise, would not change, and it is the latter quantity that is required for the subsequent modeling. Specifically, when calculating model visibilities, the most relevant quantity is the noise value in Jy at a given LST, which can be derived from the data themselves using LST differencing. The noise values per visibility record per polarization are root(2) lower than the mean values listed in Table 1 for the difference spectra.

Is it possible that systematic variations due to gain variations bias the noise to higher values in these measurements? Certainly, the XX polarization difference spectra show broad spectral structure. However, the YY difference spectra appear noise-like. However, using just the YY data, reduces the system temperature estimates by less than 8%.

For reference, the antenna temperature due to Fornax itself, at 70 Jy, is given by:

$$\mathrm{T_A} = 0.00036 \times \mathrm{A_{eff}} \times \mathrm{S}_\nu\ \mathrm{K} \quad (3)$$

with A_{eff} in m^2, and S_ν in Jy (Condon & Ransom 2018). For an effective area of 110 m^2, Fornax contributes just 3 K to the system temperature.

The HERA sky and receiver temperatures were also derived using the autocorrelation spectra and a model for the sky and primary beam (Beardsley 2017; see also Parsons & Beardsley 2017). Unfortunately, RA = 03:12 was not covered in that analysis. The values for the receiver temperatures at 150 MHz were $\sim$ 300 K, and about 200 K at 175 MHz, again with a scatter of about 30%. The receiver temperatures at 125 MHz were much higher ($\sim$ 700 K), 'likely due to an imperfect beam model'.

3. Summary

LST differencing of spectra appears to be a viable means to derive the system noise of HERA, with the caveat that residual frequency dependent gain errors could increase the derived noise values in some cases. I derive mean system temperatures of 481 K, 360 K, and 296 K, at frequencies of 125 MHz, 150 MHz, and 175 MHz, respectively, with a scatter of about 30%. The data are grossly fit by a model of a constant receiver temperature of 260 K, plus a sky temperature model appropriate for a cold patch of the sky. However, the measured system temperatures appear to increase more rapidly with decreasing frequency than this simply model.

References

Beardsley 2017, HERA memo 16 (http://reionization.org/science/memos/)

Condon & Ransom, Essential Radio Astronomy

Fagnoni, de Lera Acedo, Kolitsidas 2017, HERA memo 29

Kern, Carilli, Bernardi 2018, HERA memo 42

Parsons & Beardsley 2017, HERA Memo 34

Thompson, Moran, Swenson, 2018, Interferometry and Aperture Synthesis in Radio Astronomy

Table 1: Noise values and T_{sys}

	1.142.xx	1.142.yy	14.141.xx	14.141.yy	11.123.xx	11.123.yy	12.124.xx	12.124.yy	Mean
	Jy	Jy	Jy	Jy	Jy	Jy	Jy	Jy	Jy
125 MHz	12.0	10.3	13.2	10.3	18.0	12.2	10.4	10.4	11.3
150 MHz	7.5	7.2	8.2	7.6	12.1	9.1	10.1	9.4	8.4
175 MHz	8.2	4.4	7.9	8.4	11.3	7.4	6.7	5.5	6.9
	K	K	K	K	K	K	K	K	K
125 MHz	512	440	564	440	768	520	444	444	481
150 MHz	320	308	350	324	516	388	431	401	360
175 MHz	350	188	337	358	482	316	286	235	296

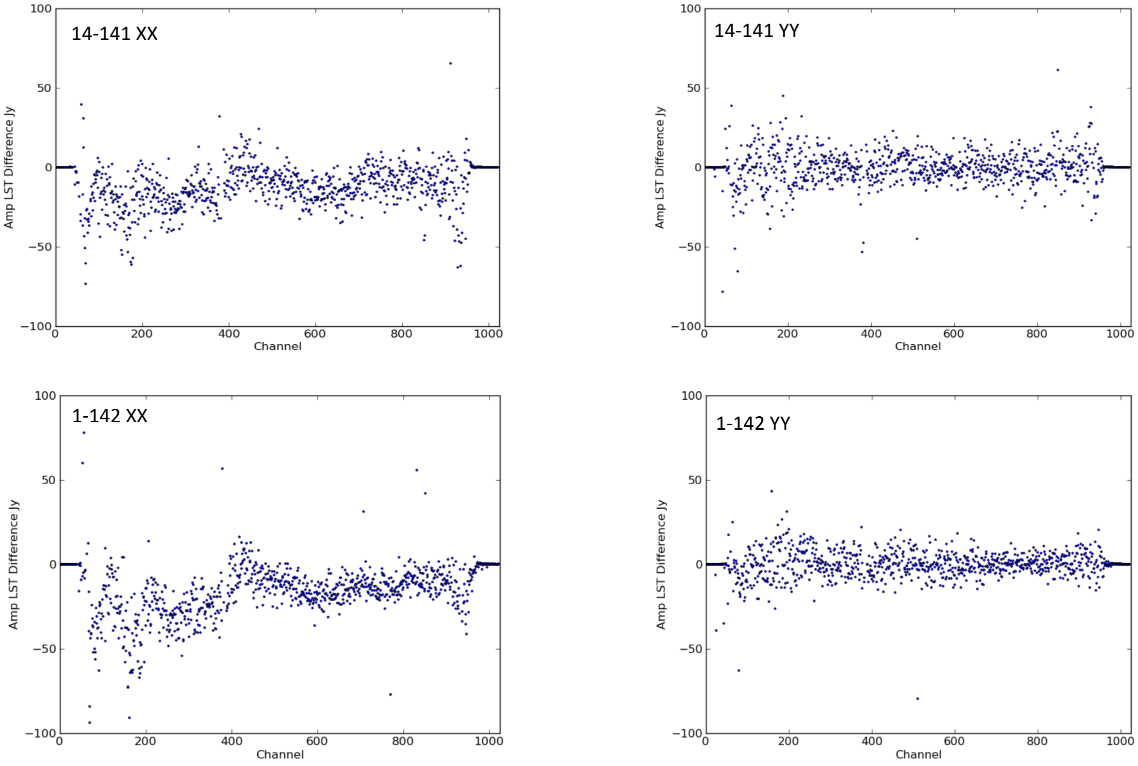

Fig. 1.— Difference spectra for baselines and polarizations listed in the frames. The differencing is between the same LST on two adjacent days.

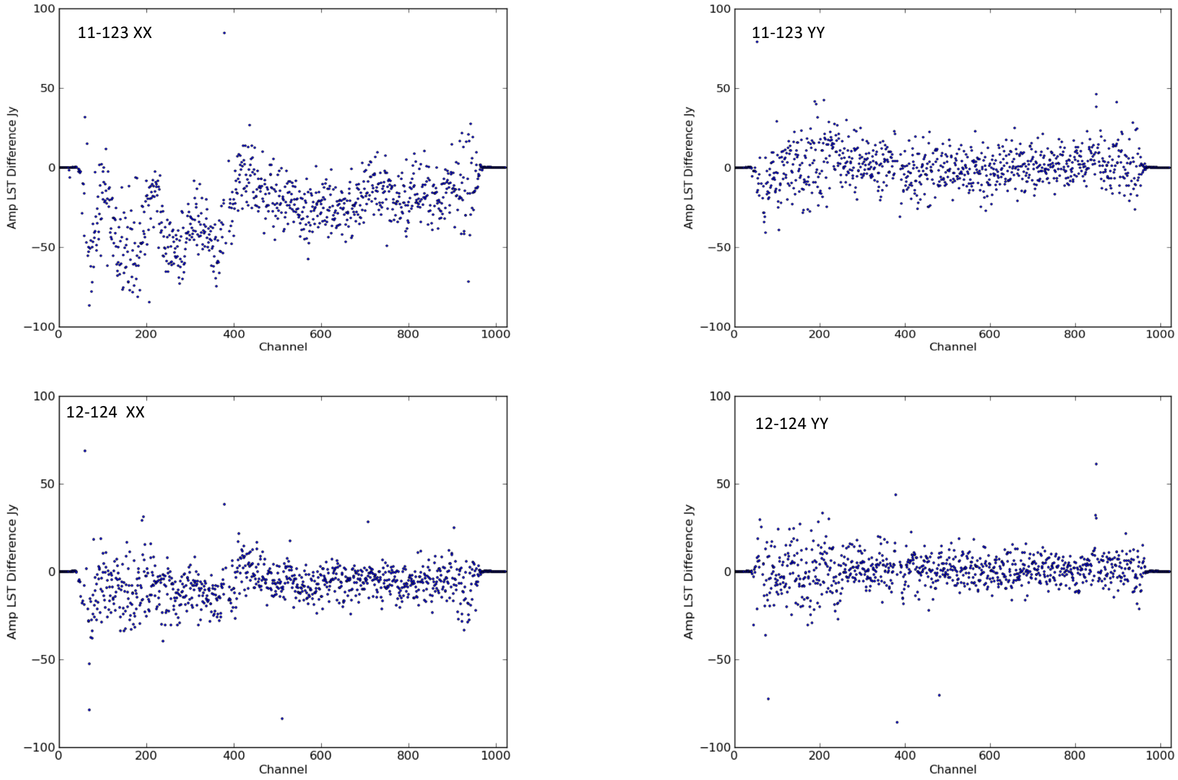

Fig. 2.— Difference spectra for baselines and polarizations listed in the frames. The differencing is between the same LST on two adjacent days.

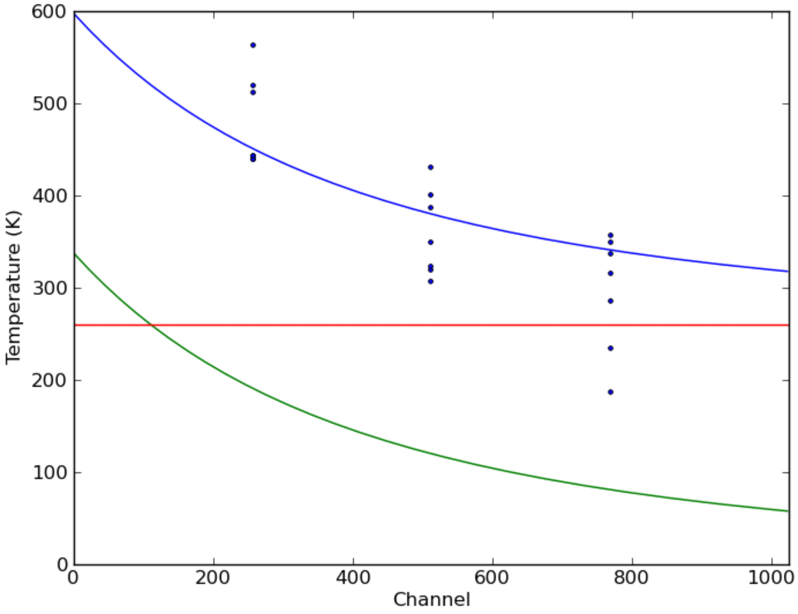

Fig. 3.— The points are the system temperature data from Table 1, excluding 11.123.XX. The red curve is a constant receiver temperature of 260 K. The green curve is a model of the sky temperature, as given in equ. 2. The blue curve is the sum.