# An early look at HERA-19 system temperature

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Original Memo: June 23, 2016
Updated: April 3, 2017

**Abstract**

Using the auto-correlation data from JD=2457458 I investigate the system temperature of the HERA-19 array and the various PAPER sub-arrays. I use the Global Sky Model and the HERA beam model to create a sky temperature vs LST template, which I use to fit a simple model for the auto-correlation gain and receiver temperature. The scripts I've used here are available in my fork of `capo`[1], in the `apb` directory.

## 1 Data

The data used here encompasses 12 hours on Julian date 2457458, 04:41 < LST < 16:43, in 10.8 s integrations. I look at both xx and yy auto-correlations. I make no attempt at flagging, so RFI abound. I also look at the full 100 MHz band, which I average to frequency channels of 1.56 MHz each (64 channels). The data reading was done with script `apb/HERA_IDR1_read_autos.py`. The fitting described below treats each frequency channel independently, so while RFI and band edges yield unreliable channels, they will not corrupt results from clean channels.

## 2 Sky temperature calculation

Next I created templates for the expected sky temperature, $T_{\mathrm{sky}}$, as a function of frequency and LST. This was done by importing a beam model and integrating against the global sky model (GSM). The script use was `apb/Tsky_v_LST.py`.

The HERA beam used was from a CST simulation and is available on enterprise at
`/data2/beards/instr_data/HERA_HFSS_X4Y2H_4900.hmap`.
This file combines the models available in `hera-cst/mdl04`[2], which were generated at 1 MHz intervals from 90 to 220 MHz, and are in `HEALPix` format with `nside` = 32. This frequency dependent beam was interpolated to the observation frequencies. The Y polarization beam was estimated by rotating the X beam 90 degrees. The PAPER beam used was a pretty terrible one. In the absence of a good beam model, I simply used a frequency dependent gaussian.

I next used the `PyGSM` module[3] to create a mock GSM observation, rotated to the location of HERA at varying LSTs. I then perform a weighted average of the GSM using the beam values as the weights. The result is a $T_{\mathrm{sky}}$ vs LST curve for HERA and PAPER at each observed frequency. Figure 1 shows a sample of these curves.

## 3 Template fitting

The goal here is to match the auto-correlation data to a template based on the sky temperature curves calculated in the previous section. Using this fit I can roughly estimate the antenna gain amplitudes and the receiver noise level. The script used is `apb/fit_IDR1_autos.py`.

[1] https://github.com/adampbeardsley/capo
[2] https://github.com/david-deboer/hera-cst
[3] https://github.com/telegraphic/PyGSM

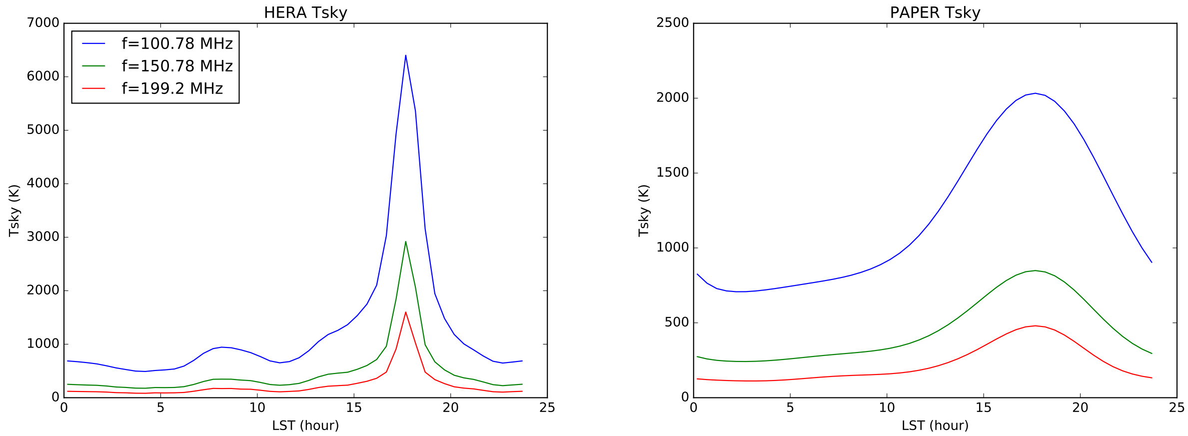


Figure 1: Sky temperature model for HERA and PAPER at low (blue), middle (green), and high (red) frequencies within the observed bandwidth.

First I parameterize the template to fit as

$$\texttt{Template}(LST) = (A_0 + A_1 \times LST) \times T_{\text{sky}}(LST) + (R_0 + R_1 \times LST). \tag{1}$$

The coefficients $A_0$ and $A_1$ make up a gain amplitude with a linear slope, and the $R_0$ and $R_1$ are related to a receiver temperature with a linear slope (after dividing by the gain terms). This fit is certainly not perfect as it allows for negative gains and temperatures. But it actually does a pretty good job matching the HERA data, and is a good first go.

I fit each 1.56 MHz channel on each antenna to this template, using the appropriate $T_{\text{sky}}$from the previous section. Figure 2 shows example fits for HERA and PAPER antennas. The quantity plotted is the data, matched to the model using the template fit. In other words, after fitting for $A_0$, $A_1$, $R_0$, and $R_1$, we plot the measured sky temperature, $T_{\text{sky}}{}'$. All the $T_{\text{sky}}$plots are available on enterprise at `/data2/beards/IDR1_auto_data/`.

$$T'_{\text{sky}} = \frac{\texttt{data}(LST) - (R_0 + R_1 \times LST)}{A_0 + A_1 \times LST} \tag{2}$$

All the HERA fits are of comparable quality to the one shown in Figure 2, save spurious RFI and some other small peculiarities (again, all these plots are available for your perusal on enterprise). However, few PAPER fits are of the quality shown in Figure 2. Figure 3 shows a sampling of a what is seen with the PAPER fits. Broadly speaking, the fits can be grouped into four categories: 1. good fit, given the poor beam model (∼10%); 2. low signal – low enough to see quantization noise in the fitted data (∼17%); 3. good but jagged – these fits follow the general trend of $T_{\text{sky}}$, but have periodic sawtooth-like features as a function of LST[4] (∼44%); 4. peculiar features – these data have very odd features, perhaps indicated unstable receiver chains (∼29%)? In most cases (but not all) the two polarizations on a single antenna fall under the same category.

We can also look at the gains as a function of antenna, frequency and LST. Remember each frequency is treated independently, but the gains are restricted to a linear function of LST. Figure 4 shows two example HERA waterfalls. Note that plotted here is $A_0 + A_1 \times LST$, which is the square of a single antenna gain amplitude. All the HERA dishes show a negative gain slope over the central part of the band. This is probably not physical, but rather a limit of the $T_{\text{sky}}$model owing to either the low resolution beam model (`nside`=32) not capturing exactly when structure enters the field (note the end of the night is the upward edge when the galaxy begins to enter the field of view), or the fact that the GSM is not perfect, especially at these frequencies.

[4]Interestingly, not all the sawtooths line up.

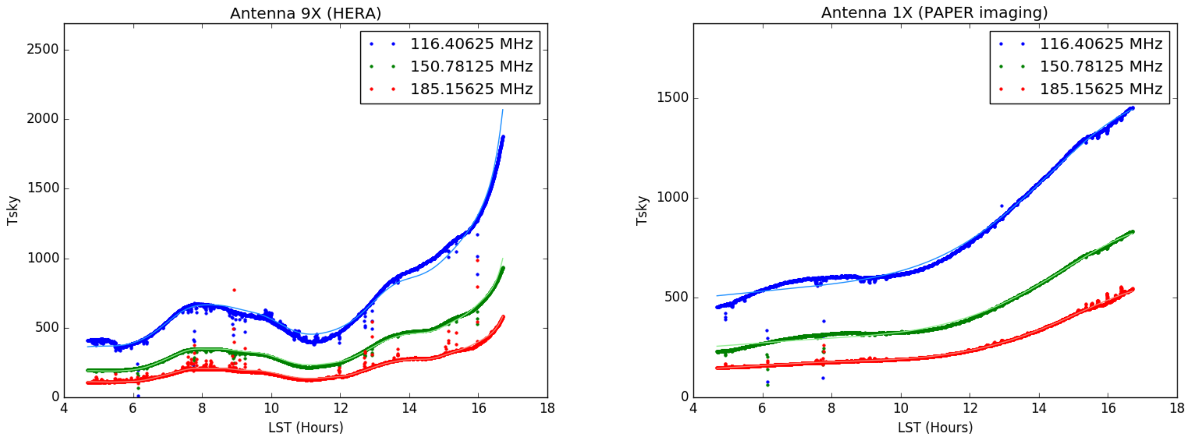


Figure 2: Fit sky temperature for two example antennas (HERA left, PAPER right), at three frequencies, low (blue), middle (green), and high (red). The data is plotted with large dots, while the $T_{\rm sky}$calculated in the previous section is shown with the lighter colored thin lines. The HERA data is able to fit the time dependent structure fairly well, but the PAPER data exhibits structure not seen in the model. This is not surprising owing to the simple gaussian beam model used for PAPER.

Figure 5 shows the average gain amplitude for each antenna and polarization, color coded by the subarrays. All the HERA dishes have respectable gains, while a spattering from each of the PAPER subarrays have zero, or even negative, gains.

We can also estimate the receiver temperature, $T_{\rm rxr}$, using our fits.

$$T_{\rm rxr} = \frac{R_0 + R_1 \times LST}{A_0 + A_1 \times LST} \tag{3}$$

For a good fit, this should yield a decent estimate of the receiver temperature. However, in cases where the gain approaches zero, we will likely get unrealistically high temperatures. Luckily the HERA gains are well behaved over the bulk of the bandwidth. Figure 6 shows example receiver temperature waterfalls corresponding to the same antennas as were shown in Figure 4.

Unfortunately, the cases where the fit *is* bad contaminate the average receiver temperatures. I need to improve my template to fix the poor fits, or flag some of the data, before I can show a plot similar to Figure 5 for the receiver temperature.

# 4 Conclusions

Using a pretty crude model of the sky temperature, I was able to get decent fits for the gains and receiver temperatures of HERA dishes. The PAPER antennas did not fit the model nearly as well, due to both a poor beam model, and due to poor data. I am currently working on a better template to fit to the data in order to enforce positive gains and temperatures. The slope in gain amplitudes for HERA dishes is a little concerning and may point to either bad sky model or too low beam model resolution to capture the bright structure entering the field of view.

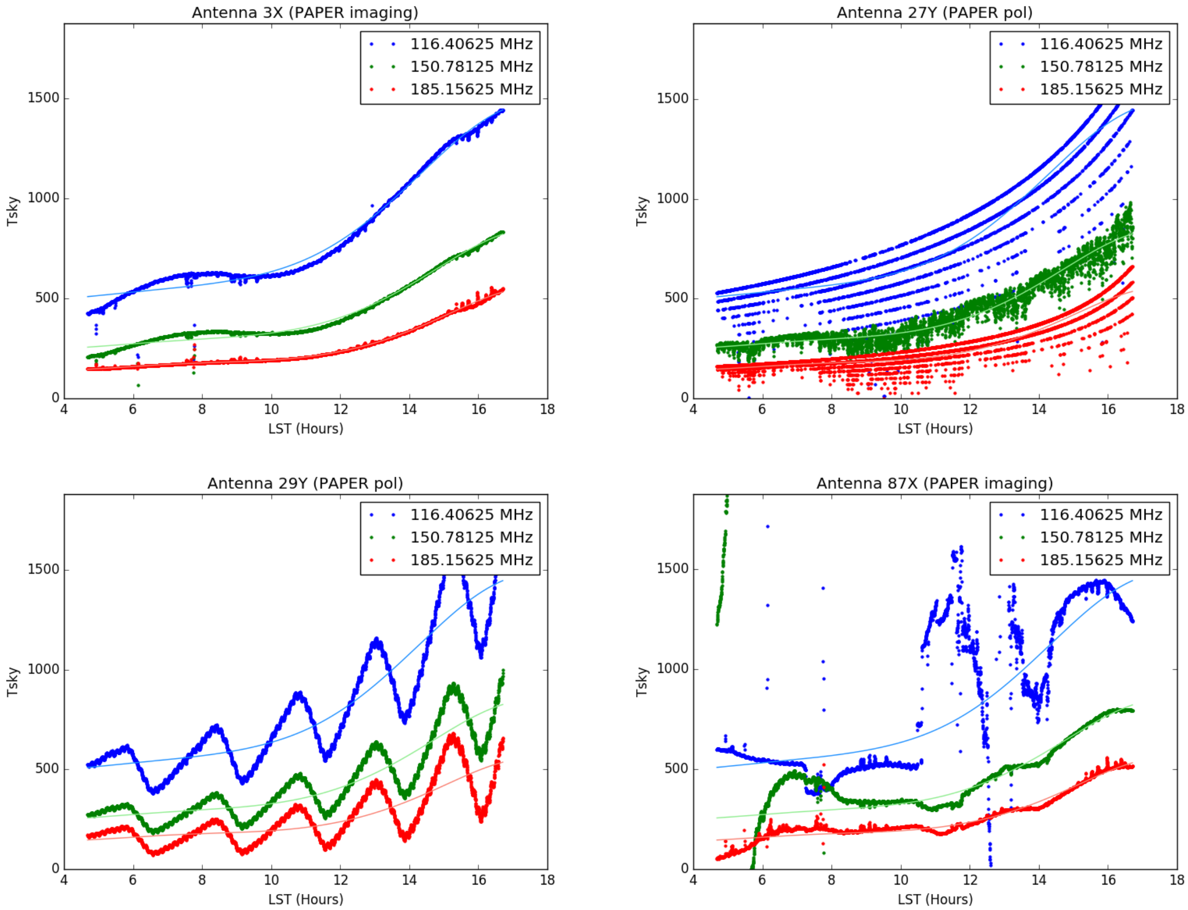


Figure 3: Gallery of PAPER $T_{\rm sky}$fits. *Upper left:* Another example of a good fit. *Upper right:* An antenna with very low signal that, when boosted to the $T_{\rm sky}$level, shows quantization error. *Lower left:* An antenna showing the jagged gain structure over time. *Lower right:* A poor fit that does not really fit into the other categories.

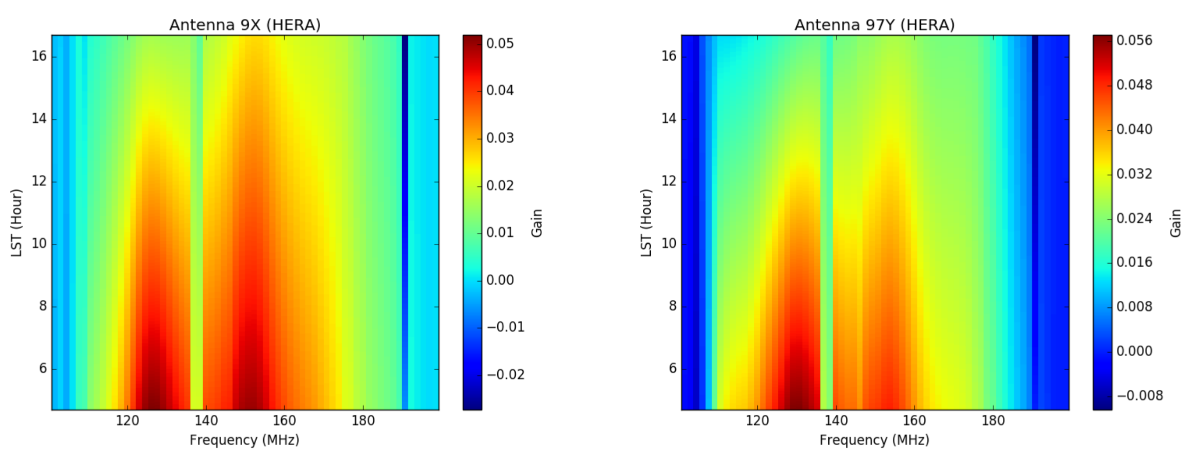


Figure 4: Two example gain waterfalls for HERA dishes. All the HERA dishes show relatively high gain early in the night, and decreasing gain as the night goes on (and the galaxy begins to enter the field of view around $LST = 16$.

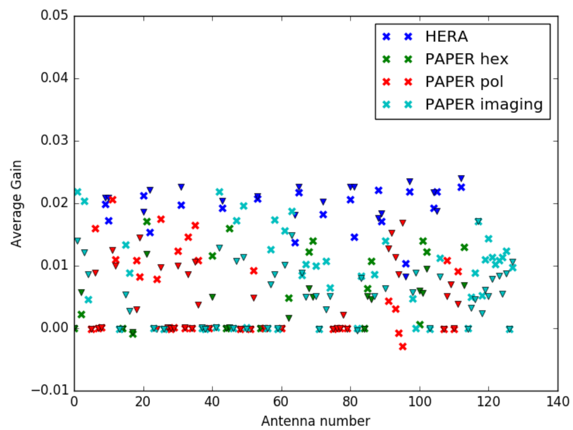


Figure 5: Average gain amplitudes for all antennas and polarizations. The “x” symbols correspond to X polarization, and the triangles correspond to Y polarization. Colors indicate the four subarrays.

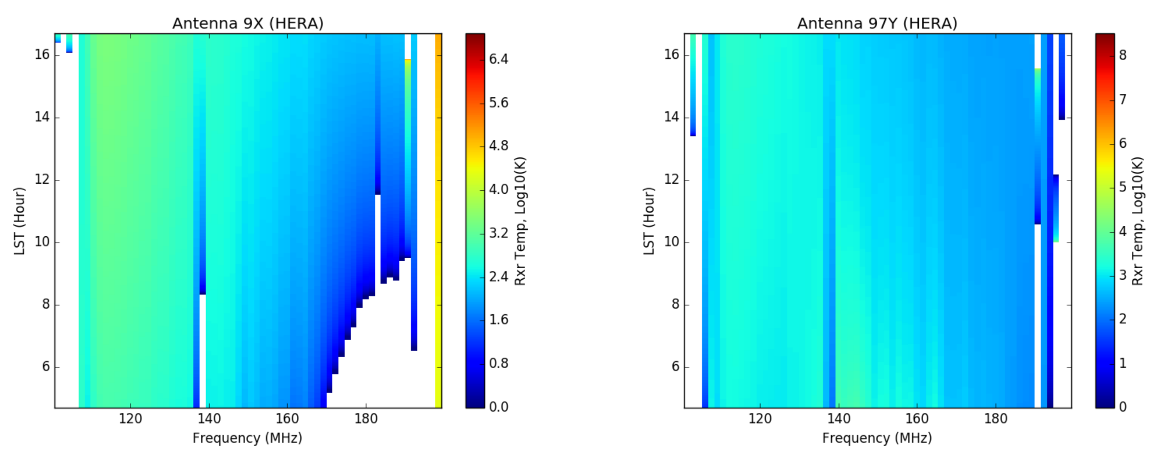


Figure 6: Receiver temperature waterfalls for two example HERA dishes.

## 5 UPDATED – April 3, 2017

I decided to revisit this analysis to simplify it a big and get out an "answer" others can use. I only ran this for HERA dishes because we saw the PAPER fits were less than stellar above.

Besides the simplifying changing described below, I also recently incorporated Nicolas Fagnoni's beam models[5]. While these beams are believed to be more accurate, the very coarse analysis here is hardly sensitive to the precision improvements, and the results are not affected much (order percent levels in the gain solutions).

I've changed the fit so I no longer allow the gain and receiver temperature to change with time. While in principle they both can change, the time dependence I was getting seemed far more extreme than one would expect. So I force them both to be constant. It is also more straightforward now to force the gains to be positive. Doing the same for receiver temperature is a little harder, which will be seen below. I also subtracted the mean $T_{\rm sky}$to force the two parameters to be more orthogonal. My new template looks like:

$$\texttt{Template}(LST) = A_0 \times (T_{\rm sky}(LST) - \langle T_{\rm sky}\rangle) + R_0. \tag{4}$$

The following relationships relate the fit parameters to physical parameters.

$$T_{\rm rxr} = \frac{R_0}{A_0} - \langle T_{\rm sky}\rangle \tag{5}$$

$$g_{\rm Jy} = \left(\frac{A_e}{2761.3006}A_0\right)^{1/2} \tag{6}$$

$g_{\rm Jy}$ is the amplitude of the per-antenna gain which will put the data in units of Janskies. The numerical value in the expression for $g_{\rm Jy}$ accounts for the various unit conversions, and $A_e$ is the dish effective area in m$^2$. We can see from these equations that forcing $A_0$ to be positive in the fit also enforces $g_{\rm Jy}$ to be positive (and real). However, the restrained on $R_0$ to force $T_{\rm rxr}$ to be positive is less straightforward and is left to future work if needed.

Using these new constraints the fits are not as good as they were above, but I think they are closer to the truth. Figure 7 shows an example HERA fit compared to the old fit (same dish as Figure 2, left panel). The fits for the mid- and high- ends of the band seem fairly good, but noticeably worse at the lower end. With the stated goal of getting the gain amplitudes within an order of magnitude, I think we're in the ballpark.

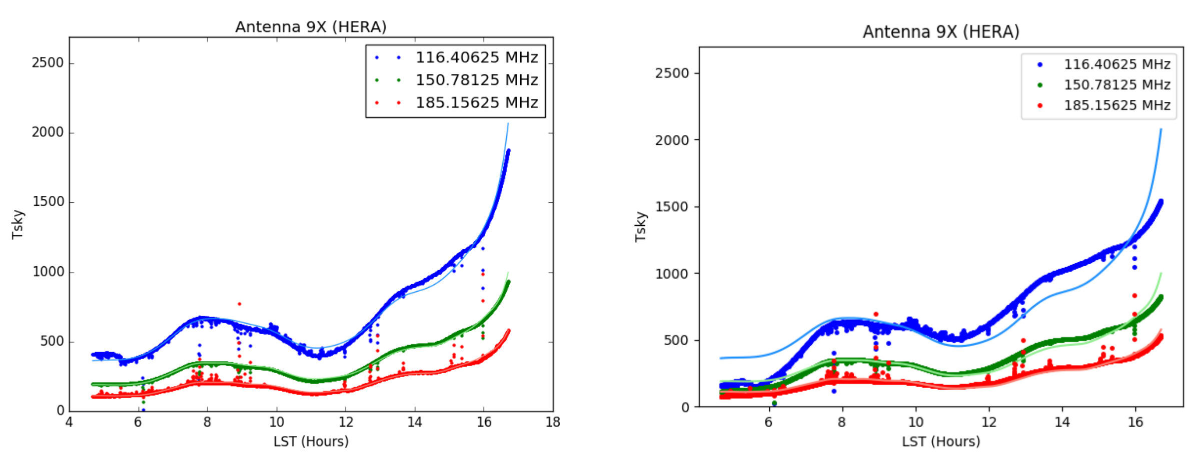


Figure 7: Fig sky temperature for the old fitting routine and the new. Now that I no longer allow the gain and offset terms to drift with LST, the fits do not accommodate the model $T_{\rm sky}$ as well. However, I believe this is due to an old-ish beam model and imperfect sky model, rather than due to actually drifting gains and receiver temperatures.

[5]https://github.com/Nicolas-Fagnoni/Simulations

Next we look at the gains as a function of frequency and antenna in Figures 8 and 9. The shapes of the bandpasses seem entirely reasonable, and the amplitudes are near unity. The unity value is a bit surprising given that old PAPER solutions seemed to be on order 0.005. The effective area of a HERA dish is obviously bigger than that of PAPER, but I believe that ratio is closer to 20:1, not 200:1.

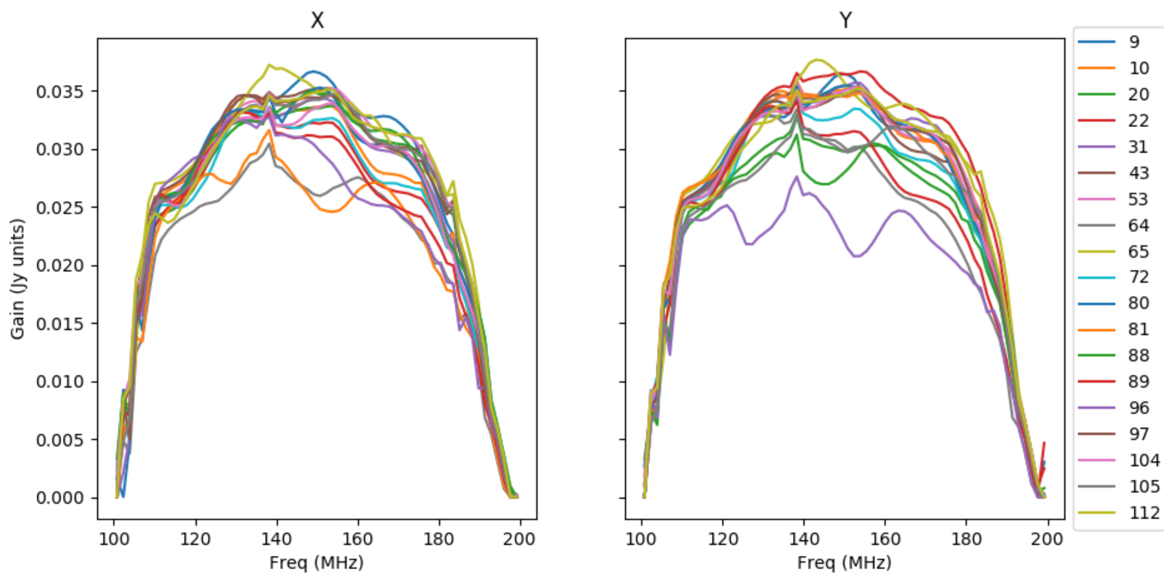


Figure 8: Antenna bandpasses. These are the amplitudes of the gains which, when divided from the data will result in visibilities in units of Janskies.

The receiver temperatures are shown in Figures 10 and 11. The upper end of the band (excluding the edge) doesn't seem crazy (order 200 K). But the lower end of the band is certainly larger than expected. My suspicion is that this is due to an imperfect beam model because we already saw that the fits down there are weren't great. Of course, this also makes the bandpass suspect. It will be very interesting to run again with a newer beam model.

The code used for this update can be found on my fork of `capo`, specifically the script located at https://github.com/adampbeardsley/capo/blob/master/apb/get_number_for_aaron.py. The output data (gains and receiver temperatures per antenna and frequency) can be found at https://www.dropbox.com/s/oonw34krd5iuo29/gains_and_Trxr.npz?dl=0.

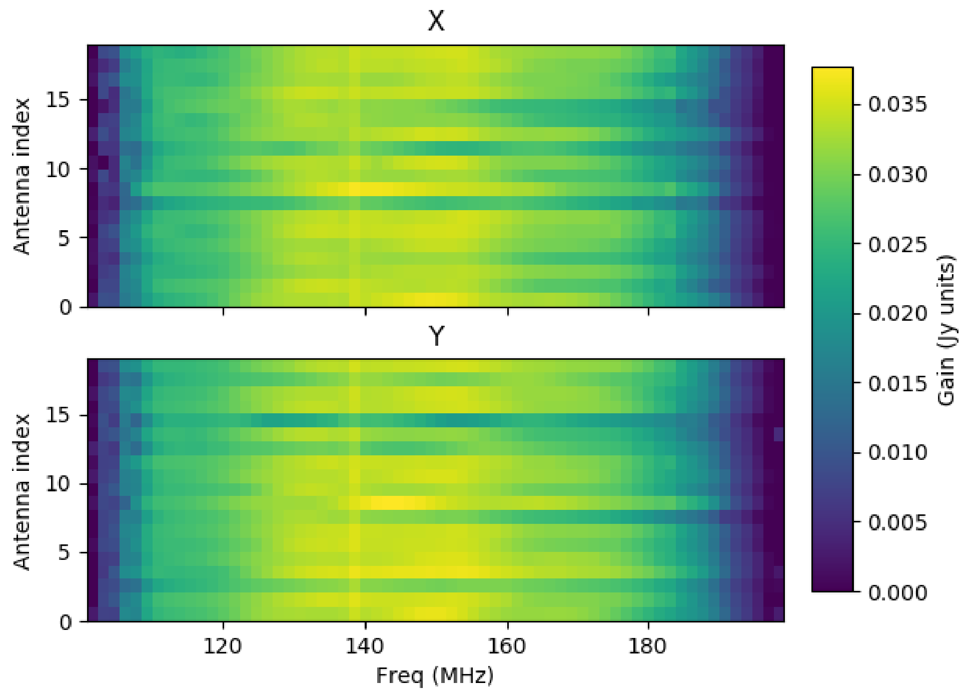


Figure 9: Same data as Figure 8, but shown as a waterfall to separate different antennas. The antenna index refers to the HERA antenna in ascending order. For example, HERA dish 9 has index 0, HERA dish 22 has index 3, etc.

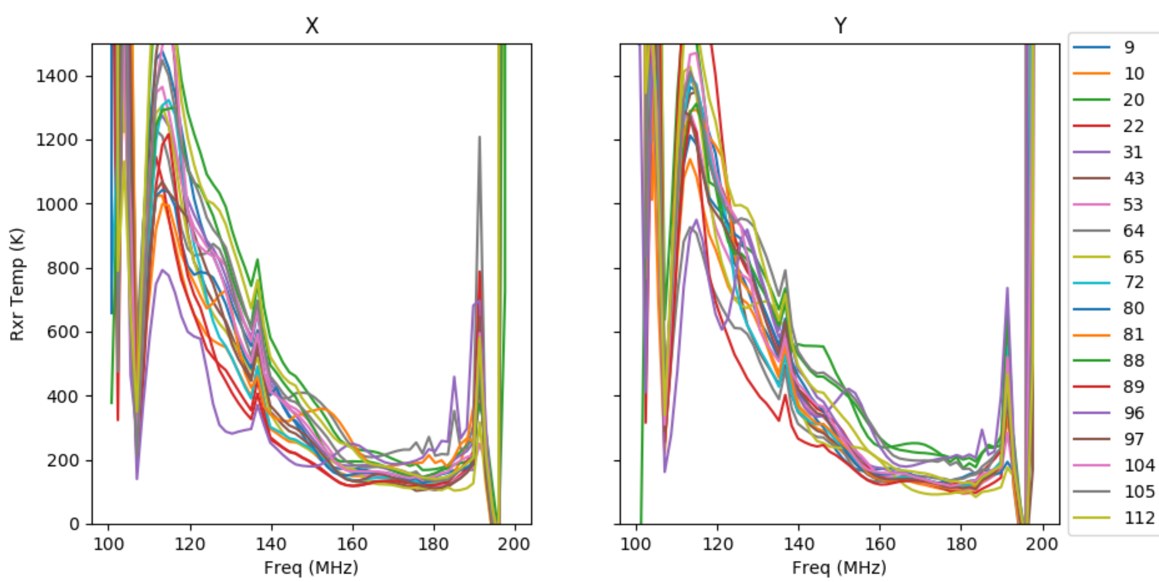


Figure 10: Receiver temperatures as a function of antenna and frequency, in Kelvin units. The low end of the band shows surprisingly large receiver temperatures. This is likely due to an imperfect beam model, as we saw that the fits at the low end are not great.

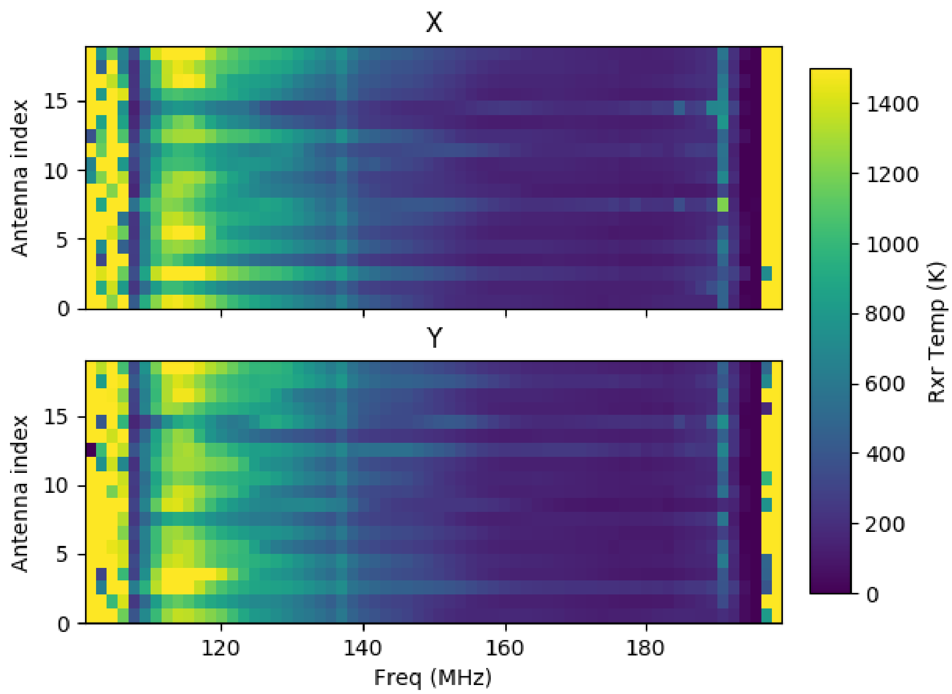


Figure 11: Same data as Figure 10, but shown as a waterfall to separate different antennas.