

An early look at HERA-19 system temperature

A.P. Beardsley

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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, $04:41 < \text{LST} < 16:43$, 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_{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/md104`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` module³ 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_{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>

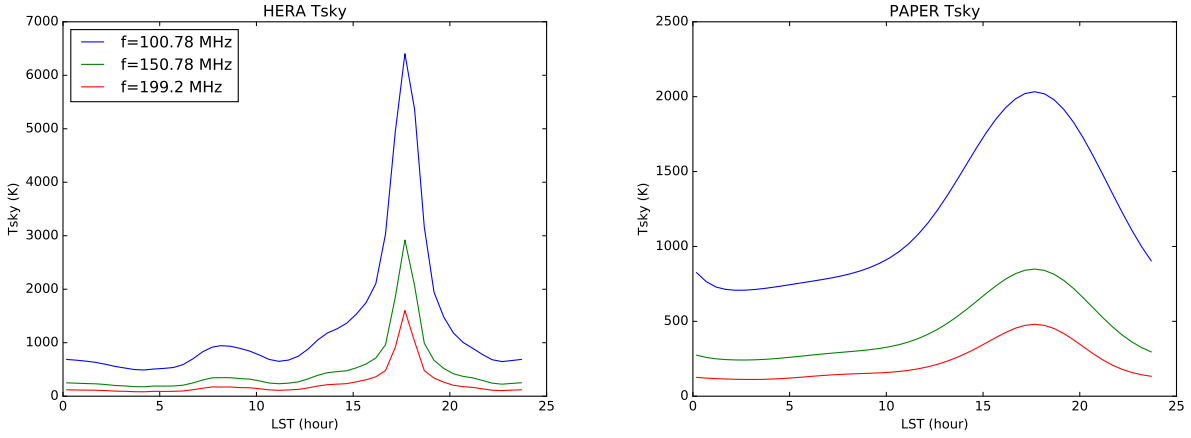


Figure 1: Sky temperature model for HERA and PAPER at low (blue), middle (green), and high (red) frequencies within the observed bandwidth.

First I parameterize the template to fit as

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

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_{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_{sky}' . All the T_{sky} plots are available on enterprise at `/data2/beards/IDR1_auto_data/`.

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

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 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 ($\sim 10\%$); 2. low signal – low enough to see quantization noise in the fitted data ($\sim 17\%$); 3. good but jagged – these fits follow the general trend of T_{sky} , but have periodic sawtooth-like features as a function of LST^4 ($\sim 44\%$); 4. peculiar features – these data have very odd features, perhaps indicated unstable receiver chains ($\sim 29\%$)? 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_{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.

⁴Interestingly, not all the sawtooths line up.

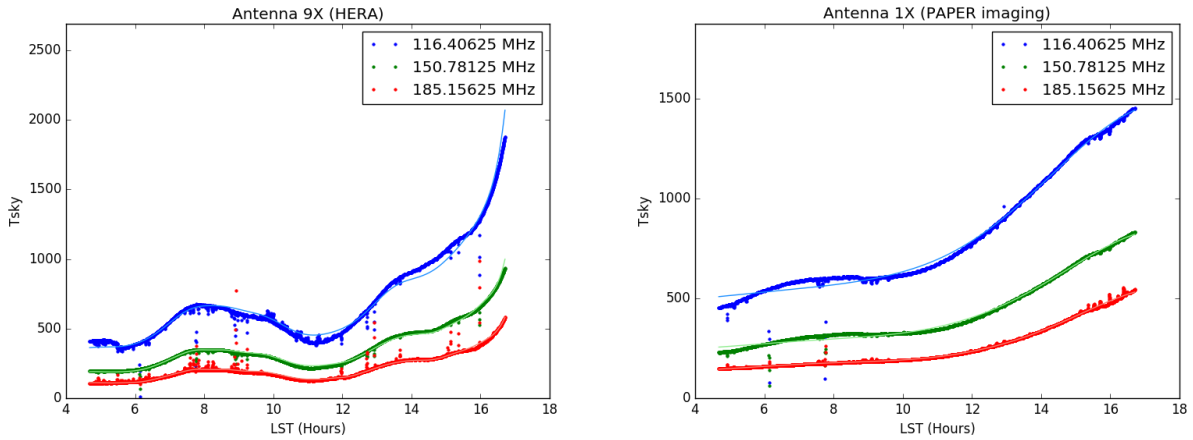


Figure 2: Fit sky temperature for two example antennas (HERA left, PAPER right), at three frequencies, low (blue), middle (green), and high (red). The data is plotted with large dots, while the T_{sky} calculated in the previous section is shown with the lighter colored thin lines. The HERA data is able 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_{rxr} , using our fits.

$$T_{\text{rxr}} = \frac{R_0 + R_1 \times LST}{A_0 + A_1 \times LST} \quad (3)$$

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.

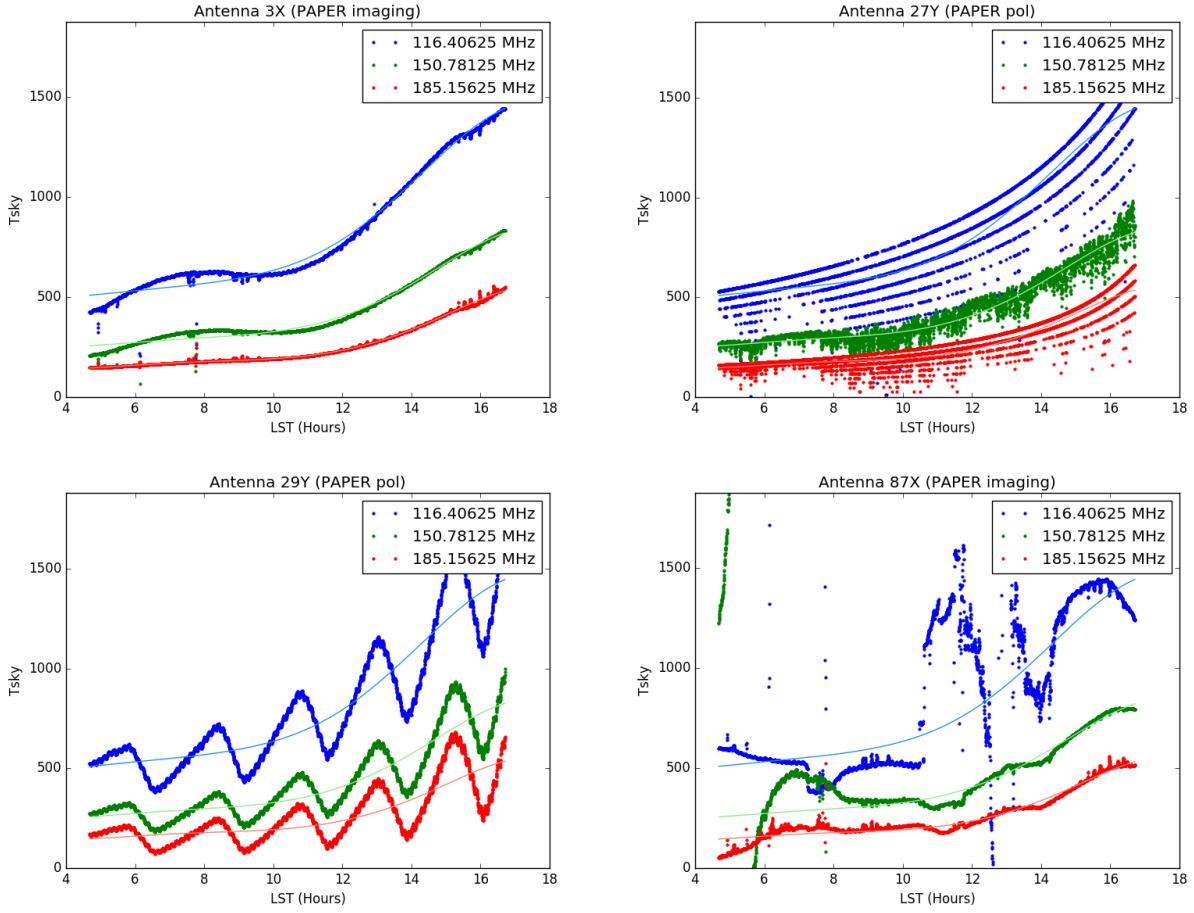


Figure 3: Gallery of PAPER T_{sky} fits. *Upper left*: Another example of a good fit. *Upper right*: An antenna with very low signal that, when boosted to the T_{sky} level, shows quantization error. *Lower left*: An antenna showing the jagged gain structure over time. *Lower right*: A poor fit that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

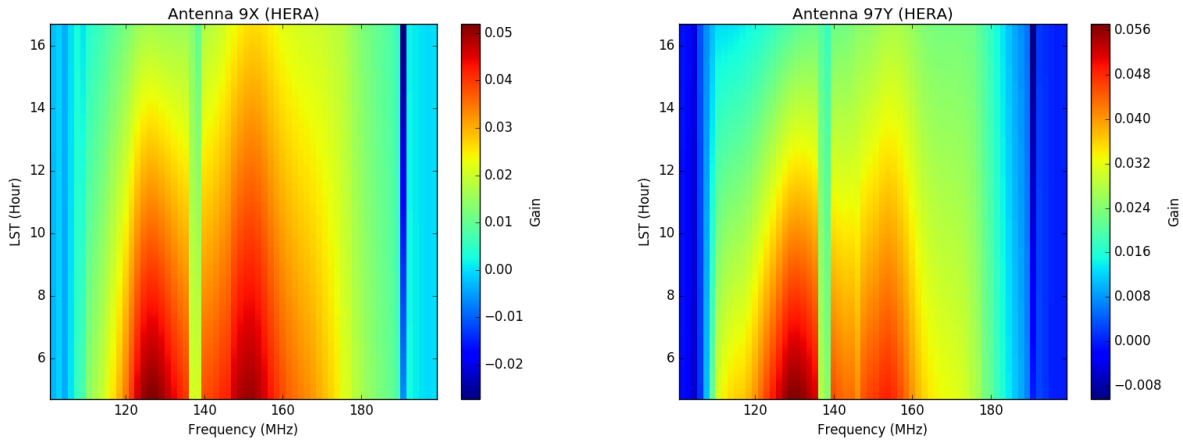


Figure 4: Two example gain waterfalls for HERA dishes. All the HERA dishes show relatively high gain early in the night, and decreasing gain as the night goes on (and the galaxy begins to enter the field of view around $LST = 16$).

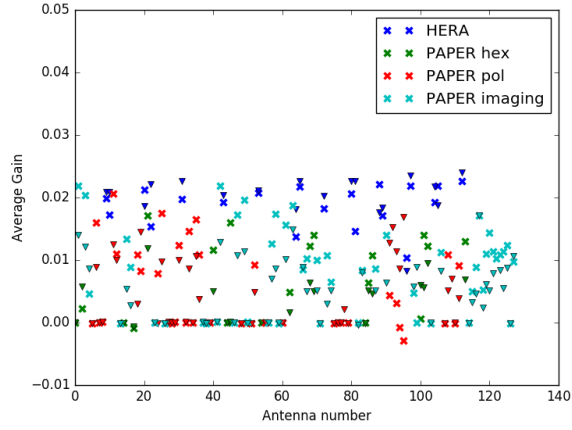


Figure 5: Average gain amplitudes for all antennas and polarizations. The “x” symbols correspond to X polarization, and the triangles correspond to Y polarization. Colors indicate the four subarrays.

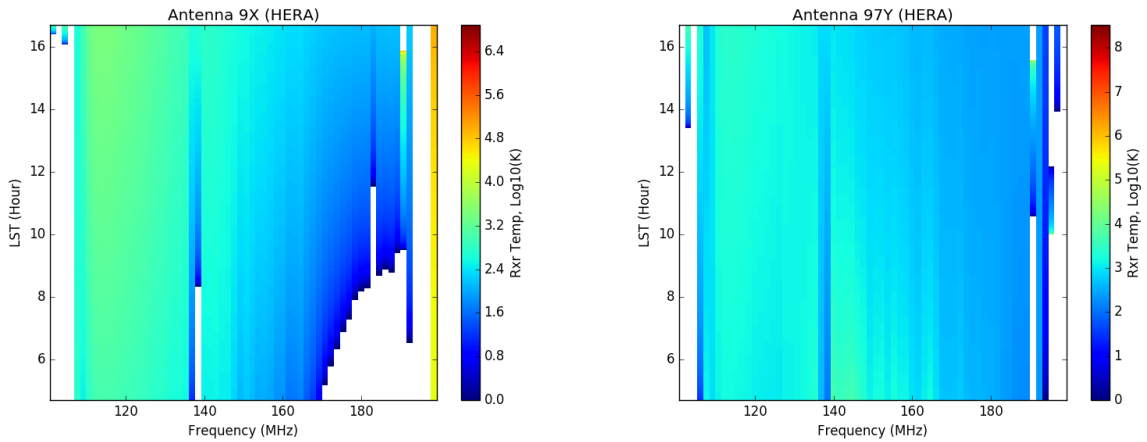


Figure 6: Receiver temperature waterfalls for two example HERA dishes.