HERA Dish Reflectometry

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1. Introduction

There are several different sources of instrumental chromaticity for radio telescope systems that can result in non-ideal performances and unwanted systematic effects in measured data. One such non-ideality is the mismatch between the impedance of free space and the antenna and transmission line, which results in a partial coupling of the sky signal into the antenna while the rest is reflected into space. For any reflector antenna, such as the HERA dish antenna, this signal illuminates the reflector and part of it reflects back and forth several times in between the dish feed and the vertex of the dish. Such reflections generate multiple reduced strength copies of the incident sky signal at various delays, and this produces spurious correlations in the visibilities of interferometric data.

The design specification of HERA elements is such that the amplitude of the signal that arrives at the feed at a delay of $60ns$ (after multiple reflections off the dish) should be reduced by $60dB$ relative to the first incident signal at the feed. We aim to verify this by carrying out reflectometry measurements at the HERA antenna prototype in Green Bank, WV. Understanding the nature of antenna reflections in the HERA dish is of the utmost importance in characterizing the performance of the dish. As HERA progresses as an experiment, it is necessary to build optimal dishes that aim to minimize the challenges of chromaticity in our quest for the Epoch of Reionization.

2. Theory

In practice, a HERA dish receives signal from the sky[1]. Plane waves incident on the parabolic dish are focussed at the feed with focal height l. For a well-designed feed, one that matches the impedance of free space[2], most of the signal will enter the system while only a small percentage will be reflected back towards the dish for a secondary reflection into the feed (blue arrows in Figure 1). In the following discussion, we consider the reflection off the feed and the subsequent reflection off the dish as one reflection.

Quantitatively, if the incident power from the sky signal is P_{sky}, the feed reflection coefficient is Γ_a, and the dish reflection coefficient is Γ_d, then the net power entering the feed after an n^{th} reflection off the feed and the dish is:

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[1] All astronomical telescopes operate in this way.

[2] The impedance of free space is $Z_0 = \mu_0 c_0 = \frac{1}{\epsilon_0 c_0} \approx 377\Omega$.

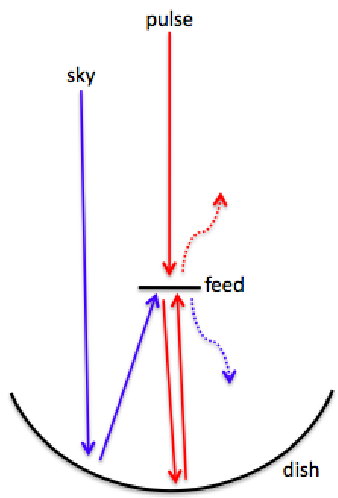

Fig. 1.— The blue solid lines represent an original sky signal entering the feed. A small percentage of it (dashed blue) is reflected off the dish, and it is these reflections that we are concerned about. In our measurements however, the reflections measured contain most of the original pulse signal (solid red), so it is crucial to adjust for this difference in our analysis.

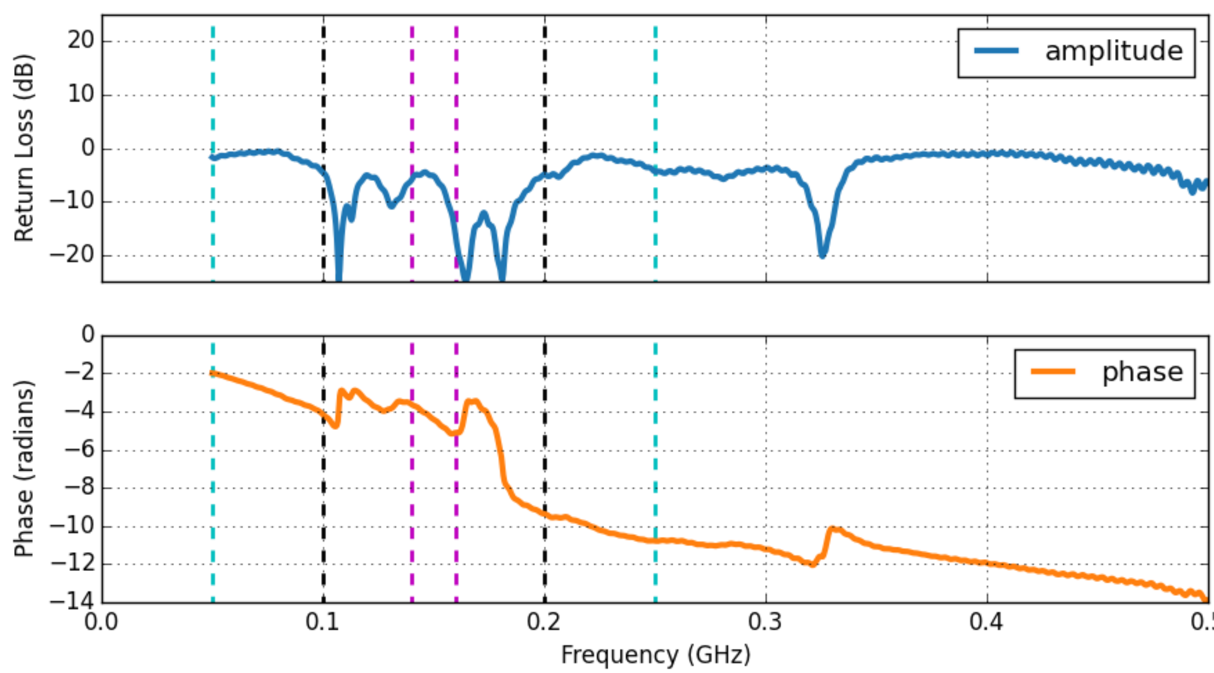

Fig. 2.— Amplitude and phase of the measured return loss. Colored dashed lines mark three different frequency bands: $140-160MHz$, $100-200MHz$, and $50-250MHz$.

$$P_{in} = P_{sky}(1-\Gamma_a)\Gamma_d[1+\Gamma_a\Gamma_d e^{i\phi} + (\Gamma_a\Gamma_d)^2 e^{i2\phi} + ... + (\Gamma_d\Gamma_n)^n e^{in\phi}] \tag{1}$$

where, $\phi = 2l(\frac{2\pi}{c})f$ is the propagation delay of a lightwave of frequency f due to a reflection over a focal distance l. Therefore:

$$\begin{aligned} \frac{P_{in}}{P_{sky}} &= (1-\Gamma_a)\Gamma_d[1+\Gamma_a\Gamma_d e^{i\phi} + (\Gamma_a\Gamma_d)^2 e^{i2\phi} + ... + (\Gamma_d\Gamma_n)^n e^{in\phi}] \\ &= (1-\Gamma_a)\Gamma_d \frac{1-(\Gamma_d\Gamma_a e^{i\phi})^n}{1-\Gamma_d\Gamma_a e^{i\phi}} \end{aligned} \tag{2}$$

The ratio in Equation 2 quantifies the amount of power received with respect to the incident sky power. Realistically, the incident sky power is not easily quantifiable, but it is a quantity we need to know to accurately characterize reflections.

Therefore, in our experimental set-up, instead of using sky signal, we employ our feed as a transmitter and transmit a pulse. If the initial pulse is a broadband signal, P_{tr}, sent to the feed antenna via a $75m$ long cable by a vector network analyser (VNA), a delay domain measurement of the system is accomplished by measuring the complex return loss of the feed. When the signal is incident on the feed, part of the incident power (Γ_a) is reflected back to the measuring device (dashed red arrows in Figure 1) and $(1-\Gamma_a)$ is radiated by the feed (solid red arrows in Figure 1). The signal radiated by the feed illuminates the dish, and the signal incident at the dish vertex is reflected by the dish and returns to the feed. [XXX All the signal incident on the dish is reflected, but we are only considering radiation from the vertex]. This incident signal is now reflected back and forth in between the feed and the dish much like the sky signal reflection discussed previously. Hence, if P_r is the power incident back on the feed for the first time then the reflected power P_{ref} back into the VNA would be:

$$P_{ref} = P_r(1-\Gamma_a)\Gamma_d[1+\Gamma_a\Gamma_d e^{i\phi} + (\Gamma_a\Gamma_d)^2 e^{i2\phi} + ... + (\Gamma_d\Gamma_n)^n e^{in\phi}] \tag{3}$$

Once again, note that we consider one reflection from the feed and its subsequent reflection from the dish as one reflection in total. Equation 3 is similar to Equation 1, with different incident powers.

Recall that P_r is the initial power that is incident back on the feed, which is just the feed radiated power reflected off the dish:

$$P_r = \Gamma_d(1-\Gamma_a)P_{tr} \tag{4}$$

Also note that the first reflection of the signal sent by the VNA occurs at the antenna end. Hence the total returned power P_{ret}, to the VNA would be:

$$
\begin{aligned}
P_{ret} &= \Gamma_a P_{tr} \\
&+ \Gamma_d^2(1-\Gamma_a)P_{tr}(1-\Gamma_a)[1+\Gamma_a\Gamma_d e^{i\phi}+....+(\Gamma_d\Gamma_n)^n e^{in\phi}]
\end{aligned}
\tag{5}
$$

Simplifying:

$$
\frac{P_{ret}}{P_{tr}} = \Gamma_a + \Gamma_d^2(1-\Gamma_a)^2\frac{1-(\Gamma_d\Gamma_a e^{i\phi})^n}{1-\Gamma_d\Gamma_a e^{i\phi}}
\tag{6}
$$

The ratio in Equation 6 is the returned power to the VNA with respect to the transmitted power sent by the VNA. It is identical to the sky observation case in Equation 2 but differs by two factors. The first factor corresponds to an additive amplitude difference arising from Γ_a, which physically accounts for the initial reflection at the feed. The second difference is a multiplicative term which informs us about the first reflection. Both of these terms need to be corrected for in order to relate our measurements to real observations.

The VNA measures the magnitude and phase of the quantity $\frac{P_{ret}}{P_{tr}}$ as a function of frequency as shown in Figure 2. In our measurement set-up, the first reflection occurs at the antenna terminal Γ_a, so $(\frac{P_{ret}}{P_{tr}} - \Gamma_a)$ gives an estimate of the delay spectrum of the sky signal. In delay domain, the relative signal strength at zero delay represents the factor Γ_a while the signal strength at any other delay represents any delayed signal that enters the feed after being reflected from the feed surroundings.

[XXXAnother bit about corrections at low and high delays needs to be in here.

3. Methodology

Our reflectometry measurements are made using a prototype HERA dish (Figure 3) at NRAO in Green Bank, WV. The dish is a $14\,m$ diameter parabolic reflector structurally supported with 3 telephone poles. The reflective material is made up of wire mesh that is attached to PVC pipes, forming the parabolic shape of the dish. With the current iteration of the HERA dish, the feed consists of a PAPER dipole encased in a cylindrical cage encompassing the backplane. The PAPER feed and the backplane (which is aimed at preventing feed-to-feed interaction between neighboring dishes) is raised and lowered by a three-pulley system. The focal height of the dish is $4.5m$ ($\sim$ 14.76ft).

Our measurements are made with a FieldFox in VNA mode. In this mode, a pulse is generated in the FieldFox and sent through a $75ft$ 50Ω cable that connects to the feed with a 4:1 passive balun. The return loss as a function of frequency, from 50 to $500MHz$, is saved. Both the amplitude of the relative power and phase information are saved. The frequency and delay resolution of the measurements is $\Delta\nu = 0.44Mhz$ and $\Delta t = 2.22ns$, respectively. In addition, we note that the round trip of a reflection from feed to the dish is $9m$, which corresponds to a delay of $30ns$.

In order to make our delay domain return loss measurements, we Fourier transform the frequency domain data we inherently measure with the VNA. However, since we are Fourier transforming a finite data series, and therfore a series multiplied by a square window function, we are actually convolving the fourier transform of our measurements with a *sinc* function. This results in excess power at high delays due to the sidelobes of the *sinc* function. To minimize the sidelobes we must use an appropriate window function before taking the Fourier transform. We have chosen a Hamming [XXX] window for our analysis. The effectiveness of this window function compared to a square window function is illustrated in Figure 4.

As mentioned in Section 2, there is a mis-match in amplitude between the reflections that we measure (originating from the FieldFox pulse) and reflections produced by sky signal. The reflections that we measure (at high delays) must be lowered by a factor to represent weaker reflections that would occur after most of the sky signal is received by the feed. For our compensation, we multiply our entire delay spectrum by its DC component [XXX what factor is this in the above equations. Why can we ignore the other factor]. We note that this correction is only accurate at high delays where our reflections of interest occur. At low delays, our spectrum amplitude should be increased to represent the original sky signal, but we do not apply this correction because it is not relevant to our analysis.

4. Results

Figure 2 shows the return loss for a frequency bandwidth of 50 to $500MHz$. This measurement was taken with the feed suspended at $13.96ft$, which was our closest measurement to the actual focal height. Because the return loss is the ratio of the power received to the power transmitted, higher reflections can clearly be seen outside of the PAPER bandwidth. This is not surprising, since the feed is tuned specifically for PAPER. The return loss minima are locations where our feed is well-matched to free space.

In Figure 5, the return loss is plotted versus delay for three chosen bandwidths: the HERA bandwidth, the PAPER bandwidth, and a typical power spectra bandwidth when using a Blackman-Harris window function. It is again shown that the reflections are minimized for the PAPER bandwidth.

Figure 6 is again a delay plot of the return loss, but for four different feed suspension heights. We use the PAPER bandwidth and note that the measurements are near identical at low delays, implying that low delay reflections are caused primarily by reflections within the

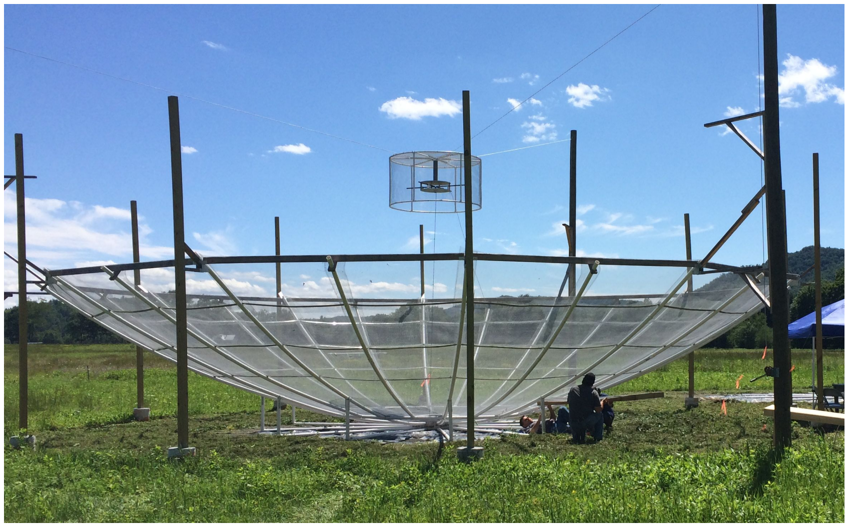

Fig. 3.— HERA dish and feed at the Green Bank NRAO site.

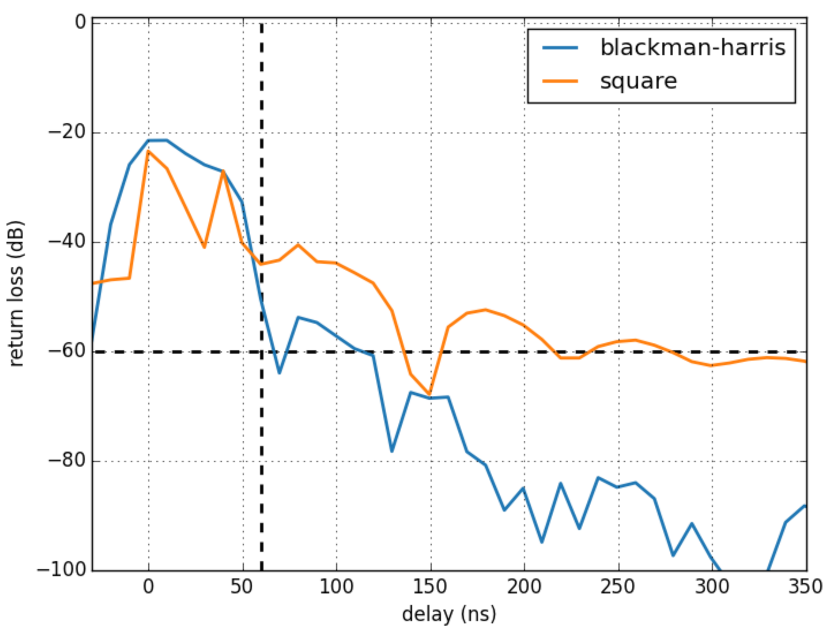

Fig. 4.— Delay plot produced using a Blackman-Harris window function vs. a square window function for the PAPER bandwidth.

feed cage. However, at higher delays we notice discrepancies between the different heights.

Finally, Figure 7 presents measurements taken of the feed away from the dish. Echosorb is placed under the feed for some of the measurements, with the expectation that it will prevent any reflections off the ground. Measurements are also taken of the feed inside its metal cage in various configurations.

5. Conclusion

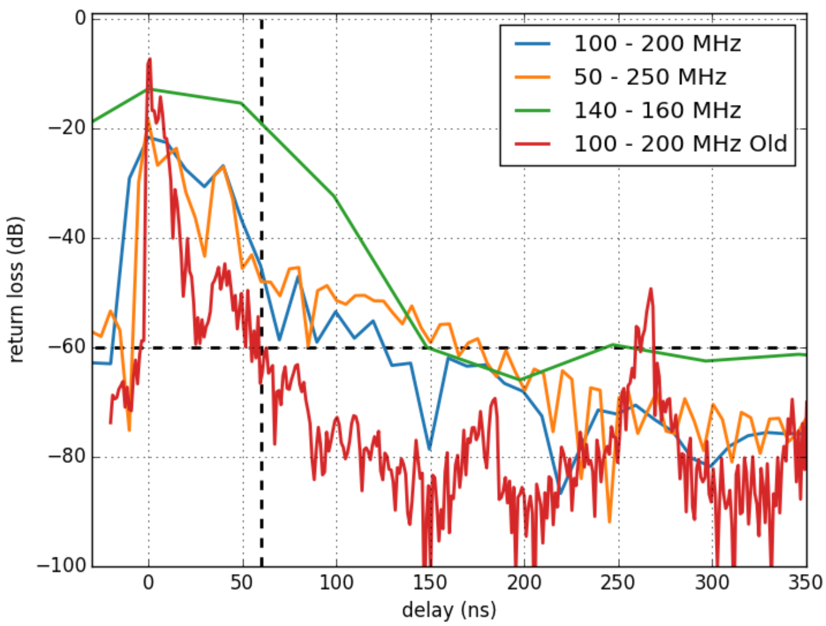

Fig. 5.— Delay plots produced using a Blackman-Harris window function for 3 different frequency bandwidths: $50MHz - 250MHz$ ("hera"), $100MHz - 200MHz$ ("paper"), and $140MHz{-}160MHz$ ("pspec"). The black dashed lines illustrate our "60 by 60" specification.

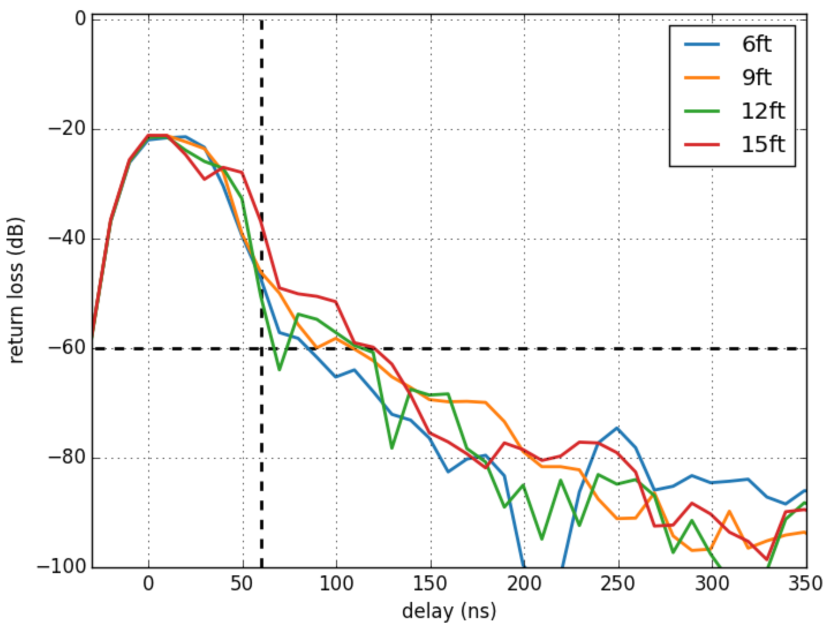

Fig. 6.— Delay plots produced using a Blackman-Harris window function for 4 different feed heights and the PAPER bandwidth. The black dashed lines illustrate our "60 by 60" specification.

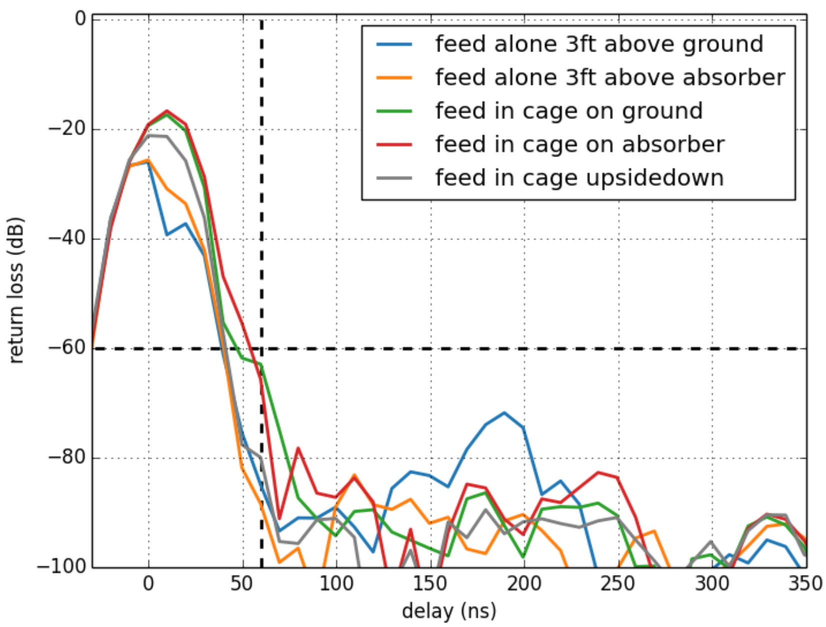

Fig. 7.— Delay plots produced using a Blackman-Harris window function for different lone feed configurations and the PAPER bandwidth. The black dashed lines illustrate our "60 by 60" specification.