HERA Dish Reflectometry

Nipanjana Patra, Zaki Ali, Carina Cheng, Aaron Parsons

1. Introduction

Non-ideal performance of radio telescope systems are often chromatic and manifests themselves in the measured data as systematic effects. One such non-ideality is mismatch between the impedance of free space and antenna as well as the transmission line which results in partial coupling of the sky signal into the antenna while the rest of it is reflected back into the space. In any reflector antenna, such as HERA dish antenna, this reflected signal illuminates the reflector. While most of the signal is reflected back in to the space by the reflector, a part of it is reflected back and forth several times in between the feed and the vertex of the dish which is shadowed by the feed (red arrows in Figure 1). Such reflections generates multiple copies of reduced strength of the incident sky signal at various delays. This produces spurious correlation in the visibility space of the interferometric data.

The design specification of the HERA elements are 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 60 dB relative to the first incident signal at the feed. We aim to verify this by carrying out Time Domain Reflectometry (TDR) at the HERA antenna prototype at the Green Bank. Understanding the nature of antenna reflections in the HERA dish is of the utmost importance in characterising the performance of the dish. As HERA progresses as an experiment, it is necessary to build optimal dishes that promise to minimise 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]. The plane waves, incident on the parabolic dish are focussed at the feed at the focal height. For a well-designed feed, one that matches the impedance of free space[2], most of the signal will be coupled into the system through the feed 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

[1] All astronomical telescopes operate in this way.

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

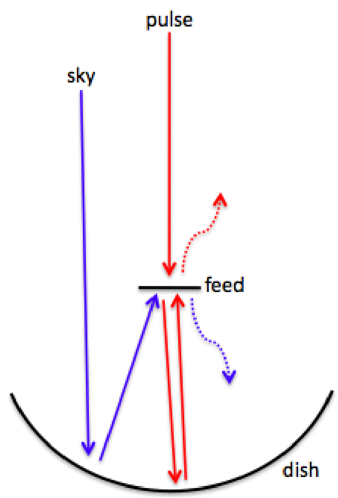

Fig. 1.— The blue solid lines represent an original sky signal entering the feed. A small percentage of it (dashed blue) is reflected off the dish, and it is these reflections that we are concerned about. In our measurements however, the reflections measured contain most of the original pulse signal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

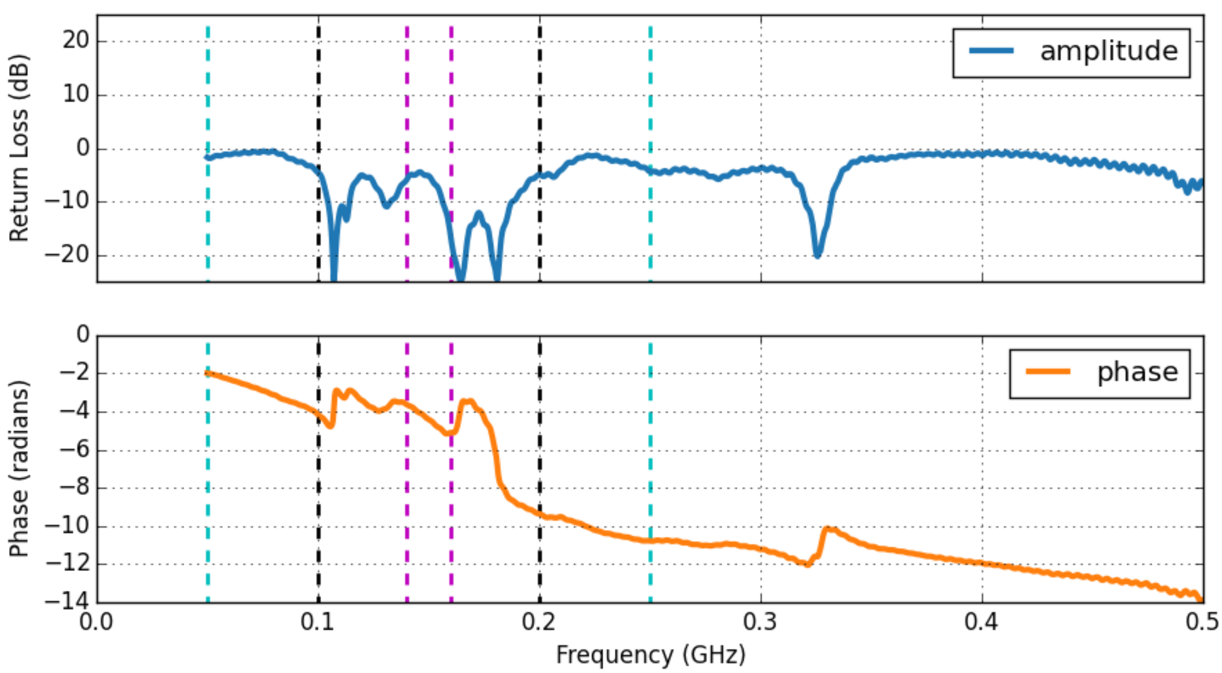

Fig. 2.— Amplitude and phase of the measured return loss. Colored dashed lines mark three different frequency bands: 140-160MHz, 100-200MHz, and 50-250MHz.

after an n^{th} reflection off the feed and the dish is:

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

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

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

Reflections causes the sky signal appear at various delays. We aim to measure the relative signal strength at various delays, referred to as the "delay spectrum" hereafter, to estimate various levels of reflections in between the feed and the dish apex. Antenna performance is reciprocal in transmitting and receiving mode and, therefore, in order to measure the delay spectrum, we measure the complex return loss of the antenna by a Vector Network Analyser (VNA) and take the Fourier transform of the measured data. Since this measurement is carried out in transmitting mode while an observation would be carried out in receiving mode, we correct our results in order to map them to represent real observations.

A broadband signal P_{tr} is sent to the feed antenna via a 75m long cable by a vector network analyser (VNA). A delay spectrum measurement of the system is accomplished by measuring the return loss of the feed while keeping it at the focal point of the dish. When the signal is incident on the feed, part of the incident power (Γ_a) is reflected back to the measuring device and $(1-\Gamma_a)$ is radiated by the feed. The signal radiated by the feed illuminates the dish, and the signal incident at the dish apex is reflected by the dish and returns to the feed. 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:

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

Once again, we consider one reflection from the feed and its subsequent reflection from the dish as one reflection in total.

Recall that P_r is the power 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:

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

Simplifying:

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

The VNA measures the magnitude and phase of the quantity $\frac{P_{ret}}{P_{tr}}$ as a function of frequencies which is plotted 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 the 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.

3. Methodology

The prototype HERA dish (Figure 4 built at the NRAO site in Green Bank, WV. is used to measure the delays associated with reflections within the dish and feed. The dish is a 14-m parabolic reflector structurally supported with 3 telephone poles. The reflective material is made up of wire mesh that is attached to PVC pipes that form the parabolic shape. With the current prototype, the feed is a PAPER dipole encased in a cylindrical cage encompassing the backplane. The PAPER feed and the backplane (which prevents 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). Feed heights quoted in our measurements represent the distance from the balun to the top of the central concrete hub. Note, however, that the actual focal height of the dish represents the distance from the backplane of the feed to the dish's wire mesh, which intersects the concrete hub between the ground and the top of the hub.

The following reflectometry measurements were taken on July 20-23, 2015 using a Field-Fox unit in Network Analyzer mode. A pulse is generated in the VNA and sent through a 75ft 50Ω cable that connects to the feed with a 4:1 passive balun. Magnitude and phase of the complex return loss of power is measured. Measurements are taken for a frequency bandwidth of 50 to 500MHz. The delay spectrum is computed by taking Fourier transform of the measured data with appropriate windowing. The measurement specifications are,

- Frequency bandwidth 450 MHz with 1024 channels i.e, frequency resolution $\Delta\nu = 0.44MHz$.
- For the measurement across 450 MHz bandwidth, resolution in the delay domain is $\Delta t = 2.22\ ns$.
- Antenna feed focal length 4.5 m which corresponds to a signal propagation delay of 0.3 ns. Hence, subsequent reflections from the dish vertex are expected to be at a delay which is integral multiple of 0.3 nS.
- Across the PAPER frequency band of $50 - 250$ MHz, the delay resolution would be 10 ns whereas the same over any $20MHz$ bandwidth would be $50ns$.

The signal at any other delays would be the result of signal reflection in the feed and the back place structure and the feed surroundings.

Fourier transform of a finite data series (such as the return loss over a finite bandwidth) can be interpreted as multiplication of data with a square window function, which is equivalent to convolving the Fourier transformed data with a *sinc* function. This results in excess power at high delays due to the sidelobes in the *sinc* function. Hence, appropriate windowing of the measurements is necessary before taking the Fourier transform. We have chosen to use a Blackman-Harris window. The effectiveness of this window function compared to a square window function is illustrated in Figure 3.

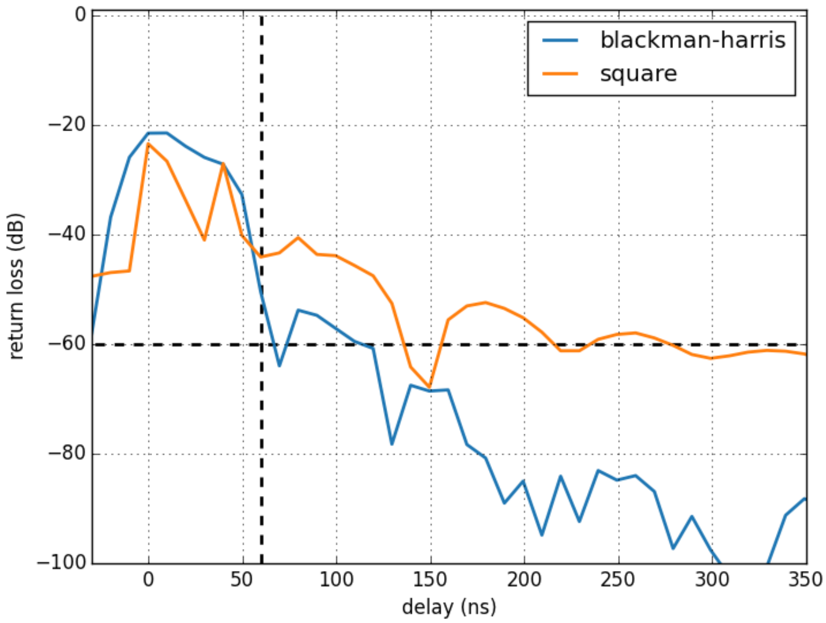

Fig. 3.— Fourier transform of the data shown in Figure 2 using a Blackman-Harris window function as well as a square window function for the PAPER observation band between 100 to 200 MHz. The dashed lines mark the specification 60 dB - 60 ns.

As mentioned in Section 2, there is a mismatch 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. 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 12ft (distance between the balun and top of the central concrete hub). 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 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

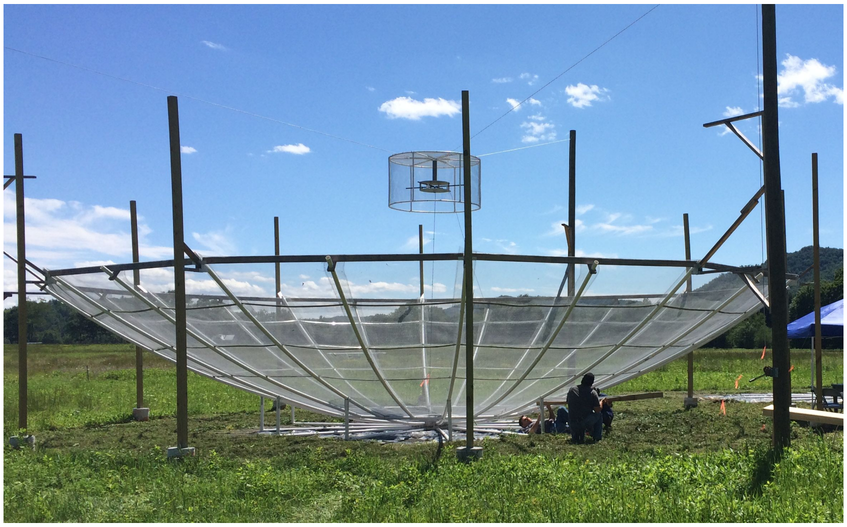

Fig. 4.— HERA dish and feed at the Green Bank NRAO site.

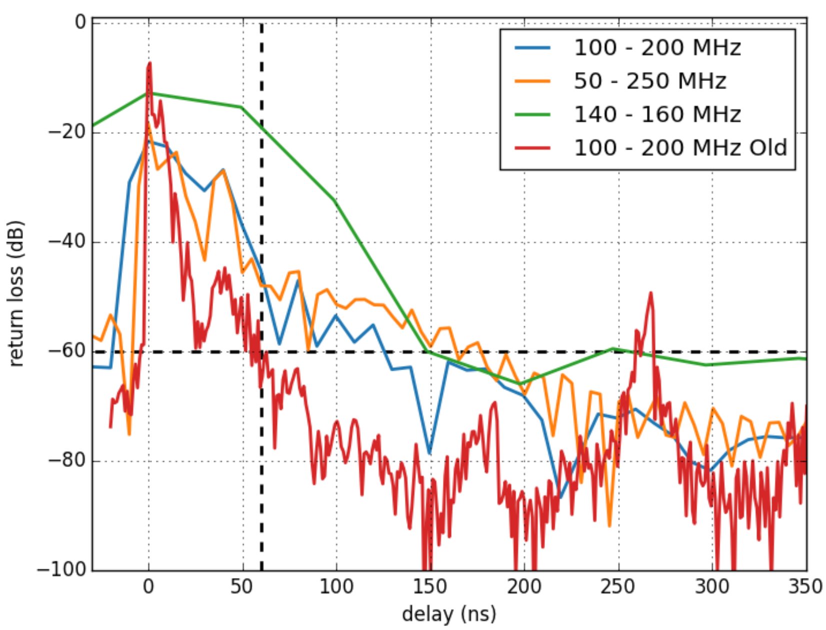

Fig. 5.— Delay plots produced using a Blackman-Harris window function for 3 different frequency bandwidths: 50MHz-250MHz ("hera"), 100MHz-200MHz ("paper"), and 140MHz-160MHz ("pspec"). The black dashed lines illustrate our "60 by 60" specification.

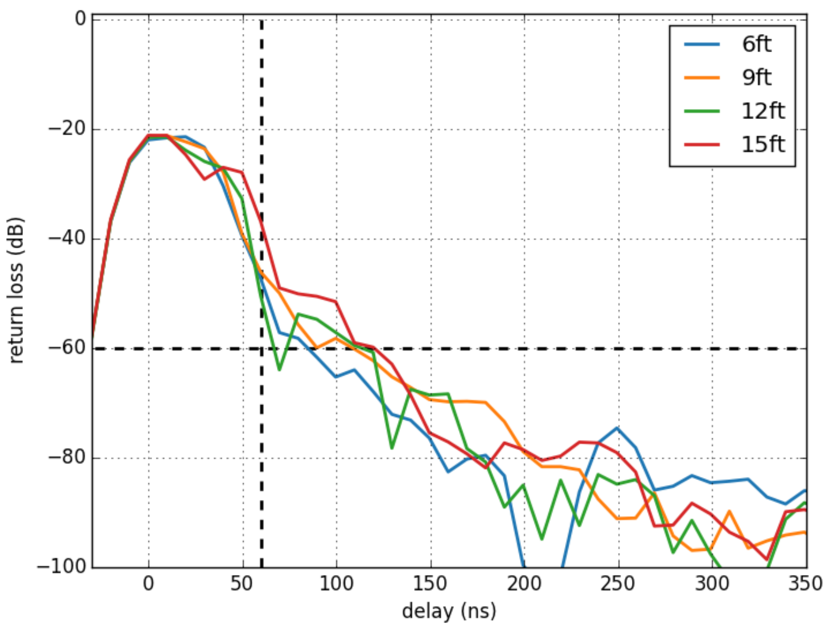

Fig. 6.— Delay plots produced using a Blackman-Harris window function for 4 different feed heights and the PAPER bandwidth. The black dashed lines illustrate our “60 by 60” specification.

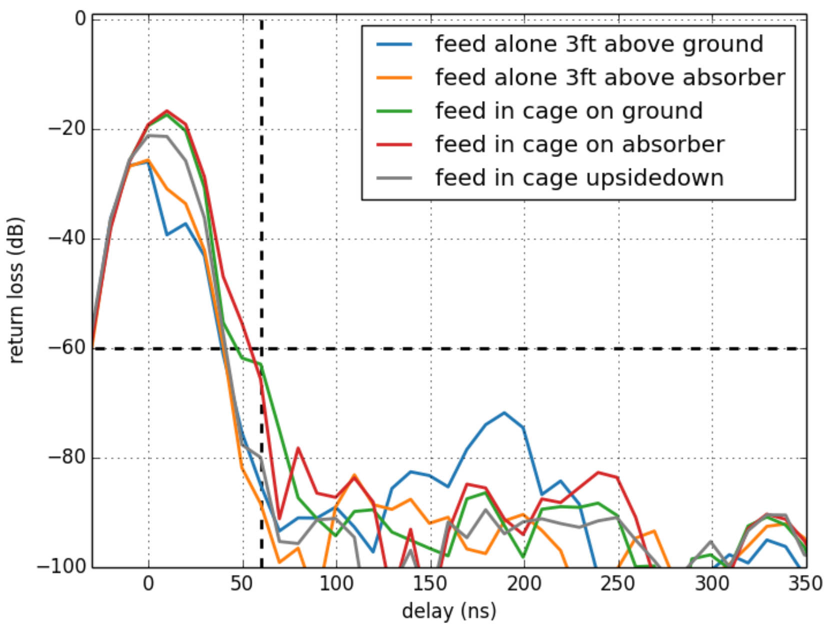

Fig. 7.— Delay plots produced using a Blackman-Harris window function for different lone feed configurations and the PAPER bandwidth. The black dashed lines illustrate our "60 by 60" specification.