Minimum RF-Over-Fiber Cable Length

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by Aaron Parsons

1 Introduction

HERA is considering changing the baseline design reported in DeBoer et al. (2016) for transmitting the RF signal from HERA dishes to the nodes where the signal is digitized. This design choice affects the expected time constant of signal reflections, which in turn can affect the extent of foreground contamination in the $(k_\perp, k_\|)$ plane. One of HERA's design goals is to minimize the extent of this contamination delivered natively by the instrument (before calibration), making the choice of cable lengths in the RF signal chain particularly important.

The original design of HERA aimed to minimize the length of cable between the dish and the node in order to minimize the time constant, $t_{\rm rf}$, of signal reflections. This time constant adds an offset to the minimum $k_\|$ mode that is uncontaminated by foregrounds as:

$$\Delta k_{\rm min} = \frac{2\pi}{Y} \cdot t_{\rm rf}, \tag{1}$$

where Y is the cosmological scalar $dL/d\nu$ relating line of sight distance to an interval in frequency (e.g. Furlanetto et al. 2006). Over the $6 < z < 12$ redshift range that HERA expects to use for science analysis, $2\pi/Y$ ranges in value from 0.00059 to 0.00043 $[h\ {\rm Mpc}^{-1}/ns]$.

```
In [11]: import capo.pspec, numpy as np
         zs = np.array([6,12])
         dk_deta = capo.pspec.dk_deta(zs)
         print 'dk/deta(z=6)=%f' % dk_deta[0], 'dk/deta(z=12)=%f [h Mpc^-1 / ns]'

dk/deta(z=6)=0.000588 dk/deta(z=12)=0.000432 [h Mpc^-1 / ns]
```

A rough tally of the expected contributions to $k_{\rm min}$ from the instrument includes:

```
In [12]: from aipy.const import len_ns
         cable_len = 35e2 # cm
         cable_spd = 0.7 # 0.7c propagation speed
         print 'Baseline Length:', 14.2e2 / len_ns * dk_deta
         print 'Feed/Dish Reflections:', 60. * dk_deta
         print 'Cable Reflections:', 2*cable_len / cable_spd / len_ns * dk_deta
         print '-' * 40
         print 'Total:', ((14.2e2+2*cable_len/cable_spd) / len_ns + 60) * dk_deta
```

```
Baseline Length: [ 0.02786408  0.02044665]
Feed/Dish Reflections: [ 0.03529623  0.02590035]
Cable Reflections: [ 0.19622594  0.14399047]
----------------------------------------
Total: [ 0.25938625  0.19033747]
```

We report an overall goal of measuring reionization at $k > 0.15$ [h Mpc^{-1}], which requires the cable reflections be down by -60 dB after two end reflections so that it does not entry into the tally above. This is probably doable with directional couplers, but it is challenging.

1.1 RF Over Fiber

We are now considering migrating to a design that transmits the RF signal over optical fiber (RFoF) from the feed to the node. This technology has been successfully applied several times in radio telescopes (e.g. ATA, LEDA), and relies on relatively inexpensive components for applications at low frequencies with modest system temperature requirements.

One of the key differences between RFoF and copper signal transmission is cable cost. RFoF systems require optical tranceivers, but cable cost and signal attenuation are fractionally small. The lower cost, the reduced signal loss, and the slim profile of optical fiber make possible to explore designs that use long stretches of cable between the feed and the node. These designs, rather than aim for short time constants for signal reflection, could instead target time constants so long that the reflections show up at k modes beyond the scale we anticipate HERA having the sensitivity to access.

From Figure 5 of Pober et al. (2013), we see that HERA is expected to have 1σ thermal noise error bars on the scale of the signal at $k \sim 1$ [h Mpc^{-1}], regardless of the foreground removal strategy. Thus, a conservative placement of foreground leakage from cable reflections would be at $k_{\rm min} \sim 1.5$ [h Mpc^{-1}].

To translate this into a constraint on the length of the optical fiber, we will use an index of refraction of 1.47 (http://www.m2optics.com/blog/bid/70587/Calculating-Optical-Fiber-Latency) and assume that reflections must traverse the cable twice (bouncing off both ends) to re-enter the receiver in the direction of the original signal.

```
In [20]: kmin = 1.5 # h Mpc^-1
         fiber_spd = 1 / 1.47 # index of refraction of 1.47
         fiber_len = kmin / dk_deta * len_ns * fiber_spd / 2
         print 'Minimum Fiber Length [cm]:', fiber_len
```

```
Minimum Fiber Length [cm]: [ 26000.84820294  35433.18338696]
```

1.2 Precision of Fiber Length

Deviations in the cut length of the optical fiber has two primary effects on HERA.

The first is that it adds a time delay to the signal path that will need to be calibrated out. This is done as a matter of course in HERA calibration and is not a major effect. The way in which this could become an issue is if the time delay became long enough that the resulting phase slope across a channel in the correlated visibility caused signal loss. As shown in Figure 9 of Parsons et al. (2008), a Polyphase Filter Bank with 4 taps will exhibit $\sim 1\%$ loss for a signal delay corresponding to 0.1 of the inverse of HERA's 100 kHz channels. Numerically, this corresponds to ~ 1000 ns. This constrains the precision of the optical fibers to a fractional accuracy of ± 50 %, which is not a stringent constraint.

```
In [22]: f_chan = 100e3 # kHz
         print 1./(f_chan / 1e9) * .1, 'ns'
         print 'Fiber Delay [ns]:', fiber_len / fiber_spd / len_ns
```

```
1000.0 ns
Fiber Delay [ns]: [ 1274.92356256  1737.4279502 ]
```

The second effect is that reflections will decorrelate in the power spectrum computed for two redundant baselines if they are orthogonal. In practice, this mitigating effect is probably not important, since the reflections are being placed outside the k range of where HERA is sensitive. However, if one wanted to be careful and leave open the possibility of measuring these modes at some point in the future, a suggestion would to dither the lengths of cables between antennas by a delay scale comparable to the width of the foregrounds. If we take the foreground width to be $\sim 60ns$ and assign antennas lengths of cable among 4 different choices (yielding 6 different choices, if the differences in cable lengths form a [0,1,4,6] Golomb ruler), we can then specify what each cable length should be:

```
In [30]: delta_ns = 60. # ns
         delta_len = delta_ns * (len_ns * fiber_spd) / 2 # divide by 2 for two refl
         print 'Delta length for 60 ns [cm]', delta_len
         golomb4 = np.array([0.,1,4,6])
         print 'Fiber lengths [cm]:', np.around(fiber_len.max() + golomb4 * delta_l
```

```
Delta length for 60 ns [cm] 611.821342857
Fiber lengths [cm]: [ 35430.  36050.  37880.  39100.]
```

1.3 Conclusion

Based on the above calculation, we estimate that fiber optic cables for HERA's proposed RFoF system should be at least 355 m in length. After that, we could optionally cut lengths that deviate by $+6.2m$, $+24.5m$, and $36.7m$ to further suppress reflections, but this is probably unnecessary.