GOOD NEWS ON USING FOURIER FILTERING FOR STANDING WAVE REMOVAL

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ABSTRACT

This is an update of my May 16, 2003 memo entitled *Bad News on Using Fourier Filtering for Standing Wave Removal*, in which I concluded that Fourier filtering helps remove ripple but not much.

In fact, Fourier filtering helps *tremendously*. My analysis in the previous memo contained grievous errors. The immediate implication is that we should correct GALFA HI profiles for this ripple. To make this correction, we require wide bandwidth data. Therefore, we should have a wide-bandwidth option on the GALFA correlator so that we can either observe the wide bandwidth simultaneously or interlace it, during a small fraction of the observing time, with the regular observations.

1. INTRODUCTION

Spectral line observers are plagued by sinusoidal ripples. These are produced by reflections, which produce standing waves. Can we remove these ripples using Fourier filter techniques? In my previous memo of May 16, 2003, I concluded "not very well". I received comments from several people, but in particular from Frank Briggs who referred me to Briggs et al (1997) showing that Fourier filtering should work; it also developed a procedure for dealing with time variability of Fourier coefficients. I finally found time to revisit the issues and find that I had made a grievous error in the previous memo. I also have incorporated Frank's procedures, which helps but is of less importance for these data, which are of fairly short duration.

2. THE DATASETS

Phil obtained LBN data over 60 MHz bandwidth by using three quadrants of the interim correlator during maintenance time. The telescope was stationary except for occasional motions in (az, za). The data consist of sets of 300 1-second spectra, so each set lasts 5 minutes. Some of the data sets, in particular set number 182, were contaminated by the Sun and showed a large ripple. This seemed like an ideal test dataset. We used Phil's *dolbn* software to extract three datasets, numbers 182, 183, and 184. We used the 5-minute average of set number 183 as the reference for set numbers 182 and 184. Set 182 was severely contaminated by the sun, and sets 183 and 184 much less so. Here we concentrate exclusively on dataset 182.

To get nice clean spectra for experimenting with Fourier filter techniques, we considered a somewhat limited frequency range that avoids the HI line just above 1420 MHz. Specifically, we included 1369.94 to 1419.92 MHz, inclusive. Conveniently, this range is contained in 2048 channels, which is handy for the FFT.

Figure 1, top shows the 5-minute average of the two polarizations for the dataset 182; the units are system temperature. The ripple is clearly evident in both polarizations. Moreover, it is similar in the two polarizations, leading us to examine the average and difference of the two polarizations, which are in the bottom panel. The ripple cancels to some degree in the difference and is very strong in the average, showing that our visual impression from the top panel is correct. The difference profile shows a lot of systematic stuff whose amplitude is even larger than the ripple in the average, which shows that there is a lot of highly polarized, frequency-random stuff in the difference spectrum.

Our main interest in GALFA is the average of the two polarizations. This seems to be dominated by the sinusoidal ripple. This ripple looks fairly concentrated in Fourier space, making it an ideal case for removing it with a Fourier (Wiener) filter. In contrast, the ripples in the polarized (DIFF) spectrum do not look concentrated in Fourier space, and are probably harder to remove. Here we restrict our attention to the polarization average.

3. FOURIER TRANSFORMING THE SPECTRA

We took the FT of each of the 300 frequency spectra. Each FT produces an array of complex Fourier coefficients versus time delay τ. We plot amplitude spectra of the 5-minute vector average of these 300 FTs in Figure 2. The spectra exhibit strong peaks at ~ 0.8 μsec, equivalent to about 240 meters, which corresponds to the separation of the feed from the primary. In each figure, the bottom two panels show the power spectra for the difference and average; the very bottom panel shows the average, which is our main concern.

4. FOURIER FILTERING THE DATA

For each 5-minute dataset we have 300 FTs, each of which has 2048 time delays (τ) in the FT. Thus each time delay τ in the FT is characterized by 300 complex numbers, each of which can be written as an amplitude and a phase. For a particular time delay τ, plotting the 300 phases reveals that they usually change linearly with time. We fit a linear time dependence to the 300 phases, replacing the noisy phase of each with the well-determined least-square phase value. We smoothed the amplitudes over about 10 seconds.

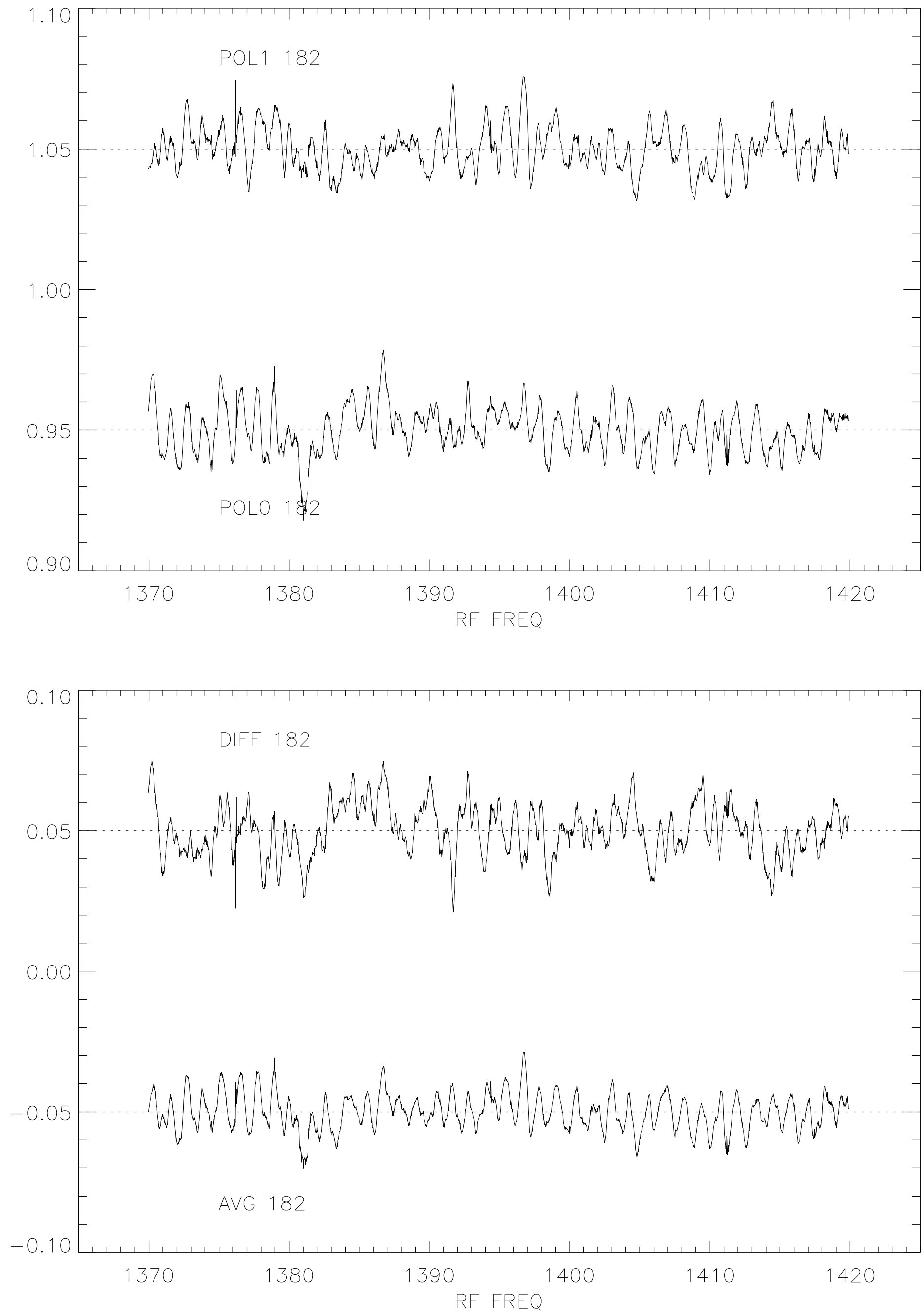

Fig. 1.— The severely-rippled dataset 182. The top panel shows the 5-minute average of both polarizations separately; the bottom shows the average and the difference.

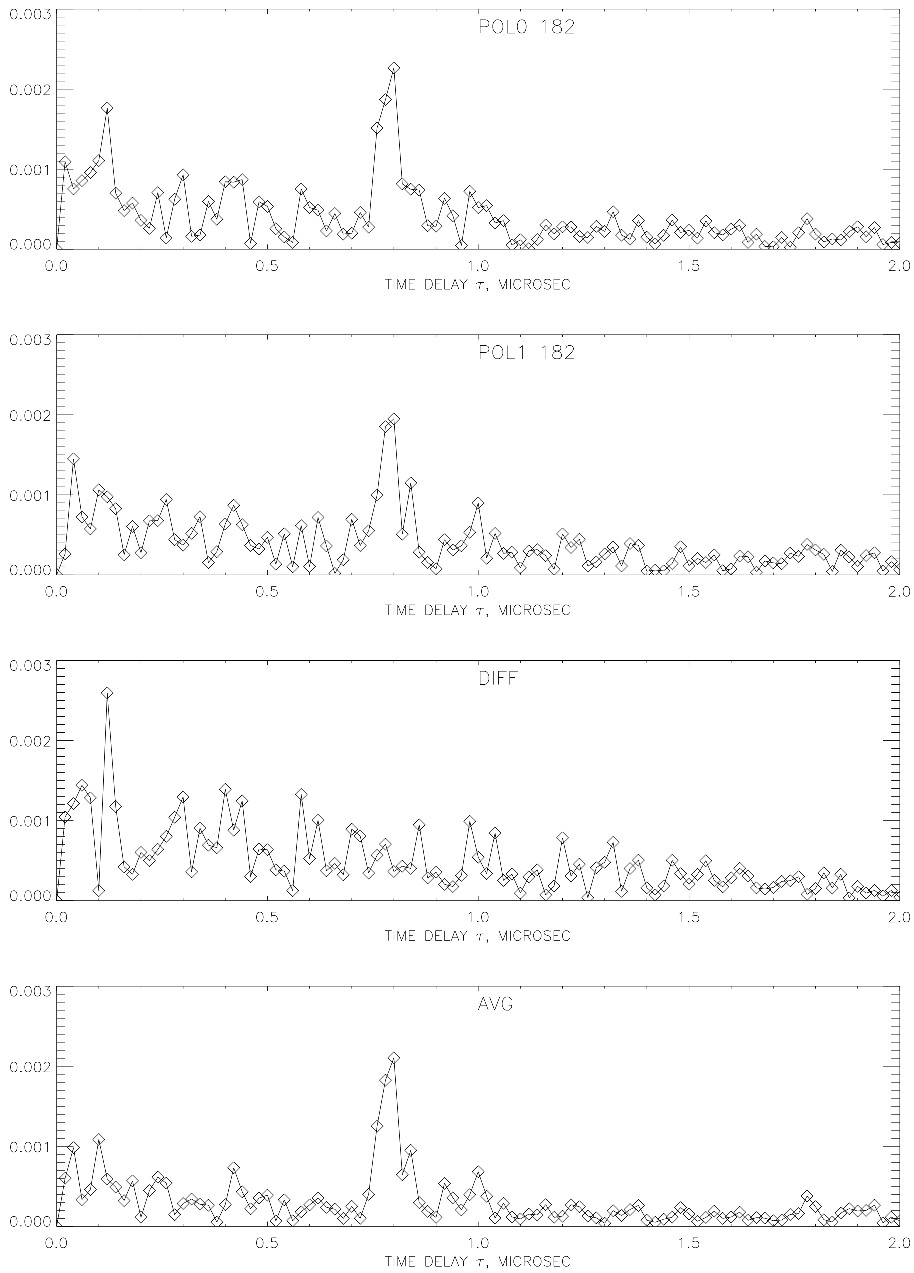

Fig. 2.— Amplitude spectrum of the 5-minute vector average of the 300 FTs for the severely-rippled dataset 182. The top two panels show both polarizations separately; the bottom two show the average and the difference.

The smoothed amplitudes and fitted phases represent the contribution of the ripple to the FT. For smoothed amplitudes exceeding a threshold, we subtracted the smoothed amplitude and its fitted phase from the original complex number. Thus, we generated a new FT in which the some of 2048×300 complex numbers are replaced by the original values minus the smoothed ones. We then reconstituted the original frequency spectra from the modified FTs. In the particular test illustrated here, the threshold is 0.0005.

It is important to note that we do not simply zero the offending FT components. Rather, we estimate the ripple component and replace offending components with the original value minus the ripple estimate. This removes the ripple, but not power that is associated with, for example, the HI line.

Figure 3 shows the filtered dataset in exactly the same format as the unfiltered one in Figure 1. The Fourier filtered dataset is a clear improvement over the original dataset because the ripple is gone. We have yet to experiment with details such as determining how lowering the threshold, which removes more ripple, interacts with distorting the shape of the HI line.

5. CONCLUSION

Comparison of the unfiltered and filtered spectra show a very significant improvement with respect to the ripple. This is achieved by considering only the polarizations individually, or their average. We had thought that reflections might be highly polarized so that looking at other Stokes parameters might afford more insight into the ripple. However, from the present data this does not appear to be the case.

These results have ramifications for the GALFA spectrometer. We can remove ripple by the Fourier technique. The quality of our results will increase with the time resolution $\delta\tau$ in Figure 2. The time resolution $\delta\tau$ is equal to the reciprocal of the bandwidth analyzed. Thus, we should obtain wide-bandwidth spectra at the same time as we observe our HI line. This could be done either with a separate correlator or by interlacing wide-bandwidth observations with the HI observations; with interlacing, only a small fraction of the observing time would be required for the wide-bandwidth observations. We don't need many channels on the wide-bandwidth observations; obtaining a total delay of about 2 μsec is sufficient. Thus, for a bandwidth of 100 MHz, we need about 200 channels.

6. REFERENCES

Briggs, F.H., Sorar, E., Kraan-Korteweg, R.C., & van Driel, W. 1997, Pub Astr Soc Australia, 14, 37.

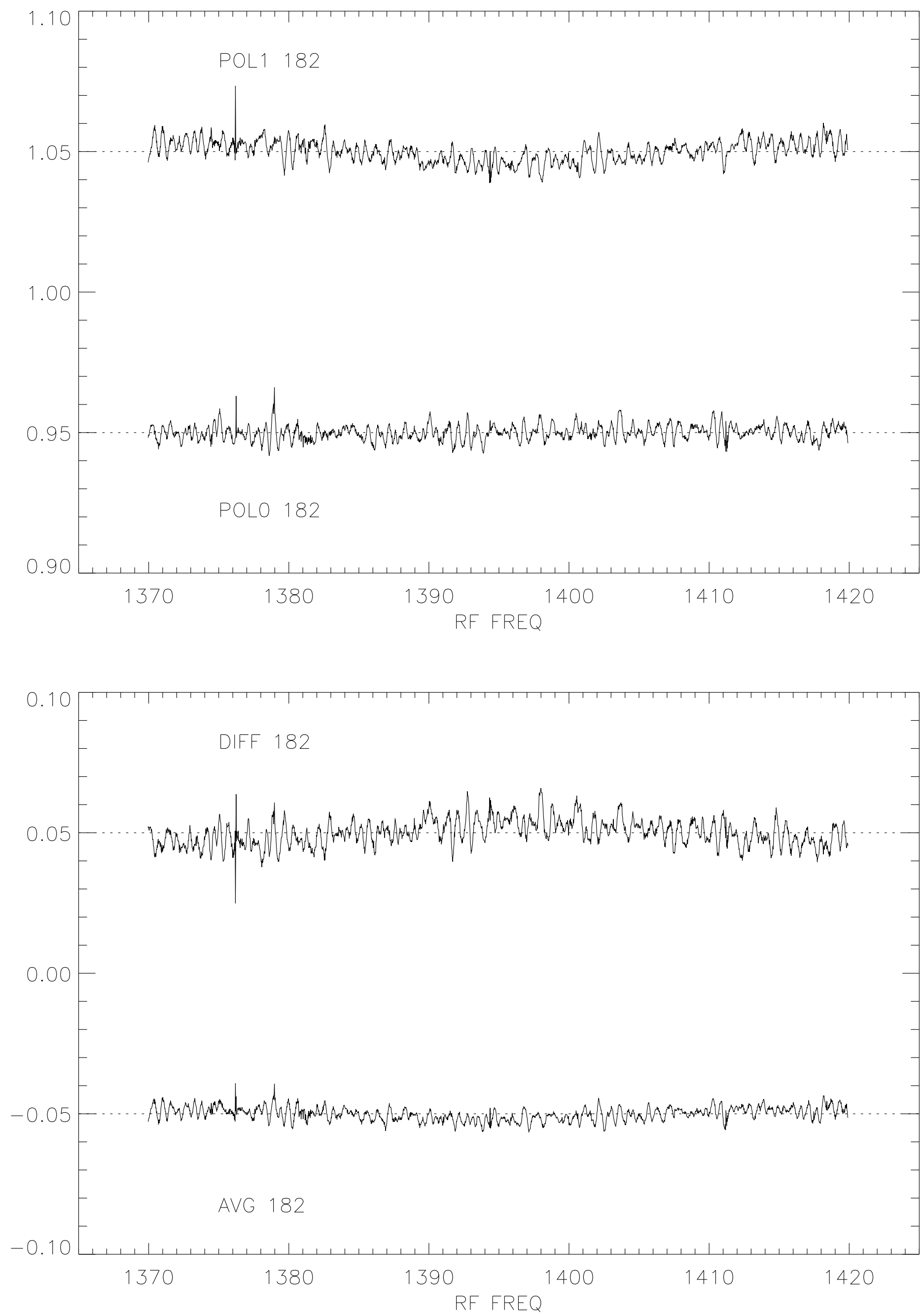

Fig. 3.— The severely-rippled dataset 182. The top panel shows the original average dataset and the bottom the Fourier filtered dataset. both polarizations separately; the bottom shows the average and the difference.