RFI SUBTRACTION WITH A REFERENCE HORN:

APPLICATION TO PULSARS AND VLBI

F. H. Briggs[1], **M. J. Kesteven**[2]

[1] ***Kapteyn Astronomical Institute, Postbus 800, 9700AV Groningen, The Netherlands, fbriggs@astro.rug.nl***

[2]***CSIRO Australia Telescope National Facility, P.O. Box 76, Epping, NSW 1710, Australia,***
mkesteve@atnf.csiro.au

ABSTRACT

Cross correlation of an RFI reference signal with the corrupted radio astronomy data channels permits construction of the adaptive correction that is suitable for radio spectroscopy where time-averages are recorded. The reference signal is constructed from the cross power spectrum of the signals from the two polarizations of a reference horn pointed at the source of the RFI signal. The method is immune to the effects of multi-path scattering in both the astronomy and reference signal channels. Here, we demonstrate the generality of our result by applying it to the correction of time sequence data, such as pulsar timing observations.

INTRODUCTION

We have been experimenting with an intuitive but powerful RFI cancellation technique that is especially well suited for radio astronomical spectroscopy, where time-averages are recorded. The method requires computation of cross power spectra between the RFI contaminated astronomical signals and high signal-to-noise ratio RFI “reference signals” obtained from a separate receiving system that senses the RFI but not the astronomical signal. The correction terms that remove the unwanted RFI are computed from closure relations obeyed by the RFI signal. The test applications reported here derived the reference signal from a separate horn antenna aimed at the RFI. For the present new experiments, we used the publicly available data sets [1] from the Parkes Telescope, recorded by digitally sampling baseband signals from two polarizations for both the reference horn and astronomy feeds. We performed the cross correlations in software off-line. However, the method could use correlation spectrometers of the sort already in use at radio observatories to perform much of the computational task in real time.

The purpose of this paper is to demonstrate that the method can be used to build an adaptive filter for correcting time series data. We further comment on how the method could be implemented in VLBI applications.

OVERVIEW OF THE METHOD

During these experiments, both orthogonal linear polarizations A and B from the Parkes Telescope were recorded, along with two orthogonal linear polarizations, labeled 1 and 2, obtained from the reference horn aimed at the source of the rfi. The full mathematical development [2] shows how the rfi contamination $|g_{AI}|^2\langle|I|^2\rangle$ in the power spectrum $P_A(f)$ measured for the ‘A’ polarization,

$$P_A(f) = |g_A|^2\langle|A|^2\rangle + |g_{AI}|^2\langle|I|^2\rangle + \langle|N_A|^2\rangle, \tag{1}$$

can be estimated and subtracted. Here, $g_A(f)$ and $g_{AI}(f)$ are the complex, frequency-dependent voltage gains describing the coupling of the astronomical signal A and the interfering signal I to the measured power spectrum, and N_A gives the strength of the noise in the A polarization data channel. The symbols <…> are used to signify averages over an integration time that could be as long as 1 s in the tests described here. When similar expressions are adopted for the power spectra and cross power spectra between all pairs of the data channels, an estimate of the contamination term can be written as

$$|g_{AI}|^2\langle|I|^2\rangle = \langle|I|^2\rangle\,(g_{AI}\, g_1^*)(g_{AI}^*\, g_2)/(g_1^* g_2) \approx C_{A1}\, C_{A2}^*/C_{12}^* \tag{2}$$

where * is used to indicate complex conjugation and C_{ij} (f) represents the complex cross power spectrum between the i and j data channels. The term C_{12} represents the cross power spectrum of the two polarizations sensed by the reference horn, for example. The approximate relation at the right side of (2) applies provided the rfi signals are the only strongly correlated signals in the cross power spectrum; this is expected to be the case, since none of the noise N_1, N_2, N_A or the astronomical signal should be present in all three channels. In fact, a simple way to implement (2) that copes with low INR (interference to noise ratio) ranges in the spectrum is to compute the correction as

$$|g_{AI}|^2 \langle |I|^2 \rangle \approx C_{A1}\, C_{A2}{}^*\, C_{12} / (\psi(f) + C_{12}\, C_{12}{}^*) \tag{3}$$

where $\psi(f)$ represents the noise level in this data channel. Here we approximate that $\psi_0 \approx \psi(f) \approx$ constant across the band.

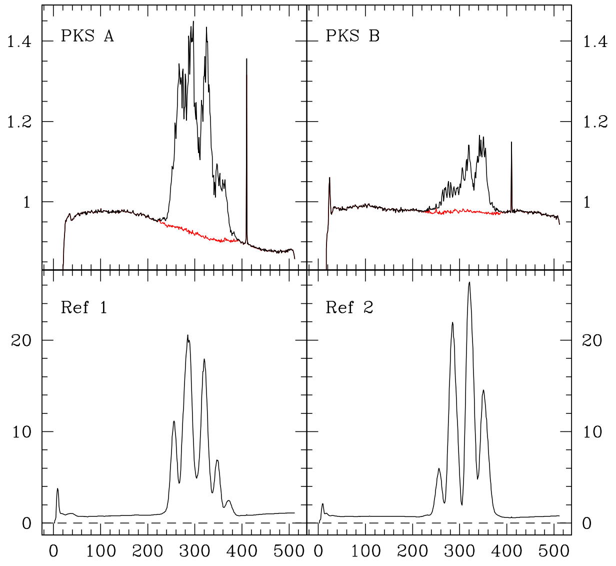

Fig. 1. The scan-average power spectra for scan SRT00502 (approximately 25 seconds of data). A passband calibration has been applied to compensate for the gain dependence of the 5 MHz band limiting filters. The upper spectra are the two polarizations from the Parkes Telescope receivers -- both before and after cancellation. The lower spectra are orthogonal polarizations recorded through the reference horn.

Fig.1 shows the result of applying this technique to Parkes observations centered at 1499 MHz [1]. For display purposes, a 5 MHz band is split into 512 spectral channels. The spectra in the figure were corrected on time scales of 0.1 s and then averaged to obtain the result shown in Fig.1. For integrations longer than 1 s, the complex gain factors apparently begin to vary, as the telescope sidelobes falling on the rfi source change, and the subtraction loses precision.

APPLICATION TO PULSARS

Once the complex gains that couple the rfi signal to the astronomical data channel have been measured by the cross correlation technique, then those gains can be applied for the length of time that they are stable to correct the time series data. In [2], a procedure is outlined for constructing the appropriate filter to apply to the reference horn signals that will produce an estimate of the rfi contribution to the Parkes data streams. In fact, these filters could be Fourier transformed to obtain a set of coefficients that could be used in FIR time-domain filters. In the implementation used here, the frequency domain filters were computed on a 100 msec time-scale, and these filters were applied to the Fourier transforms of short 8192 sample segments of the time-series. For simplicity, the filtered data was inverse transformed to form a clean time-series that was then folded on the pulsar period in order to coherently integrate the pulse profile. (A more practical implementation could be made that avoided much of the computational overhead.)

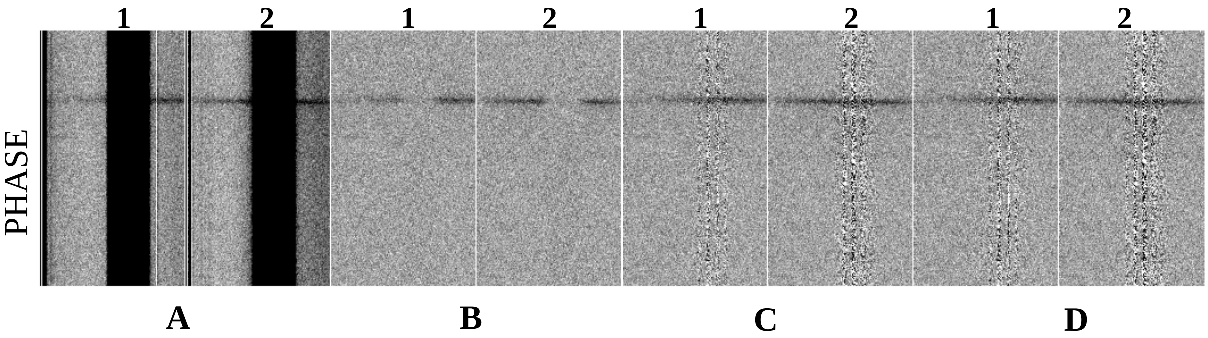

Fig. 2. Dynamic spectra for Pulsar J0437-4715, folded on the pulsar period for scan SRT00604. Eight spectra are shown side-by-side, with phase through the pulsar period running vertically and frequency running left to right. The dynamic spectra are grouped in pairs of two polarizations – 1 and 2 – as labeled at top: (A) the raw spectra, (B) normalized by the average total power spectra, (C) rfi subtraction with Ψ_0 parameter equal 0.01, (D) rfi subtraction with $\Psi_0 = 0.001$.

Dynamic spectra for examples of the use of these filters are shown in Fig. 2. These dynamic spectra have been folded on the period of the pulsar, rather than displayed in a pure time sequence. The left most pair of spectra has the two polarizations from the Parkes Telescope with no compensation for the presence of the rfi, which saturates the grey scale of the display in order to make visible the presence of the pulse in the frequency ranges outside the contaminated channels. The examples to the right show the result of applying the corrective filtering. To the left center is a simpler – but remarkably effective – spectral weighting scheme, which does no actual "subtraction;" instead, the spectra are simply normalized by the average passband (see Fig. 1.) obtained for the data in the 25 s scan itself. This serves to de-weight the spectral channels that have rfi, thus whitening the noise for these channels and throwing away any information about the pulsar.

The results of Fig. 2 show that the method has been able to recover the pulse in the channels that were contaminated. However it is also reasonable to ask why these channels are so "noisy," representing an incomplete rfi subtraction. The process would have been expected to do better, if the filter had worked as well for this pulsar application as for the spectral application in Fig. 1. The difference between the two cases is that the interference-to-noise ratio (INR) in the first case (scan SRT00502) is nearly 100, while it is closer to 2 in the data set shown in Fig. 2 (scan SRT00604). Unfortunately, among the publicly available data sets presented in [1], there are no pulsar observations with a higher INR in the reference data streams.

In order to compare the achieved signal-to-noise ratio in the average pulse profile measured for the combined frequency channels, Fig. 3 shows the scan averaged pulse profiles for the data in Fig. 2. The profiles are plotted with equal rms fluctuation in the time ranges away from the pulse, so that the pulse height is a direct measure of the SNR. An interesting conclusion in this case is that the simple, spectral weighting scheme has actually delivered the best SNR for this particular data set, although the rfi subtraction scheme that we set out to test would be able to do much better, had the INR of the reference been higher.

APPLICATION TO VLBI

Finally, it is worth commenting on how easy it would be to implement the subtraction method in a very long baseline interferometry (VLBI) context, since there the baseband data is recorded and played back into a correlator in a way that closely parallels the way our experiment has been implemented here. VLBI observations could be performed by including a pair of tape tracks with containing high INR reference signals along with the astronomical tracks. During the subsequent playback, correlation and analysis stages, the reference horn data would be included as a separate "station" in the antenna array. Then, during the post-correlation processing, the rfi subtraction would be handled as part of the routine calibration.

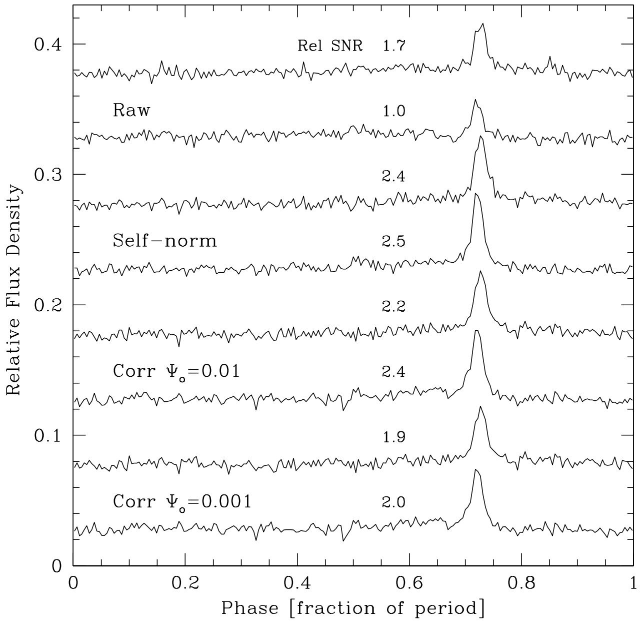

Fig. 3. Comparison of average pulse profile obtained in each of the four scenarios illustrated for the dynamic spectra of Fig.2.

While VLBI has long been known to have the advantage that local rfi at one station does not correlate with signals at other stations, the rfi does raise the effective noise level of the receiving system. Use of the rfi subtraction technique effectively subtracts the rfi phase-coherently, thereby removing even this additional noise power contribution.

REFERENCES

[1] J. F. Bell, P. J. Hall, W. E. Wilson, Sault, R. J., et al., “Base band data for testing interference mitigiation algorithms,” *Publ. Astron. Soc. Aust.*, 18, pp. 105-113, 2001.
[2] F. H. Briggs, J. F. Bell, M. J. Kesteven, “Removing radio inteference from contaminated astronomical spectra using an independent reference signal and closure relations,” *Astron. J.*, vol. 120, pp. 3351-3361, 2000.