RADIO FREQUENCY INTERFERENCE MITIGATION IN RADIOASTRONOMY

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ABSTRACT

RFI is increasingly a problem for radioastronomy with the ever expanding use of the radio spectrum by both the communications industry (transmitting) and the radioastronomers (receiving). Regulation can protect a few windows in the radio spectrum, but many experiments now need to access parts of the spectrum outside the reserved regions. Spectral lines, for example, may be significantly doppler-shifted, and therefore require an observation window far from their rest frequencies.

A variety of RFI mitigation techniques have been developed in recent years. Most of these will have analogues in other disciplines, but the specifics of the radioastronomers' experiments allow for some interesting refinements. The astronomer is generally not interested in recovering a symbol stream in the data, but rather wants a more general description of the statistics. This makes a number of post-correlation techniques valuable and computationally viable.

1. INTRODUCTION

The days of interference-free observations in radio astronomy are now long gone. Increasingly, experiments such as the search for doppler-shifted spectral lines will need to be made outside the bands allocated to radio astronomy. There are also substantial pressures from commercial, defence and other interests for greater access to the radio-frequency spectrum. This means that the radio astronomers can no longer rely on the regulatory authorities for an environment free from interference, and they need to look seriously at mitigation strategies.

RFI mitigation is a well established discipline in other areas (see, for example, Ghose [1]), but it is relatively recent in radioastronomy.

This paper presents an overview of some recent developments in RFI mitigation designed for the radioastronomer.

2. WHY HAS MITIGATION BECOME NECESSARY?

Astronomers now have to take RFI mitigation seriously because of a conjunction of a number of factors:

1. Telescopes are becoming ever more sensitive. This means that their threshold for detecting unwanted signals is also moving to fainter levels, exposing the telescopes to greater numbers of RFI sources.
2. With more sensitive telescopes comes the problem that every field of view of the telescope will contain more detectable objects, which then puts pressure on the image quality. If the dynamic range in the imaging is compromised by RFI, then the faint objects will be blurred, confused or missed.
3. Better, more sensitive telescopes mean that the astronomers' experiments become more challenging, exploring a wider range of the spectrum with wider instantaneous bandwidths.
4. The commercial use of the spectrum is increasing as well, so there is more RFI present.

3. THE IMPACT OF RFI ON THE RADIOASTRONOMER

Most modern radiotelescopes consist of arrays of antennas (VLA [2], SKA [3], LOFAR [4]). These are imaging arrays that exploit the van Cittert-Zernicke theorem to synthesise apertures comparable to the array extent. The astronomer measures, for each antenna pair, the correlation function :

$$C_{i,j}(f,t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} V_i(f,\tau).V_j^*(f,\tau)d\tau$$

An array consisting of N antennas will measure, at each integration, N(N-1)/2 different samples of the coherence function. As the earth rotates the array's orientation to the astronomical target will change, providing a steady stream of fresh samples. The quality of the image reconstruction is set by the quality of the sampling - ideally it should be closely and evenly distributed over as large an area as possible.

RFI corrupts this process in several ways :

- RFI which is coherent over parts of the array will generate statistically significant visibilities which will then be processed by the imaging machinery, leading to artefacts in the image.

Most observations will include a regular sequence of calibration observations. These are critical to the quality of the imaging, and it is probably here that RFI-mitigation is most important.

- Strong local RFI which is not coherent over the array may still play a role by raising the noise level with products between receiver noise and RFI.

3.1. Some Mitigating Factors

The signal processing and the astronomical communities both deal with weak signals; but they differ in their requirements: the communication world expects to recover the underlying symbol stream, whereas the astronomer is searching for a statistical characterisation of the data - the spectral power density, for example.

The nature of the data, and the data processing algorithms used in radioastronomy are such that there a number of options available to the radioastronomer that would probably not be suitable elsewhere. To give one simple example: in some cases it is not out of the question to blank the receiving system when the RFI exceeds a given threshold. This would result in a degradation in signal-to-noise, and possibly reduce the imaging fidelity, but the science goals would still be achievable.

The changing orientation of the array relative to the astronomical target helps: time variable delays are needed to ensure that the signals from the target object add coherently at the processor. Since the delay trajectory for the astronomical target will rarely match the RFI, the RFI will decorrelate when averaged over all the baselines of the array, and when averaged over the duration of lengthy observations. (see Thompson [5]). Future antenna arrays have an advantage here, with greater number of antennas, and with longer baselines.

In addition, in modern telescope arrays which tend to be spread out over large distances, the RFI is likely to be local to just a sub-set of the array's antennas.

4. SOME RECENT RFI MITIGATION STRATEGIES

The central issue in RFI mitigation is to identify the RFI. A number of successful strategies have operated in the post-correlation domain - in essence, within the imaging machinery.

This approach has the very attractive feature of substantially reduced the computer load, when compared to mitigation strategies operating on the raw data streams.

4.1. The Post-Correlation Adaptive Filter

The canonical adaptive filter (Haykin [6]; Barnbaum [7]) is a powerful tool for removing RFI. The filter is able to remove RFI from a corrupted data channel once it is given an independent copy of the RFI. The drawback, from the astronomer's point of view, is the presence of a spectral echo of the RFI in the filtered channel. The RFI itself is seriously attenuated, by a factor $\sim 1/(1+INR)^2$, where INR is the interference-to-noise ratio in the reference channel. However, the filtered channel also suffers an injection of noise, with a spectral distribution which mimics the RFI. A long integration, the traditional method of improving the detectability of weak signals, will not remove the echo - it will simply reduce the noise in the baseline and in the echo.

An alternative design, the post-correlation adaptive filter (Briggs [8]) , is shown in figure 1. The correlator creates, for each pair of signals, the spectral cross-correlation :

$$C_{i,j}(f) = < V_i(f).V_j^*(f) >$$

The algorithm is outlined in figure 1. From the three cross-spectra that contain a reference signal we can estimate the contribution that the RFI makes to the observed spectrum. The estimate is, statistically, zero-mean, so that we have a distinct advantage over the adaptive filter : we have cancellation with noise but no bias, as opposed to attenuation with noise. (The two reference channels, Rx and Ry, provide copies of the RFI with independent receiver noise. This ensures the cancellation with no bias. A single channel model would require the receiver bandpass to be stable and known (calibrated) to high precision).

It should also be noted that the filter continues to work well at low INR levels: the real-time adaptive filter will cease to be effective when the INR approaches 1, while the post-correlation filter can work to a level of -20dB.

This filter can be generalised to provide RFI mitigation in an array. The scheme is shown in figure 2. Each antenna-pair (baseline) is cleaned separately, and the cleaned ensemble is passed to the calibration/imaging machinery. Figure 3 shows an example of the scheme in operation. The raw RFI affected data were collected over a 12-hour period. Figure 3a shows the the result of imaging the raw data. Figure 3b has the image from the filtered data. The field is essentially empty, but 3 or 4 weak sources can be seen. The rms noise in the image (the RFI) has been reduced by two orders of magnitude.

The RFI filtering requires additional correlator resources, equivalent to adding one antenna to the array. The increase, for an array of N antennas amounts to (N+1)/(N-1).

This scheme works well, allowing imaging in the presence of severe RFI. It is limited however, as it requires the location of the RFI to be known *a priori* so that the reference antenna(s) can be optimally directed to the source of the RFI.

4.2. RFI mitigation in the image domain

Several groups have demonstrated that RFI can be identified and removed within the image processing operation (Wijnholds [9], Cornwell [10]). The advantage is that there is then no need for a separate reference antenna that would provide the clean copy of the RFI. The distinguishing feature that identifies the RFI is the known movement of the RFI relative to the imaged sky. (In the VLA case [10] the target was stationary with respect to the array. A moving RFI source - a satellite, for example - could be accomodated in this formulation, provided that the trajectory were known with some precision).

4.3. Generalised Spatial filtering

In the previous section the RFI was identified by a spatial signature established at the imaging stage. A more general and elegant scheme has been described by Leshem et al [11]. Given an array of N antennas, we form the correlation matrix **R** over all N(N+1)/2 antenna combinations over some time interval τ. **R** describes the array's response to the astronomy within the field of view, to the RFI, and, along the diagonal, to the receiver noise. To the extent that the RFI is stronger than the astronomy component, an eigen decomposition will recover the RFI vector, so that a projection operation could remove the RFI.

The RFI excision exacts a computing penalty, as the array's response to a point source varies over the field of view. However, the benefits of the better defined procedure for identifying the RFI make this an attractive option.

5. RFI MITIGATION FOR THE NEXT GENERATION OF TELESCOPE ARRAYS (SKA)

It is clear that the SKA, an array of very many antennas, will present a substantial challenge to the software groups involved in the calibration, imaging and analysis operations. RFI mitigation is in danger of swamping that endeavour.

The array will consist of a number of"stations", each containing a number of antennas whose signals will be combined in a small number of beamformers. The stations are distributed over large distances, so much of the ground-based RFI will be confined to one or two stations.

This suggests that the RFI mitigation should parallel this architecture:

- a station-level mitigation to provide a RFI-cleaned output from the beamformer. This could involve wide-band array nulling. A station-level correlator will be needed to provide the calibration needed for the beamformer, so much of the required machinery will already be in place. Recent work at the Allen telescope ([12]) suggests that this may entail substantial processing effort. Alternatively, adaptive filtering on the beamformer output is a possibility.

- an SKA-level mitigation at the post-correlation stage.

6. CONCLUSION

RFI mitigation is still in its infancy in radioastronomy, but recent developments suggest that it will soon be installed on-line and become part of an observatory's standard routine.

The computing effort is significant, but less daunting than other software components of a modern telescope array.

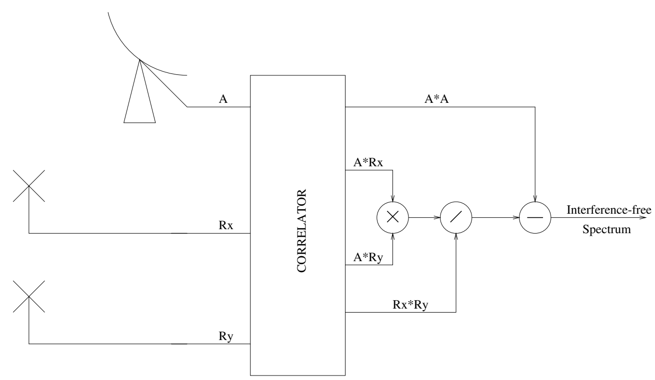

Figure 1. A single antenna post-correlation adaptive filter

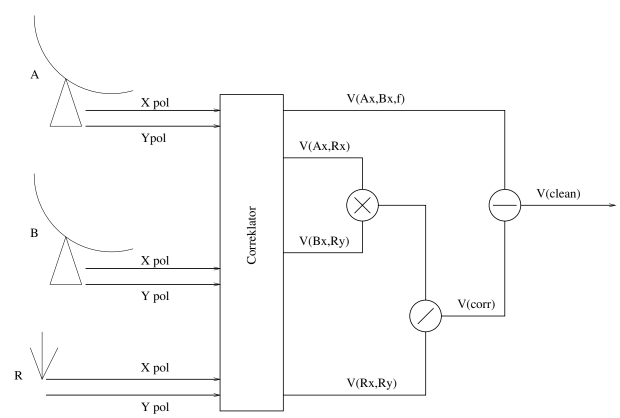

Figure 2. An array-based post-correlation adaptive filter

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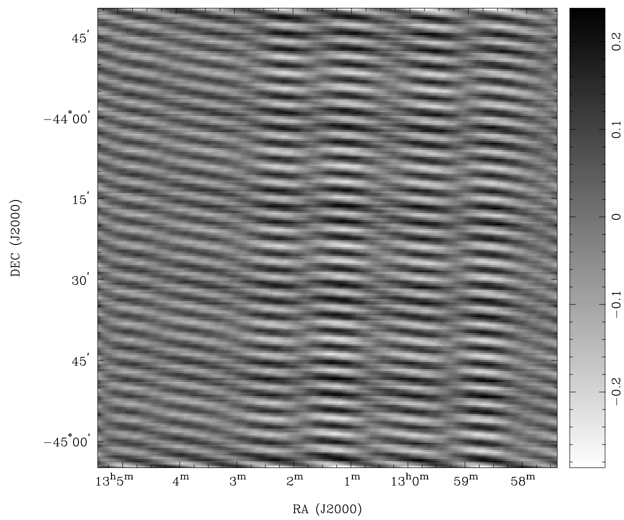

Figure 3a. Image based on the raw, unfiltered data

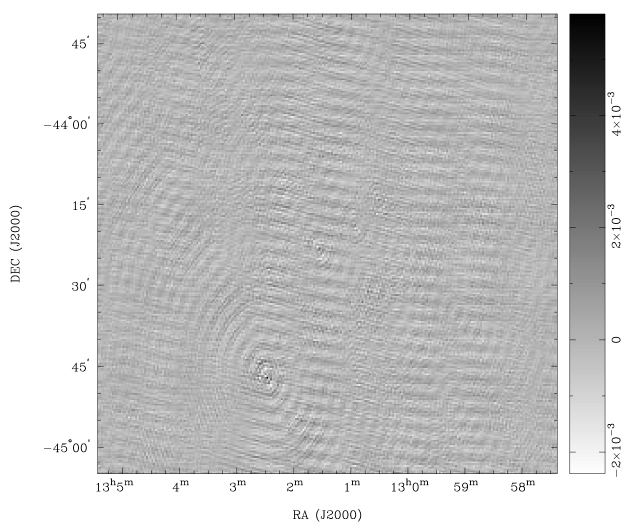

Figure 3b. Image based on the filtered data