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RFI Mitigation in Radio Astronomy: an Overview

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Abstract
Radio astronomy is a passive service and is equipped to observe extremely weak signals from outer space. The sensitivity of current state-of-the-art telescopes is over ten orders of magnitude higher than in most communications systems. Although radio telescopes are best located in relatively remote areas, astronomical observations may be still hampered by man-made radio frequency interference (RFI). In this paper we will consider different interference mitigation options. After a quick overview of techniques already implemented in current radio telescopes, we will focus on the innovative possibilities induced by the new generation of radio telescopes. In particular, phased array architecture can lead to interesting spatial filtering approaches. Examples on real data from LOFAR and from Nançay radio telescopes will be shown.

1. Introduction

Observed radio astronomical signals are very weak, typically 40 to over 100 dB weaker than signals from active services. Furthermore, the coming two decades will see the setting up of radio telescope systems which are one to two orders of magnitude more sensitive than the traditional systems. Examples are the Low Frequency Array (LOFAR) [1], which enters its fully operational mode in the Netherlands, and the Square Kilometre Array (SKA)[2], which is currently in an engineering phase.
Because of the denser active use of the spectrum, and because of higher telescope sensitivities, radio astronomy is increasingly hampered by radio frequency interference (RFI) from other spectrum users. In [3], we have carried out a survey on RFI mitigation techniques. In this paper, we provide some practical examples on recent results using data from the LOFAR and Nançay radio telescopes (see Fig. 1). Although non digital approaches (RF filtering, shielding …) are also relevant, we will mainly focus on digital approaches.

Figure 1: Nançay observatory with the decimeter radio telescope (NRT) and the French LOFAR station (FR606).

2. RFI detection approaches

When the RFI does not continuously share the same time-frequency slots as the signal of interest, the corresponding polluted time-frequency slots can be flagged, blanked or excised from the data without completely losing astronomical information. Prior to the flagging/blanking/excision process, a detection procedure must indicate if the time-frequency slot is polluted or not. Traditionally, such techniques are applied in radio astronomy to post correlation data (see example [4]). However, the detection can be conceptually implemented everywhere in the processing line.

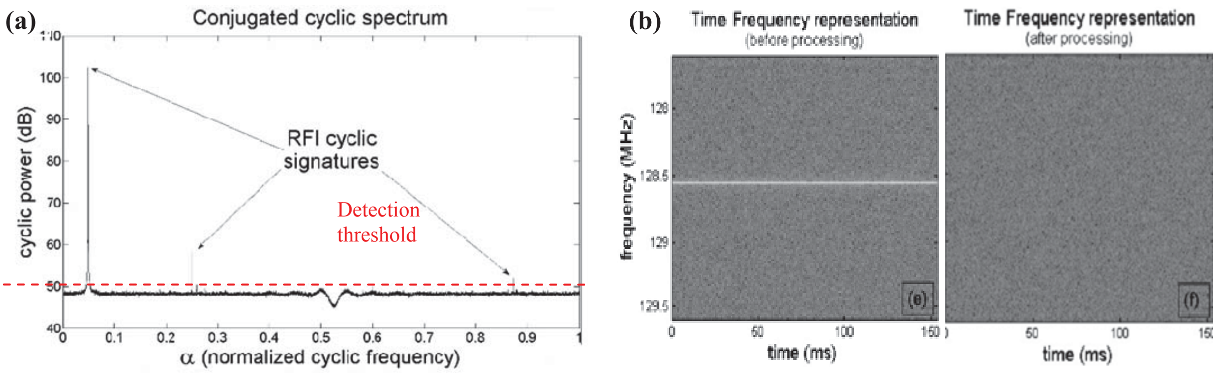

Figure 2: RFI mitigation cyclostationary simulations on a LOFAR data set (M = 10 antennas and $L = 2^{15}$ samples) corrupted by an airborn signal at 128.6 MHz [5]. ***(a)*** A cyclostationary blind detector obtained by calculating the Frobenius norm of instantaneous correlation matrices. ***(b)*** Cyclic spatial filtering results. The RFI nulling has been derived from singular value decomposition of the cyclic correlation matrix.

For phased array radio telescopes, detection at station level and post-correlation level at core site seem to be relevant approaches. The multidimensional array approach is more effective than the single antenna approach and should be preferred. This technique is based on the antenna correlation matrix, **R** (see below), which will be computed anyway at station level (for calibration purposes) and of course at post-correlation level. An ad-hoc detector, associated with this correlation matrix, is the Frobenius norm detector (see example on Fig.2.a).

3. Spatial selectivity approaches

3.1. Presentation

If an interferer and the signal of interest continuously share the same part of the time-frequency plane, excision and blanking are useless but spatial selectivity is an approach which can be used in telescope arrays. In such approaches, we assume that the processing bandwidth is sufficiently narrow, so that all propagation delays between antennas can be modeled by a phase shift of the signal. All this spatial information is represented by the array output covariance, **R**.
Classic beamforming consists in electronically steering a direction of interest using the phased antenna array output data [6]. The power, σ_{class}^2 , reached in the spatial direction θ is then

$$\sigma_{class}^2(\theta) = \mathbf{w}(\theta)\mathbf{R}\mathbf{w}(\theta)^H \quad \textbf{[1]}$$

where $\mathbf{w}(\theta)$ is the steering vector, or beamforming phase coefficient vector.
If we suppose all signals uncorrelated, and a calibrated array, the covariance matrix model of the antenna array radio telescope can be written as $\mathbf{R} = \mathbf{A}\mathbf{R}_{\mathbf{RFI}}\mathbf{A}^H + \mathbf{N}$ where **A** is a MxN matrix containing the N RFI column steering vectors. $\mathbf{R}_{\mathbf{RFI}}$ is the NxN RFI covariance matrix. Its diagonal contains the RFI powers. $\mathbf{N} = \sigma_n^2\mathbf{I}$ is the MxM noise covariance matrix, σ_n^2 being the noise power on each antenna and **I** the M-dimensional identity matrix. $(.)^H$ stands for the hermitian transpose.
Performing a subspace decomposition on **R** using a Singular Value Decomposition (SVD) highlights two signal subspaces : an interference subspace, generated by the N singular vectors related to the N dominant singular values of **R**, and a noise subspace generated by the M-N other singular vectors. The RFI subspace obtained after SVD spans the same subspace than the subspace generated by **A**. This RFI subspace can also be estimated from some other sets of correlation matrices such as cyclic matrices (see example on Fig. 2.b) or time lagged matrices [7].
The orthogonal projector [8] is a linear transform allowing an RFI subspace cancellation while keeping its orthogonal subspace intact. This transform is defined by: $\mathbf{P}_{\mathbf{orth}} = \mathbf{I} - \mathbf{A}(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H$ and it leads to the construction of an orthogonal projection beamformer applied in this way:

$$\sigma_{orth}^2(\theta) = \mathbf{w}(\theta)^H\mathbf{P}_{\mathbf{orth}}\mathbf{R}\mathbf{P}_{\mathbf{orth}}^H\mathbf{w}(\theta) \quad \textbf{[2]}$$

The main issue with this beamformer is the orthogonality requirement between the direction of interest $\mathbf{w}(\theta)$ and the projected out subspace **A**. Without this condition, the estimated power, $\sigma_{orth}^2(\theta)$, will be biased.
The oblique projector [9] is another kind of linear transform that does not require the latter condition in order to recover the right power reached in the direction θ:

$$\sigma_{obl}^2(\theta) = \mathbf{w}(\theta)^H\mathbf{E}\mathbf{R}\mathbf{E}^H\mathbf{w}(\theta) \quad \textbf{[3]}$$

where $\mathbf{E} = \mathbf{w}(\theta)\left(\mathbf{w}(\theta)^H\mathbf{P}_{\mathbf{ortho}}\mathbf{w}(\theta)\right)^{-1}\mathbf{w}(\theta)\mathbf{P}_{\mathbf{ortho}}$.
In the next section, all the 3 approaches are compared on real signals.

3.2. Tests

The Electronic Multi-Beam Radio Astronomy ConcEpt (EMBRACE, [10]) is a dense aperture array designed for covering a frequency range going from 500MHz up to 1.5GHz (see Figure 4.a). In its current architecture, this phased antenna array is composed of 16 tile-sets made of 288 antennas elements. Each second, a covariance matrix of these 16

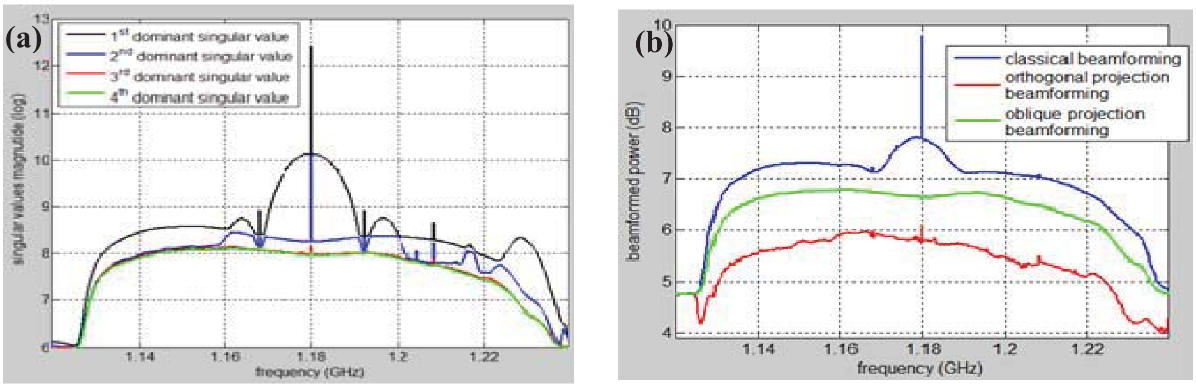

Figure 3: EMBRACE experiment **(a)**Spectra of the 4 dominant singular values of an observations between 1.12GHz and 1.24GHz **(b)** Spectra after steering in direction of the zenith for the classic beamforming (blue curve),the orthogonal projection beamforming (red curve) and the oblique projection beamforming (green curve)

tile sets is provided for a unique frequency bin. After 512 seconds, the system released 512 covariance matrices covering the whole band of interest (that might be lower than the full frequency range).
Figure 3.a shows the spectra of the 4 dominant eigenvalues of an observation acquired between 1120MHz and 1240MHz over 512s. The central main lobe is due to a GPS satellite signal (GPS BIIF-2). 4 peaks are also appearing on this spectrum : the strong and central one is a home-made pure carrier signal. The 3 other peaks correspond to other unknown RFI.
Figure 3.b shows processed spectra of this observation with the classic beamforming (i.e. Eq.1), the orthogonal projection beamforming (i.e. Eq. 2) and the oblique projection beamforming (i.e. Eq.3). In this comparison, the array is steering in direction of the zenith. Over the whole spectrum and for both orthogonal and oblique projectors, the RFI subspace is based on the 3 dominant singular vectors of **R**. As expected, the oblique projection beamforming recovers the best the signal reached in direction of the zenith (noise only).
It is worthwhile to note that we are applying these developments on corrupted SMOS (a space based earth observation satellite [11]) data. Illustrations will be shown at the time of the conference.

4. Miscellaneous techniques

There are other promising techniques which will be presented during the conference such as a parametric approach [12], a RFI post-correlation estimation [13] and a robust approach for giant pulse detection [14].

5. Conclusions

The effectiveness of RFI mitigation is limited by the estimation and detection accuracies of the signals involved. Different astronomical observing modes may require different interference mitigation techniques and approaches. Examples of these modes are spectral line observations, polarisation measurements, synthesis imaging, and transient research.
There are many ways to define categories for interference, such as narrow band or wide band, fixed or moving sources, categories based on statistical properties (e.g. spatial and temporal coherence) or based on modulation type, distinctions based on the amount of a-priori information of the transmitter or on differences in spatial properties or polarisation, categories based on field strength, power and temporal-spectral occupancy, and categories of overlapping signal parameter domains.
Clearly, a great diversity of approaches is possible, and in choosing an optimal approach one should consider the following:

- Depending on the interference properties, the architecture of the radio telescope and the type of observation, the same RFI mitigation technique can be useless or very efficient.
- Efficiency is generally linked with specificity. The more a priori information on the RFI can be exploited, the better the RFI mitigation algorithm will be.

In other words, it is impossible to define one single approach which will cover all current and future scenarios. The consequence is that several (as far as possible “orthogonal”) methods have to be implemented such that they can be used in conjunction. For exotic or unexpected scenarios, the radio telescope architecture should be flexible enough to allow reallocation of signal processing resources to RFI mitigation.
If we push this idea a little further, we might consider that for several frequency bands (except for example satellite and air-traffic bands) the RFI challenge in the SKA sites in Australia and South Africa will not be so great. Under this assumption, one basic or recurrent scenario could be to carefully design the analogue parts, taking RFI threats into consideration, but to limit the digital measures to “flagging". In that case, the digital signal processing resources could be fully dedicated to regular signal processing tasks most of the time and could be partially re-used (scheduled) for observations facing specific RFI issues. In particular, it would be worthwhile to continuously monitor the quality of the

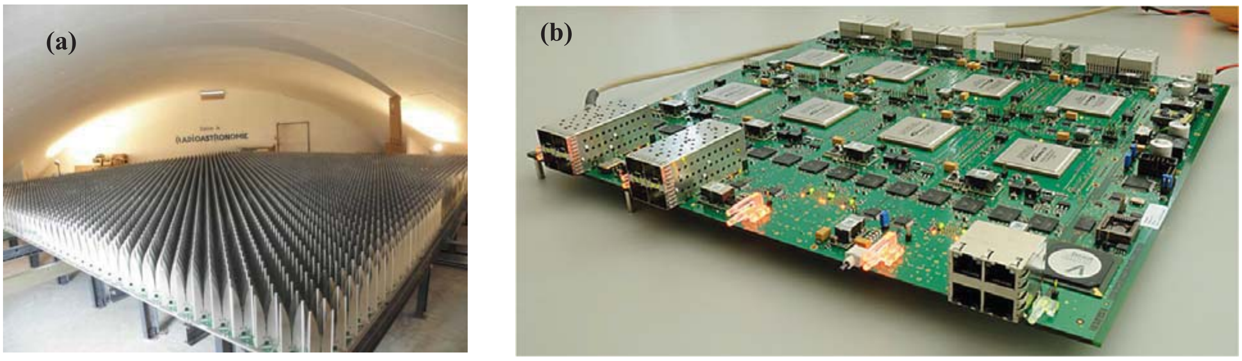

Figure 4 : **(a)** EMBRACE at Nançay **(b)** UniBoard [18] is a generic high-performance computing platform for radio astronomy, developed as a Joint Research Activity in the RadioNet FP7 Programme. The hardware comprises eight Altera Stratix IV Field Programmable Gate Arrays (FPGAs) interconnected by a high speed transceiver mesh. Each FPGA is connected to two DDR3 memory modules and three external 10Gbps. The digital signal processing capability of the board exceeds 644.10^9 complex multiply-accumulate operations per second.

data. Given the extreme sensitivity of the SKA telescope, this task has to be a byproduct of the radio telescope it-self (i.e. an auxiliary antenna will not be sensitive enough). We are currently testing this approach on the dense array prototype EMBRACE (see Figure 4.a) where several detection methods (robust power [15], cyclostationarity [15], and kurtosis [16]) are implemented at different stages along the processing line inside a specific computing platform (see figure 4.b). All RFI detections are stored along with the radio astronomical data on a database driven by a dedicated science data model (SDM) similar to the one derived in [17].

All this efforts should not be understood by other spectrum users as possible way to soften radio regulation agreements. Indeed, mitigation always includes a cost both in terms of money and often also in terms of signal integrity. In practice, RFI mitigation counter measures should be balanced in the sense that the cost of including RFI measures in the design is justified in terms of regained spectrum.

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