SPECTRAL ESTIMATION OF RADIO ASTRONOMICAL SOURCES CORRUPTED BY DIGITAL MODULATED RADIO FREQUENCY INTERFERENCES

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ABSTRACT

In radio astronomy, the radio spectrum is used to detect weak emission from celestial sources. However, more and more observations are polluted by man-made radio frequency interferences (RFI). To some extent, the final power spectral estimation can be preserved by processing the polluted channels in real time. In the case of digital modulated RFI, we propose to use their cyclostationary properties with a view to detecting/blanking or estimating/cancelling them. An example of detection/blanking on real data and a cancellation algorithm are discussed.

1. INTRODUCTION

In radio astronomy, the radio spectrum is used to detect weak emission from celestial sources. By spectral averaging, observation noise is reduced and weak sources can be detected. However, radio astronomy has to face two contradictory trends. On the one hand, the exponential expansion of telecommunications has generated a growing demand on the electromagnetic spectrum, reducing the number and the size of bandwidths available for good quality radio astronomical observations. On the other hand, radio astronomical needs in terms of sensitivity and bandwidth have also grown. As a result, radio frequency interference (RFI) mitigation has become a significant issue for current and future radio telescopes. In the short term, the objective is to preserve observation capabilities on previously observed objects. In the medium and long term, the objective is to make observations of fainter signals everywhere in the spectrum, even outside the protected radio astronomy bands.

Various methods have been experimented to eliminate RFI depending on the type of interference and the type of instruments. Time, frequency and/or spatial properties have been considered in order to find efficient mitigation techniques (see [1], [2] ,[3] ,[4] for a comprehensive survey of such methods). The present study focuses on mono dimensional signals coming from a single dish antenna. In the case of digital modulated RFI, we propose to use their cyclostationary properties with a view to detecting/blanking or estimating/cancelling them.

The first section will present the hypothesis and the properties of the different signals used in this paper. The second one will illustrate the interest of cyclostationary RFI properties in the detection scheme. The third section will discuss theoretical and pratical considerations about the use of cyclostationary RFI properties in the cancellation scheme.

2. SIGNAL MODEL

Considering a receiver connected to a single dish antenna, we model the received signal, $s(t)$ as the sum of two independent signals: an Gaussian noise, $n(t)$, and a cyclostationary RFI, $b(t)$.

$$s(t) = n(t) + b(t). \tag{1}$$

Practically, the Gaussian noise $n(t)$ includes all the signal contributions except the RFI (i.e. system noise, sky noise and the astronomical source) and it can be considered as an almost white Gaussian noise (the main part of the correlation is due to the receiver spectral shape which is ideally a perfect lowpass filter).

The RFI, $b(t)$, is a cyclostationary signal which means that its statistics are periodic [5]. In our case, we are interested in the second order moment periodicity. Indeed, most of the signals generated by telecommunication systems present such cyclostationarity due to their digital modulation. $b(t)$ is then assumed to have a periodic autocorrelation function:

$$R_b(t+T_c,\tau) = R_b(t,\tau) \tag{2}$$

where T_c is the cyclic period and $R_b(t,\tau)$ is defined by

$$R_b(t,\tau) = E\left[b(t+\tau/2).b(t-\tau/2)\right] \tag{3}$$

where $E[.]$ is the exceptation.

The next sections will propose two different cyclostationary uses for performing RFI mitigation.

3. DETECTION AND BLANKING SCHEME

Time-frequency (t-f) blanking consists in removing data blocks detected as polluted in the power t-f plane before integration in order to clean up the final power spectrum. The t-f plane is obtained in real time by a digital filter bank based on FFT or polyphase filter [6]. If possible, the t-f blocks of this plane must be adapted to the temporal and spectral RFI properties. Blanking decisions are based on a statistical contrast which has been proposed in [7]. Its principle is to compute a normalized version of the cyclic autocorrelation at time lag zero:

$$I_s^{Tc} = \left| \frac{\frac{1}{T_c}\int_{T_c} R_s(t,0)\exp(-j2\pi\frac{t}{T_c})dt}{\frac{1}{T_c}\int_{T_c} R_s(t,0)dt} \right|^2 \tag{4}$$

This method has been applied on real data acquired with the decimeter radio telescope at the Nançay Observatory (see Figure 1.a). The observed astronomical source was the mega maser IIIZw35 which is located in the band also used

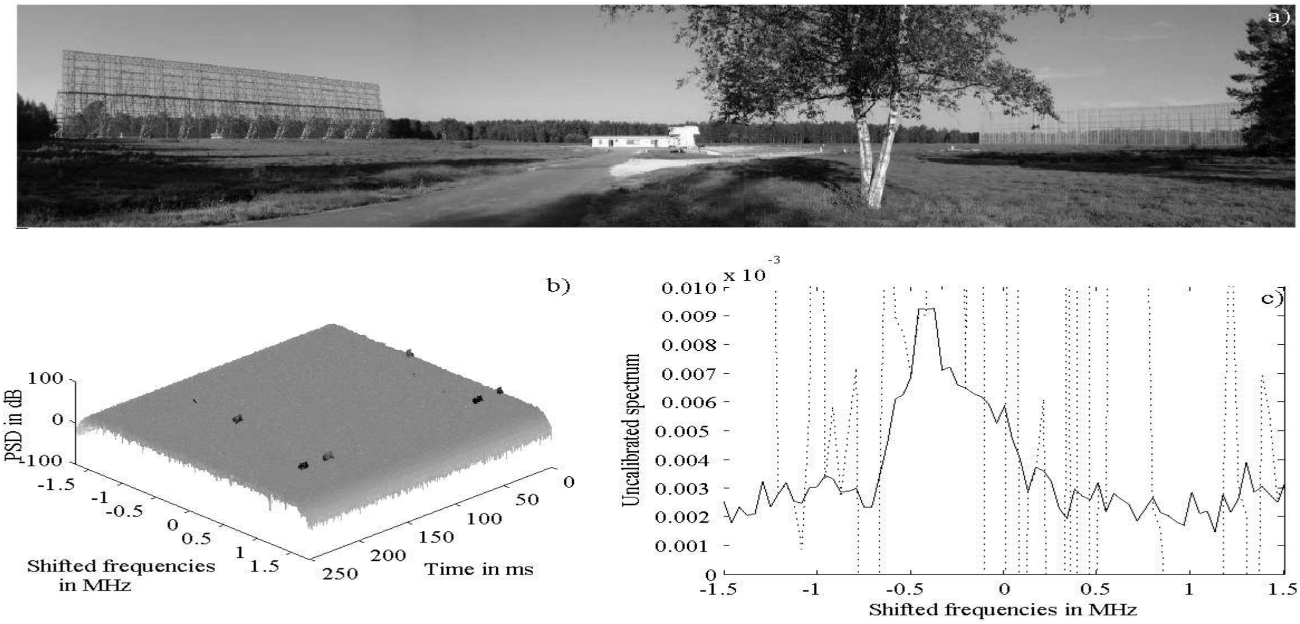

Figure 1: Detection and blanking scheme applied on the IIIZw35 observations. **(a)** The decimeter radio telescope of Nançay. **(b)** Time-frequency (t-f)representation of the observations. Some of the t-f slots used by the Iridium constellation satellites are clearly visible. IIIZw35 source is scrambled by the RFI. **(c)** Normalized averaged spectrum without (dashed line) and with (continuous line) blanking. The receiver filter shape has been subtracted.

by the constellation of Iridium telecommunication satellites. Their TDMA (Time Division Multiple Access) and FDMA (Frequency Division Multiple Access) modulations lead to RFI bursts spread in time and frequency (see Figure 1.b). Figure 1.c shows the averaged spectrum without blanking (dashed line). The 3.5 MHz bandwidth has been channelized into 84 sub-bands (41.6 kHz bandwidth which is close to Iridium channel bandwidth) through a polyphase filter bank (the prototype filter was 5376 coefficients long). Our indicator defined in Equ. 4 has been applied on each sub-channel with $Tc = 1.6666.T_s$, where T_s is the sampling period. The blanking threshold was set empirically to 0.31. The measured percentage of removed samples was 7.9% including both true and false alarm samples. Figure 1.c shows the averaged spectrum with this blanking (continuous line). The expected profile of IIIZw35 is recovered.

The detection and blanking scheme is relevant when RFI (t-f) occupancy is partial (i.e. free (t-f) slots still exist...). If not, other strategies must be developed. The next section describes a method which can process continous emitting RFIs.

4. CANCELLATION SCHEME

The proposed method is based on the analysis of the time varying autocorrelation function defined in Eq. 3. First, the stationarity of $n(t)$ and the independence between $b(t)$ and $n(t)$ yield :

$$R_s(t,\tau) = R_b(t,\tau) + R_n(\tau) \tag{5}$$

where $R_s(t,\tau)$ and $R_n(\tau)(= R_n(t,\tau))$ are defined in same way as for $b(t)$ in Eq. 3. In our radio astronomical context, a measure of $R_s(t,\tau)$ can be derived from real time radio astronomical correlators (see section 4.3). The objective is then to extract $R_n(\tau)$ from this measure. Several cases are now discussed depending on an *a priori* assumption attached to $b(t)$ (see sections 4.2 and 4.1). First, the model of our cyclostationary signal $b(t)$ needs to be specified:

$$b(t) = m(t).cos(2\pi f_0 t + \theta_0) \tag{6}$$

where $m(t) = \sum_k a_k.h(t - kT_c)$, the a_k represent the symbols of the white random digital message, $h(t)$ is the shaping pulse, f_0 is the carrier frequency and θ_0 is the carrier phase chosen between 0 and 2π. With this model, $R_m(t,\tau)$ becomes:

$$R_m(t,\tau) = \sigma_a \sum_k h(t - kT_c - \tau/2).h(t - kT_c + \tau/2) \tag{7}$$

with σ_a the variance of a. The derivation of $R_b(t,\tau)$ from Eq.6 and Eq.7 depends on the link between f_0 and T_c. Thus, if $2f_0.T_c$ is not an integer, then the carrier phase θ_0 could be seen as a random phase else θ_0 will be seen as a deterministic phase.

4.1 The case where $2f_0.T_c$ is not an integer

The classical shaping pulse of a digital modulation is rectangular, i.e.

$$\begin{aligned} h(t) = h_r(t) = &\quad 1 \quad t \in [-T_c/2, T_c/2] \\ = &\quad 0 \quad \text{otherwise} \end{aligned} \tag{8}$$

In this case, $R_b(t,\tau)$ becomes:

$$R_b(t,\tau) = \frac{\sigma_a}{2}.h_r(t - \tau/2).h_r(t + \tau/2).cos(2\pi f_0 \tau) \tag{9}$$

Figure 2 illustrates this equation. In particular, for $t = T_c/2$, we obtain:

$$\begin{aligned} R_b(T_c/2,\tau) = &\quad \tfrac{\sigma_a}{2} \text{ for } \tau = 0 \\ = &\quad 0 \text{ otherwise} \end{aligned} \tag{10}$$

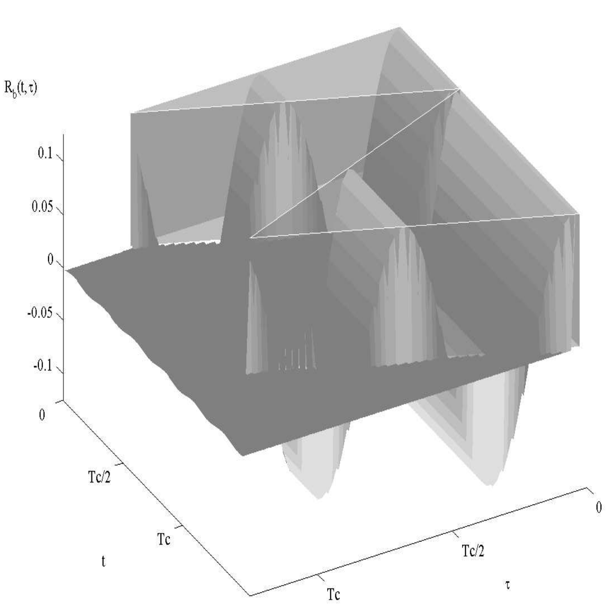

Figure 2: The time varying autocorrelation, $R_b(t,\tau)$, of a binary phase shift keying modulation. T_c is the rectangular pulse width. The carrier frequency, f_0, is equal to $1/33.f_s$, with f_s the sampling frequency.

Consequently, by observing $R_s(t,\tau)$ at $t = T_c/2$, an estimation of $R_n(\tau)$ can be obtained through $R_s(T_c/2,\tau)$:

$$R_s(T_c/2,\tau) = \frac{\sigma_a}{2}.\delta(\tau) + R_n(\tau) \tag{11}$$

Given that the constant $\frac{\sigma_a}{2}$ has just an offset effect on the spectrum, it can be easily removed by an off-line normalization processing. All this discussion can be extended to any pulse shaping as long as its impulse response, $h(t)$, is shorter than Tc. If this hypothesis is not valid (other pulse shaping (see figure 3.a) or strong effect of the channel propagation path), the method can still be used to reduce the RFI impact on the spectral profile by looking the slice t where the influence of $R_b(t,\tau)$ is minimized. For example:

$$R_n(\tau) \approx R_s\left(\arg_{t\in[0,T_c]}\left(\min\int R_s^2(t,\tau)d\tau\right),\tau\right) \tag{12}$$

The interest of the method is that even when the RFI is continuously present over the astronomical source, a spectral estimation is still possible, especially when the shaping pulse length is close to T_c. Besides, the hardware modification on the correlator is simple (see section 4.3).The drawback is that only $\frac{1}{T_c}$th of the observation time is used.

4.2 The case where $2f_0.T_c$ is an integer

In this section, we will discuss the case where the carrier frequency has a cyclic period compatible with T_c. Then, the following relation must be verified:

$$2f_0.T_c = k \text{ with } k \in N \tag{13}$$

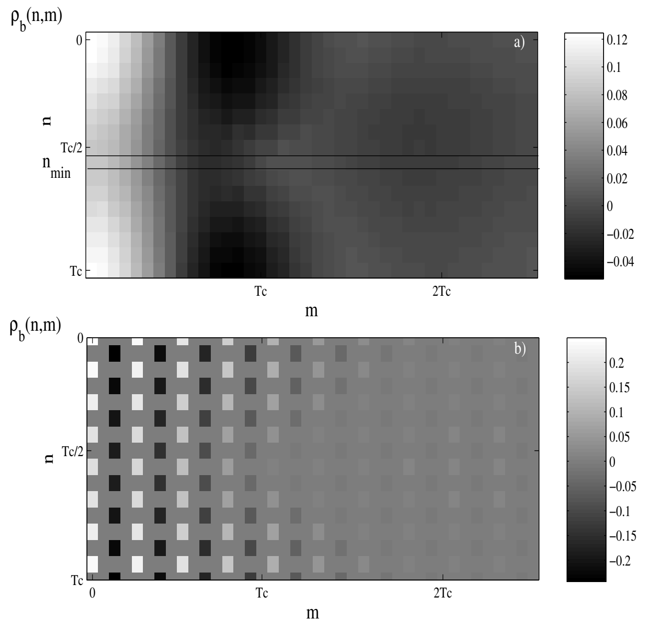

Figure 3: The estimated time varying autocorrelation, $\rho_b(n,m)$ (see Eq. 18 for the definition, n and m are similar to t and τ). The RFI is a binary phase shift keying modulation with $T_c = 16.T_s$, The shaping pulse is a 193 coefficient raised cosinus filter with roll-off factor equal to 0.5. **(a)** The case where $2f_0.T_c$ is not an integer ($f_0 = 1/30.f_s$ and $\theta_0 = 0$ rad). The black box represents the autocorrelation estimation obtained when the RFI impact is minimal.**(b)** The case where $2f_0.T_c$ is an integer ($f_0 = 0.25.fs$ and $\theta_0 = 0$ rad). The slots where the RFI is cancelled are clearly visible.

In this case, $R_b(t,\tau)$ becomes:

$$R_b(t,\tau) = \frac{R_m(t,\tau)}{2}\underbrace{[cos(4\pi f_0 t + 2\theta_0) + cos(2\pi f_0\tau)]}_{g(t,\tau)} \tag{14}$$

For specific values of f_0 and θ_0, $g(t,\tau)$ can be partially cancelled. In particular, with $f_0 = 0.25.f_s$, where f_s is the sampling frequency, and $\theta_0 = 0$ $[\pi/2]$, $3/4$ of the $g(t,\tau)$ plane can be cancelled (see figure 3.b). The integration with t of the slots where $R_b(t,\tau)$ is cancelled provides a perfectly clean estimation of $R_n(t,\tau)$. This method has two additional advantages compared to the other case. First, there is no condition on the shaping pulse for a perfect cancellation. Secondly, only half of the observation is lost. The drawback is that the correlator configuration has to be driven by the RFI specifications.

4.3 Application to radio astronomy

The theoretical expression defined by Eq. 3 can be estimated by synchronized averaging [5], that is:

$$R_b(t,\tau) \approx \hat{R}_b(t,\tau) = \frac{1}{2N+1}\sum_{n=-N}^{N} b(t+nT_c+\frac{\tau}{2}).b(t+nT_c-\frac{\tau}{2}) \tag{15}$$

The same estimation can be applied to compute $\hat{R}_s(t,\tau)$ and $\hat{R}_n(t,\tau)$. When N increases, these estimated values tend towards the theoretical ones.

In radio astronomy, correlators compute the following expression:

$$\rho_s(m) = \frac{1}{2N+1} \sum_{n=0}^{2N} s(n).s(n-m) \tag{16}$$

With a slight hardware modification, namely the addition of T_c-long circular buffers in the accumulators, the correlators can compute the synchronized averaging autocorrelation, $\rho_s(n,m)$:

$$\rho_s(n,m) = \frac{T_c}{2N+1} \sum_{k=0}^{2N/T_c} s(n+kT_c).s(n+kT_c-m) \tag{17}$$

Besides, the correspondence between (t,τ) and (n,m) can be easily derived:

$$\rho_s(n,m) = \hat{R}_s((n+m/2) \bmod T_c, m) \quad \text{with } n \in [0, T_c] \tag{18}$$

where mod is the modulus operator.

Due to the RFI synchronization requirement, the second cancellation scheme involves more modifications of the correlator processing line. Thus, the RFI must be centered at $f = 0.25.f_s$ and the carrier phase must be a multiple of $\pi/2$. In practice, this constraint can be obtained through a phase lock loop controled by, for example, a nulling criterion on $\rho_s(n,m)$.

Figure 4 shows simulations on this cancellation algorithm. The simulated RFI is a Glonass spread spectrum emission (see [1] for details on this satellite constellation). The modulation can be seen as a BPSK modulation with $T_c = 8.Ts$. A raised cosinus shaping pulse (193 coefficients and roll-off equal to 0.5) has been added to show the robustness of the method to any filtering. The astronomical source is a band-limited Gaussian noise emitting in the same frequency band as the RFI. The spectrum measured without blanking is shown in Figure 4.a. Assuming that the synchronization with f_0 and θ_0 has been done, Figure 4.b shows the result after cancellation. The RFI has been completely removed. The sensitivity of the method will depend only on the precision of synchronization in f_0 and θ_0.

5. CONCLUSION

In this paper, we have proposed different uses of cyclostationarity for processing polluted radio astronomical data. First, a cyclostationary detector has been tested on a real cosmic source. This method can blank polluted slots of the time-frequency plane and it is well adapted for more or less sporadic RFI emission. For continuous emitting RFI, a cyclostationary cancellation scheme has been proposed. By a precise synchronized averaging of the autocorrelation function, an autocorelation nulling is performed. This method is very efficient and only half of the data are lost. Practical implementations must now be designed to perform real time tests on these different methods.

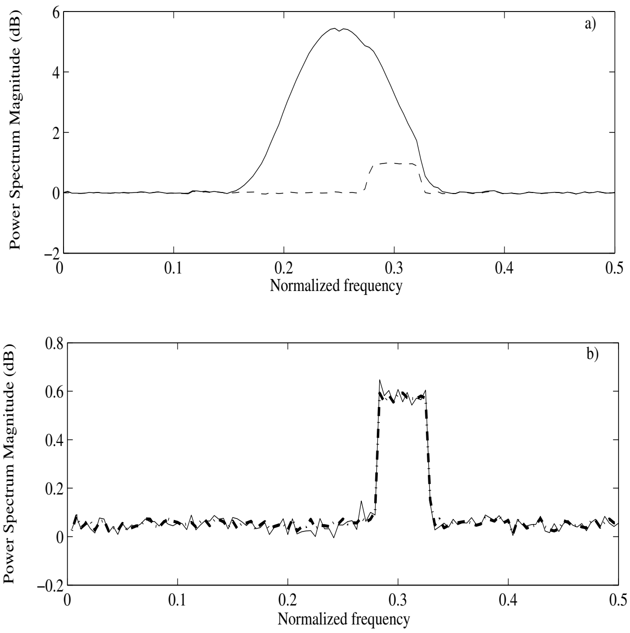

Figure 4: Simulation of cancellation with a simulated spread spectrum Glonass emission. **(a)** Spectrum estimated without cancellation. The position of the simulated cosmic source is drawn in dashed line. It cannot be detected with a classical spectral analysis. **(b)** Spectrum estimated with cancellation. The synchronized autocorrelation estimation proposed in this paper cancelled perfectly the RFI impact on the autocorrelation estimation. Thus, a clean spectral profile of the simulated source can be estimated. The dashed profile is the expected one.

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