DETECTION AND BLANKING OF GSM INTERFERENCE IN RADIO-ASTRONOMICAL OBSERVATIONS

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Radio-astronomical observations are increasingly disturbed by man-made communication signals, satellite and broadcast services. In particular, the GSM band is a highly saturated domain, full with interferers which are much stronger than radio astronomical signals. In this paper we propose a strategy to reduce this interference using its non-stationary nature. We describe a multichannel interference detector which enables us to reduce the interference by rejecting corrupted time-frequency slots. The use of multichannel detection greatly improves performance over previously suggested single channel detectors. This paper is the first to propose the implementation of advanced array signal processing methods for interference detection in radio astronomical observations.

1. INTRODUCTION

The fast growth of the wireless communication industry poses severe limitations to radio astronomical observations. Two examples of sources of significant interference are the Iridium system which will probably even cause problems within bands reserved to radio astronomy, and the GSM system which became ubiquitous and thus prevents observation in its band. These developments cause an increasing interest in suppression and rejection of man-made signals in radio astronomy. Most previous work has been limited to single dish radio telescopes and typically considers power detectors that inhibit the integration of the astronomical signal while interference is present. Examples are Fridman's detection of change in the mean power [1], implemented in the RATAN600, and Weber's detector implemented at Nançay [2]. The main drawback of these detectors is that they are single channel and thus do not exploit spatial properties of the interference. In synthesis radio telescopes the desired signal as well as the interference are received by larger telescope arrays comprising of 10–30 dishes. Hence we can perform both spectral and spatial processing to remove only narrow-band slices, for periods in which the interference is present. This type of solution is very well suited to support radio astronomical observations in the presence of TDMA communication systems such as GSM.

This paper is the first to propose the implementation of more advanced array signal processing methods to interference detection in radio astronomical observations. After introducing a simplified mathematical model of the problem, we analyze the relevance of the widely used instantaneous linear model to our problem. We conclude that in order to apply narrow-band processing we have to work with sub-bands narrower than the GSM bandwidth. In section 4 we propose a number of detectors, and in section 5 we demonstrate their performance in simulations.

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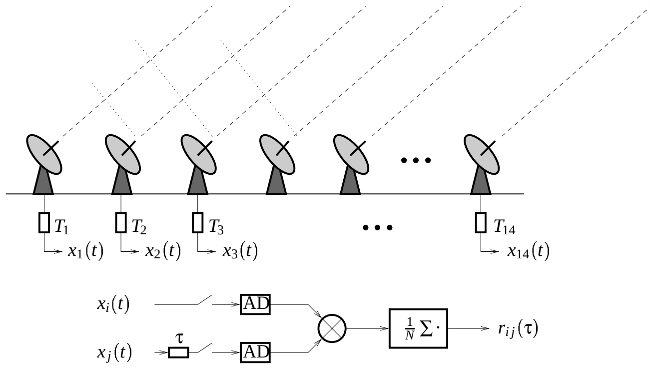

Figure 1: Schematic of the Westerbork radio telescope

2. RECEIVED SIGNAL MODEL

The Westerbork Synthesis Radio Telescope (WSRT), located in the north of The Netherlands, is a linear array consisting of 14 non-uniformly spaced parabolic dishes, each with a diameter of 23 m. The overall aperture is 3 km. A particular band of interest centers around the neutral hydrogen line and redshifts of it, say 200 MHz–2 GHz. Further details about the array geometry and receivers can be found in [3].

A simplified model of the received signal in complex envelope form is

$$x_k(t) = a_k(\theta,\varphi)s(t) + \sum_{l=1}^{q} a_{kl}s_l(t-\tau_{kl}) + n_k(t) \qquad (1)$$

where

- $x_k(t)$ is the received signal at the k-th antenna,
- $a_k(\theta,\varphi)$ is the array response toward the astronomical source at the k-th antenna in a certain look direction (θ,φ),
- $s(t)$ is the astronomical signal of interest (in fact there will be several),
- q is the number of interferers,
- $s_l(t)$ is the l'th interferer at time t,

- τ_{kl} is the relative delay of the l-th interferer at the k-th antenna.
- a_{kl} is the attenuation and phase shift of the l-th interferer in its path to the k-th antenna and at the antenna.
- $n_k(t)$ is the system noise at the k-th receiver. We assume that the system noise is temporally and spatially white Gaussian noise with covariance matrix $\sigma^2\mathbf{I}$. Typical SNR at WSRT is -70 dB with respect to the astronomical signal.

The model in (1) incorporates the fact that the received channels are delayed so as to maintain a constant look direction of the main beam. These delayed signals are processed by the correlator subsystem, which computes a set of spatial correlation matrices $\mathbf{R}(\tau)$ of dimension 14×14, for a set of 512 lags τ. In WSRT $\mathbf{R}(\tau)$ is estimated every 10 ms. The correlation can be described mathematically as

$$\mathbf{x}(t) = [x_1(t), \ldots, x_{14}(t)]^T$$

$$\mathbf{R}(\tau) \;=\; \frac{1}{N}\sum_{k=1}^{N} \mathbf{x}(kT_s)\mathbf{x}(kT_s - \tau)^H \tag{2}$$

where $T_s = \frac{1}{f_s}$ is the sampling time. Note that using the stationarity of the astronomical source this gives an estimate of $\mathrm{E}\{\mathbf{x}(t)\mathbf{x}(t-\tau)^H\}$. A typical processing bandwidth is 10 MHz, so the sampling rate is 20 MHz. In the current hardware at WSRT these 10 ms correlations are Fourier transformed to provide estimates of the spectrum at each pair of antennas. These spectra are averaged further for 10 or 60 s to provide the system noise reduction crucial for obtaining the astronomical signal, and the results are stored on tape for off-line processing and imaging.

In the presence of temporal and/or spatially non-white interference, the correlation matrices will be corrupted. The detection of such interference is currently done by a simple change-detection of the received power at each entry of $\mathbf{R}(\tau)$ individually, and by off-line inspection. Our objective is to provide a better estimate of the spatial correlation matrices by implementing an on-line multichannel interference detector, and exclude those time-frequency slices in which the interference is dominant. This will work well if the interference is concentrated in frequency and time, as e.g., in the GSM system. GSM is a TDMA system with 8 time slots (users) of 0.577 ms per frame and a bandwidth of 270 kHz [4]. An additional (optional) feature is that users are frequency hopping between frames. Thus, users are concentrated in time-frequency and space, offering good possibilities for on-line detection and excision. In this paper, we consider only simple time-frequency excision, i.e., inhibiting the integration of $\mathbf{R}$ in (2) for bands and time windows in which interference is detected. A natural processing window is either a single GSM slot in which each band contains a single dominant interferer or a GSM frame which contains 8 dominant interferers.

We note that the problem is similar to narrow-band interference excision in DS-CDMA systems [5] which is an active research topic in communication theory.

3. VALIDITY OF THE NARROWBAND MODEL

Array signal processing is significantly simplified if a narrowband assumption holds, so that the delays $\tau_{k,l}$ in (1) can be represented by phase shifts. The usual argument is as follows. Let $s(t)$ be a baseband (analytic) signal with bandwidth B, and let $s(t)e^{j\omega_c t}$ be the corresponding modulated signal with carrier frequency ω_c, as received by a reference sensor. The modulated signal received at a second sensor, delayed by τ with respect to the reference, is equal to $s(t-\tau)e^{-j\omega_c(t-\tau)}$, and in baseband this is $s(t-\tau)e^{-j\omega_c\tau}$. If $B\tau \ll 1$, then $s(t) \approx s(t-\tau)$, and we can translate the delay into a complex phase shift $e^{-j\omega_c\tau}$.

In WSRT, the largest baseline is 3000 m, and $c = 3\cdot 10^8 \frac{m}{s}$. Thus the longest delay is 10 μs. This means that signals with a bandwidth (much) less than 100 kHz can be considered narrowband.

Under the narrow-band assumption, the received signal is described by (omitting the astronomical signal for the moment since it is very weak)

$$\mathbf{x}(t) = \sum_{l=1}^{q} \mathbf{a}_l s_l(t) \;+\; \mathbf{n}(t) \tag{3}$$

where $\mathbf{a}_l$ is a complex vector containing the relative attenuation and phase shifts of the l-th interferer at each sensor, and $\mathbf{n}(t)$ is the system noise. Thus, the rank of a data matrix $\mathbf{X}$ consisting of a block of samples of $\mathbf{x}(t)$ will be equal to q, the number of interferers, assuming $q < p$, the number of sensors. This allows interference detection via rank detection, and is discussed in section 4.

In order to test the applicability of this narrowband (low-rank) model to the situation at WSRT we have done some simulations. Note that equation (3) is valid if it is valid for each of the interferers, and that the noise does not affect it. The relative power of the signal received at the different antennas might affect the validity of the model only through emphasis of some time delays compared to others. Therefore we have simulated a single signal received by the array, with unit gain at all antennas, and varied the emitter location (and hence the time delays).

Let $s(t)$ be the signal transmitted from a location (x,y,z) with respect to the radio-telescope, and

$$\mathbf{x}(t) = [s(t-\tau_1), \ldots, s(t-\tau_p)]^T \tag{4}$$

be the received signal at time t, where $p = 14$, $\tau_i = \frac{1}{c}\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}$ is the propagation delay between the source location and the i-th sensor and (x_i, y_i, z_i) are the coordinates of the i-th sensor. Suppose we collect N samples, and let $\mathbf{X}$ be the observation matrix

$$\mathbf{X} = [\mathbf{x}(1), \ldots, \mathbf{x}(N)] \tag{5}$$

and

$$\mathbf{s} = [s(1), \ldots, s(N)] \tag{6}$$

If the linear model is valid we would expect that $\mathbf{X} = \mathbf{a}\mathbf{s}$ holds, i.e., $\mathbf{X}$ is a rank-1 matrix. For known $\mathbf{s}$, the quality Q_{LS}

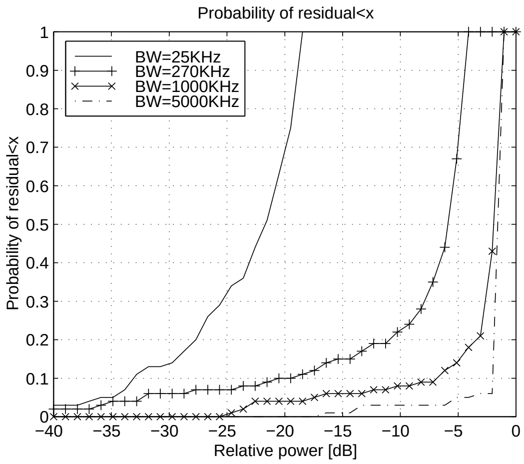

Figure 2: Probability distribution of relative residual power. $BW = 25$ kHz, 270 kHz, 1 MHz, 5 MHz. FM chirp.

of a rank-1 fit to $\mathbf{X}$ can be defined as the power of the residual signal relative to the received signal power,

$$Q_{LS} = \frac{\|\mathbf{X} - \hat{\mathbf{a}}\mathbf{s}\|_F^2}{\|\mathbf{X}\|_F^2} \qquad (7)$$

where $\hat{\mathbf{a}} = \mathbf{X}\mathbf{s}^H(\mathbf{s}\mathbf{s}^H)^{-1}$ is the LS estimate of $\mathbf{a}$.

Alternatively, for unknown $\mathbf{s}$, let $\mathbf{R} = \frac{1}{N}\sum_{k=1}^{N}\mathbf{x}(k)\mathbf{x}(k)^H$ be the sample covariance matrix with lag 0, and let $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_p$ be its eigenvalues in decreasing order. In this case, $\hat{\mathbf{a}}$ is proportional to the eigenvector corresponding to λ_1. The squared norm of the residual in this case is just the sum of all the smaller eigenvalues of the sample covariance matrix, leading to

$$Q_{LS} = \frac{\sum_{i=2}^{p}|\lambda_i|}{\sum_{i=1}^{p}|\lambda_i|} \qquad (8)$$

To check the validity of the rank-1 approximation as a function of the received signal bandwidth we have used FM chirps with bandwidth 25 kHz, 270 kHz, 1 MHz and 5 MHz. Figure 2 presents the distribution of the quality parameter Q_{LS} for a random interferer uniformly located around the WSRT ($N = 500$, 100 Monte-Carlo experiments). We can clearly see that the 25 kHz signal is almost exclusively contained in a 1-D space. This is not true for the wider signals. Hence we conclude that in order to use narrow-band signal processing techniques it is necessary to work in relatively narrow sub-bands, even narrower than the GSM signal bandwidth (270 kHz).

4. SUB-BAND MULTICHANNEL DETECTION

If the narrowband assumption holds for all interferers, then we can utilize standard rank detection algorithms to test for the presence of interference. Two such algorithms are discussed below. When wide-band interfering signals are present, the received signal in the noiseless case is no longer confined to a lower dimensional subspace, as was shown in the previous section. However, by splitting the frequency band into sufficiently narrow sub-bands we can restore the rank property of the signal subspace and use narrow-band rank detection algorithms. Sub-band processing has two other advantages:

1) Using sub-band detectors we can excise only some frequency bands rather than the complete data set at all frequencies.

2) The existing correlator structure at WSRT already provides us with a coarsely quantized version of the covariance matrix in subbands of at most 40 kHz and integrated over 10 ms. These time-frequency bins might be utilized as natural intervals for detection.

Processing separate bands is reasonable if the interference bandwidth is more narrow than the sampling bandwidth since this results in an improved signal to noise ratio at the detector input, and thus improved probability of detection. However for wide-band interferers this might cause degradation of detection probability since the correlation between various frequencies is lost.

To formulate this sub-band processing mathematically, assume that the signal received at the k-th antenna is given by

$$x_k(t) = \sum_{i=1}^{q} a_{k,i}s_i(t - \tau_{k,i}) + n_k(t) \qquad (9)$$

By dividing the N data vectors into M nonoverlapping blocks of length L and performing FFT on the blocks we obtain for $m = 1, \ldots, M$, $k = 1, \ldots, p$ and $l = 1, \ldots, L$

$$\tilde{x}_{k,m}(\omega_l) = \sum_{i=1}^{q} a_{k,i}\tilde{s}_i(\omega_l)e^{-j\omega_l\tau_{k,i}} + \tilde{n}_{k,m}(\omega_l) \qquad (10)$$

where ~ denotes Fourier transform.[1] We can now compute the covariance matrices $\mathbf{R}(\omega_l)$ for each frequency by

$$\mathbf{R}(\omega_l) = \frac{1}{M}\sum_{m=1}^{M}\tilde{\mathbf{x}}_m(\omega_l)\tilde{\mathbf{x}}_m(\omega_l)^H \qquad (11)$$

where $\tilde{\mathbf{x}}_m(\omega_l) = [\tilde{x}_{1,m}(\omega_l), \ldots, \tilde{x}_{p,m}(\omega_l)]$. At this point, narrow-band methods are applicable for each of these matrices separately.

We describe two detection algorithms to test the hypothesis that there is an interferer in the frequency band ω_l.

If the noise power σ^2 is known, we can apply the likelihood ratio test (LRT), which leads to a method due to Box [6] for testing the null hypothesis that $\sigma^{-2p}\mathbf{R}(\omega_l) = \mathbf{I}$ (no interference). The test statistic is given by

$$-Mp\log\left(\sigma^{-2p}|\mathbf{R}(\omega_l)|\right) \sim \chi^2_{\frac{(p+1)(p-2)}{2}}. \qquad (12)$$

Thus, for a given False Alarm rate, we can find a threshold t on the test statistic to reject the null hypothesis and detect an interferer. Box suggested that a better approximation is given by $-M'p\log\left(\sigma^{-2p}|\mathbf{R}(\omega_l)|\right) \sim \chi^2_{\frac{p(p-1)}{2}}$ where $M' = M - \frac{2p+11}{6}$.

[1] Windowing and use of overlapping blocks can of course improve the quality of the spectral estimates, but we shall not go into details.

Alternatively we can use the Minimum Description Length (MDL) detector [7]. In this case, the noise power and a threshold is not needed, as the test tries to find the correct model order which minimizes the description length of the data. The estimator is given by

$$\hat{k}(\omega_l) = \arg\min_k MDL(k, \omega_l) \qquad (13)$$

where

$$MDL(k,\omega_l) = (p-k)M \log \frac{\frac{1}{p-k}\sum_{i=k+1}^{p}\hat{\lambda}_i(\omega_l)}{\left(\prod_{i=k+1}^{p}\hat{\lambda}_i(\omega_l)\right)^{\frac{1}{p-k}}} + \frac{1}{2}k(2p-k+1)\log M$$

and an interference is detected if $\hat{k} \neq 0$.

5. SIMULATIONS

To assess the performance of the proposed algorithms, we describe here a preliminary experiment based on simulated data. The scenario uses the Westerbork array with standard configuration and a sampling rate of 20 MHz (the widest channel available at WSRT). We have picked 5 interfering GSM-modulated signals with baseband center frequencies $[1,3,5,7,9]$ MHz and signals powers $-[18,21,24,27,30]$ dB below the total noise power in the band (0–10 MHz). In contrast to real GSM, each interferer was on all the time.

Figure 3(a) shows the spectrum of the GSM signals, and figure 3(b) the magnitude of the Fourier transform of the output of a single antenna, after noise was added. As can be seen, a power detector (currently implemented in WSRT) will not be able to detect these interfering signals which are much below the system noise, yet detrimental after sufficient integration.

The duration of a single observation window was chosen as 1.6 ms, which corresponds to $N = 2^{16}$ samples. Each window was partitioned into $M = 64$ blocks of $L = 512$ consecutive samples, with no overlap, each block was Fourier transformed and 512 correlation matrices have been computed as in (11). Subsequently, the detectors of equations (12)-(13) have been applied. The experiment was repeated 100 times.

Figures 3(c) and 3(d) present the probability of positive decision made by the detectors at each frequency. At frequencies where there was no interference it resembles the false alarm probability, while at frequencies where the interference was present it resembles the detection probability. For the LRT, the false-alarm threshold was set arbitrarily at 10%. From the figures, LRT seems more useful than MDL, since a high detection probability is more important than a low false alarm rate in this application.

6. CONCLUSION

We have shown the great potential of excision of intermittent interference in radio astronomical observations. We have proposed two multichannel detection methods, and verified them by simulation. The performance is greatly improved compared to existing single channel total power detectors. Further results are reported in [8]; a system for testing the ideas described in this paper is currently being implemented in cooperation with NFRA/ASTRON.

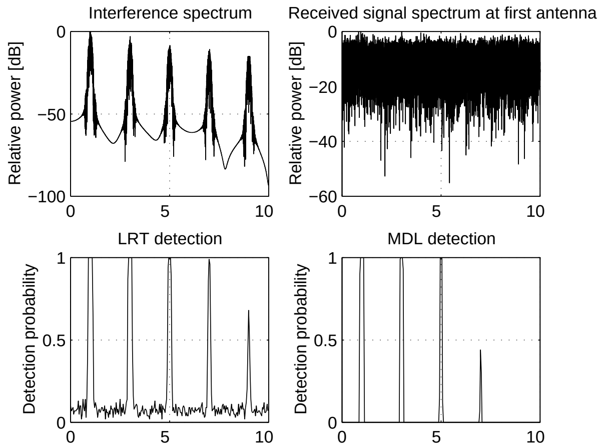

Figure 3: (a) Interference spectrum. (b) Noisy signal spectrum. (c) Detection probability vs. frequency for LRT, and (d) for MDL.

7. ACKNOWLEDGEMENT

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8. REFERENCES

[1] P. Fridman, “A change point detection method for elimination of industrial interference in radio astronomy receivers,” in *Proc. 8th IEEE Signal Proc. Workshop on Stat. Signal Array Proc.*, (Corfu), pp. 264–266, 1996.

[2] R. Weber, C. Faye, F. Biraud, and J. Dansou, “Spectral detector for interference time blanking using quantized correlator,” *Astronomy and Astrophysics Supplement Series*, vol. 126, pp. 161–167, Nov. 1997.

[3] “WSRT user documentation,” tech. rep., NFRA/ASTRON, July 1993.

[4] T.S. Rappaport, *Wireless Communications: Principles and Practice*. Upper Saddle River, NJ: Prentice Hall, 1996.

[5] M.Lops, G. Ricci, and A.M. Tulino, “Narrow-band interference suppression in multiuser CDMA systems,” *IEEE Trans. on Communications*, September 1998.

[6] G.E.P. Box, “A general distribution theory for a class of likelihood criteria,” *Biometrika*, vol. 36, pp. 317–346, 1949.

[7] M. Wax and T. Kailath, “Detection of signals by information theoretic criteria,” *IEEE Trans. Acoust., Speech, Signal Proc.*, vol. 33, pp. 387–392, Apr. 1985.

[8] A. Leshem and A.J. van der Veen, “The effect of blanking of GSM signals on radio-astronomical correlation measurements,” in *Proc. IEEE Workshop on Higher Order Statistics*, (Ceasarea), June 1999.