DIGITAL IMPLEMENTATION OF A ROBUST RADIO ASTRONOMICAL SPECTRAL ANALYSER : TOWARDS IIIZW35 RECONQUEST

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ABSTRACT

In radio astronomy, the radio spectrum is used to detect weak emission from celestial sources. By spectral averaging, noise estimation is reduced and weak sources can be detected. However, more and more observations are polluted by man-made radio frequency interferences (RFI). The impact of these RFI on spectral measurement ranges from total saturation to tiny distortions of the data. To some extent, the final spectral estimation can be preserved by blanking infected channels in real time. With this aim in view, a complete real time processing line has been implemented on a set of FPGA and DSP. The current functionalities of the system are high dynamic range (at least 70 dB), band selection facilities (from 875 kHz to 14 MHz), high spectral resolution through polyphase filter bank (up to 8192 channels with 49152 coefficients) and real time time-frequency blanking with a robust threshold detector.

1. INTRODUCTION

Radio astronomy, in common with many other users of the radio spectrum, has the advantage of a few protected frequency bands. However, most scientific questions find their answers in unprotected bands where radio astronomy is not a primary user. Moreover, even in the protected bands, out-of-band emission regulations are not always sufficient to prevent the pollution of astronomical primary bands. As a result, an increasing number of observations become unusable.

In practice, the energy flux received from astronomical objects is very weak, typically less than a few Jansky (1 Jansky is 10^{-26} watt per square meter per hertz). Thus, depending on the radio telescope sensitivity, the signal-of-interest (SOI) to noise ratio is generally around -50 dB. However, source detection can still be done by estimating the spectral information over an averaging time τ with a spectral resolution B. For instrumental considerations, the averaging time τ is chosen between a few seconds to a few minutes. If any RFI emission occurs during this averaging time, the whole spectral estimation is infected (see Fig. 1.a, Fig 1.b and Fig. 4.a), unless a fine blanking of the data can be applied (see Fig. 1.a, 1.c and 1.d).

Unfortunately, classical radio telescope spectral receivers are not designed to operate in such hostile conditions. First, their poor dynamic range induces non-linearity, which

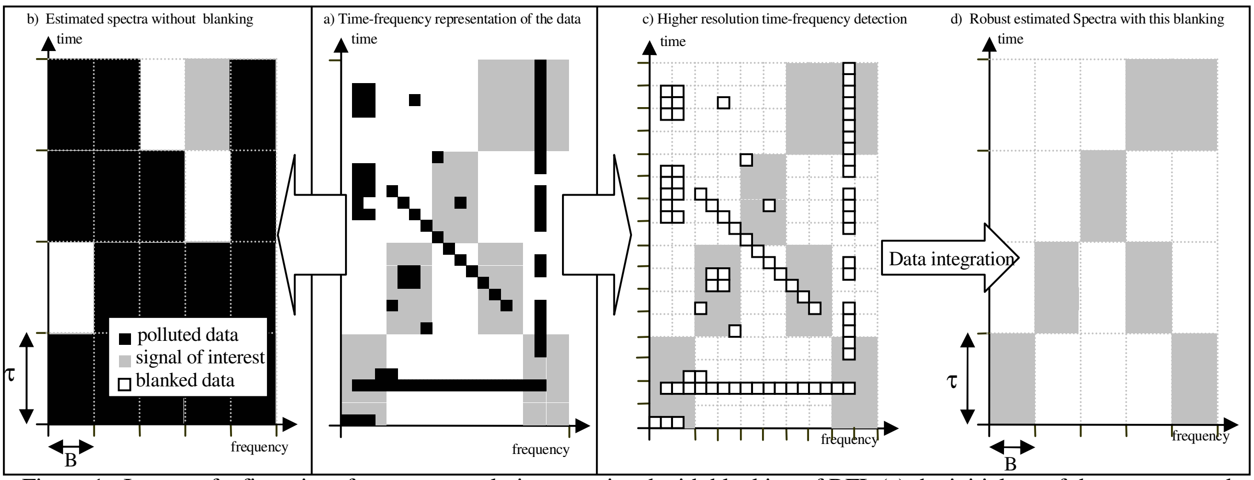

Figure 1 : Impact of a finer time-frequency resolution associated with blanking of RFI. (a) the initial set of data represented in the time-frequency plane. (b) Estimated spectra obtained with classical receiver. (c) RFI detection and blanking with finer time-frequency resolution. (d) Estimated spectra after blanking. The SOI can be recovered which was not the case in (a).

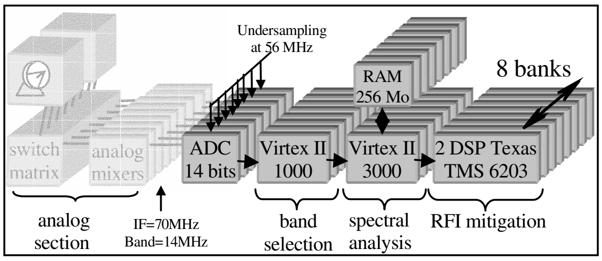

Figure 2 : Overview of the robust receiver. The flow can be reconfigured to share the calculation power between all the banks.

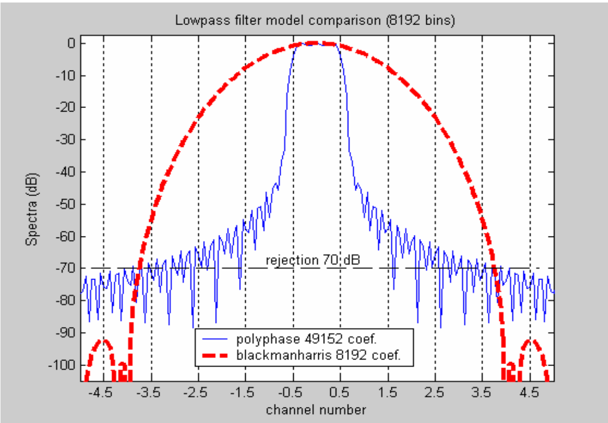

Figure 3 : Comparison of the spectral resolution and channel rejection between a Blackmanharris windowing and a polyphase filter bank with 49152 coefficients.

spreads the RFI over the whole spectrum. This problem cannot be overcome by an automatic gain control because of its negative impact on the receiver sensitivity. Secondly, the analogue filters used in such systems do not provide enough frequency rejection. Thirdly, their spectral resolution and channel rejection are often too limited to extract the free channels from the corrupted ones. Finally, their hardware architecture is too specific to allow additional functions, such as RFI detection, to be implemented.
In this paper, the design of a robust radio astronomy receiver is presented. It has been specifically designed for the single dish telescopes of the Nançay observatory (France). First, the overall architecture is given. Then, the band selection implementation is detailed. Afterwards, the high resolution polyphase filter bank is described. Finally, recent results of a real time RFI detection algorithm implemented in the receiver and applied on actual observations are shown.

2. ROBUST RECEIVER ARCHITECTURE

Figure 2 describes the global architecture of the robust receiver (RR). It can be seen as eight parallel receiver lines. An analog section shift the signals from the antennas'input frequencies to an intermediate frequency (IF) of 70 MHz, providing a final useful bandwidth of 14 MHz. Depending on a switch matrix configuration, each of the 8 inputs can be connected to one or more receiver lines. The digital section corresponds to a succession of digital modules plugged on PCI boards (HEPC9 and HERON modules from Hunt Engineering). Each of the 8 digital processing banks includes a 14 bit ADC, 1 FPGA VIRTEX II 1000, 1 FPGA VIRTEX II 3000 with 256 Mo external RAM and 2 DSP TMS 6203. A powerful industrial PC is used to drive 2 digital processing banks. The four necessary PCs are connected via a fast Ethernet link to a central computer for further data analysis, compression and storage. The primary function of the RR is to perform high resolution spectral analysis. This functionality has been implemented in the two FPGAs (see next sections), leaving the DSPs still available for post detection RFI mitigation techniques. Besides, all digital processing lines can be reconfigured and merged together to perform any other digital processing, such as specific radio astronomical observations or complex RFI mitigation techniques.

3. BAND SELECTION IMPLEMENTATION

From IF 14 MHz bandwidth, a frequency band (between 14 MHz to 875 kHz) is first digitally down converted to base band. The down conversion is digitally achieved in two steps. First, an undersampling is applied with a 56 MHz sampling frequency. Then, a direct digital synthesizer (DDS) followed by successive decimation filters selects the band of interest.
The decimation filters have been optimized both to minimize the hardware and to maximize the frequency selectivity. Thus, five half-band filters have been implemented to process the first decimation steps. A final selective FIR filter with 83 coefficients (17 bits) completes the processing. The final dynamic of this set of filters is 75 dB.
In terms of hardware implementation, with a good use of half-band properties, polyphase structures and resource sharing, a reduction of the hardware resources required is possible. Thus, only 38 multipliers are used for the whole implementation of the DDC. This design has been fitted in a VIRTEX II 1000. The input flow is 56 MHz with 14 bits real data, and the maximum output flow is 14 MHz with 16 bits complex data. The next step is the spectral analysis.

4. SPECTRAL ANALYSIS IMPLEMENTATION

The spectral analysis has two functions. The first one is to provide spectral information on the SOI to radio astronomers. The second one is to make an *ad hoc* segmentation of the time frequency plane with a view to performing the best RFI blanking.
In practice, given the large flow of data to be processed, classical radio telescope receivers use coarsely quantized correlators to perform this spectral analysis [1]. In our RFI context, this method is not well suited and Fourier Transform has been preferred. Depending on the RFI properties (see next section), the time-frequency resolution must be reconfigured. Thus, two methods have been designed for the FPGA VIRTEX II 3000. In both cases, the output is the set of channel square modulus coded with either 32 bits or 48 bits.
For a better time resolution, a weighted 2048 bin FFT with 50% overlap can be downloaded in the FPGA. The maxi-

mum time resolution is then 73.14 µs for 14 MHz bandwidth.
For better spectral resolution, an 8192 bin polyphase filter bank [2] with 50% overlap can be used. The low-pass filter model needs 49152 coefficients which are stored in the 16 bits external RAM in Q15 format. In figure 3, the performances in terms of channel rejection and spectral resolution are shown. With the polyphase filter bank, the maximum frequency resolution is 107 Hz for an 875 kHz bandwidth. The implementation is in progress and final results will be presented at the time of the conference.
A pre-integration of the spectra can be done inside the FPGA. Without pre-integration, the output flow is twice the input flow in the 32 bits mode (due to the 50% overlap). The output spectra are sent to the DSPs for disk storage or further processing such as RFI detection.

5. EXAMPLE OF REAL TIME ROBUST DETECTION ALGORITHM

Since the SOI is assumed to be a stationary Gaussian noise, we can choose to remove all the values which differ from the expected probability density function [1, 3, 4]. The algorithm currently implemented calculates a threshold level on the power spectral density and marks every points of the time-frequency domain that exceeds this value.
The calculation of the reference mean and of the reference standard deviation has to be robust to RFI (i.e. the ideal algorithm must give the same value for a corrupted signal or a clean one). Tests have shown that the usual formulae (Equ.1 and 2) do not apply for our problem. As a matter of fact, RFI are so strong that even a small number of them can significantly modify the mean and standard deviation values.

$$\mu = \frac{1}{N}\sum_{i=1}^{N} X(i) \quad (1)$$

$$\sigma = \frac{1}{N-1}\sum_{i=1}^{N} \left(X(i) - \mu\right)^2 \quad (2)$$

where X(i) is a time-frequency point in the dynamic spectrum.
The solution is, on one hand, to replace standard deviation by absolute distance (Equ. 3) so high values do not taken too much importance (no squared values) and, on the other hand, to use median filtering algorithm techniques instead of averaging to calculate mean and absolute distance.

$$AbsDis = \frac{1}{N}\sum_{i=1}^{N} \left|X(i) - \mu\right| \quad (3)$$

Median filtering sorts the set of data and returns the value of the sample located halfway in the ranking. This filter is usually used in image processing to remove impulse noise, exactly what has to be removed in the studied time-frequency domain. Our implementation is based on the Quicksort algorithm [5] that optimises sorting for large sets of data.
The algorithm has been implemented on a fixed point DSP TMS320C6203 (Texas Instruments). The DSP/BIOS is runs 3 tasks: one reading raw spectra from the FPGA chain, one handling the blanking and the last one writing processed spectra toward the host PC. The code was optimized to speed up the calculation. The system was configured to record 2048 bin spectra of 7MHz bandwidth at a rate of 2.3 ms (an integration of 16 spectra is done in the FPGA before detection).
This technique has been used to observe the mega maser III ZW35 that is located in the band also used by a constellation of LEO (Low Earth Orbit) telecommunication satellites. Their TDMA and FDMA modulations lead to RFI bursts spread in time and frequency (see Fig. 5). The source corresponds to a flux of 150.10-3 Jansky and it cannot be seen with traditional receiver (see Fig. 4.a).
In our experiment, the mean and absolute distance are extracted in real time as described previously. The detection threshold level is equal to the mean value plus 8 times the absolute distance value (equivalent to mean value plus 5 times the standard deviation). Two kinds of blanking are applied:

- Full spectrum blanking: the complete spectrum is blanked as soon as one canal exceeds the threshold. The loss in data was about 20%. This kind of blanking can be efficient to suppress broadband RFI such as radar or to guarantee very clean observations.
- Time-frequency block blanking: This method is more time consuming, but the blanking is more precise. In our example, the loss in data was only 2.5%.

Actually, in both cases, 7 minutes of averaging is sufficient to see the unmistakable shape of III ZW35 (see Fig. 4.b). In Fig. 5, the areas marked as corrupted are set in shaded red tones. It can be clearly seen that the RFI have been well detected.

6. CONCLUSIONS

In this paper, the digital implementation of a new generation of radio astronomical receivers has been presented. Our system is robust towards RFI by providing improved linearity, higher frequency rejection and better spectral resolution compared to current receiver designs. Thus, the signal integrity can be preserved and RFI mitigation techniques can be envisaged. Our system is fully reconfigurable and can be adapted to any RFI context. With a simple but robust algorithm, a radio astronomical source, unobservable for several years, has been rediscovered. Now, the key point is the development and the implementation of other efficient RFI mitigation algorithms.

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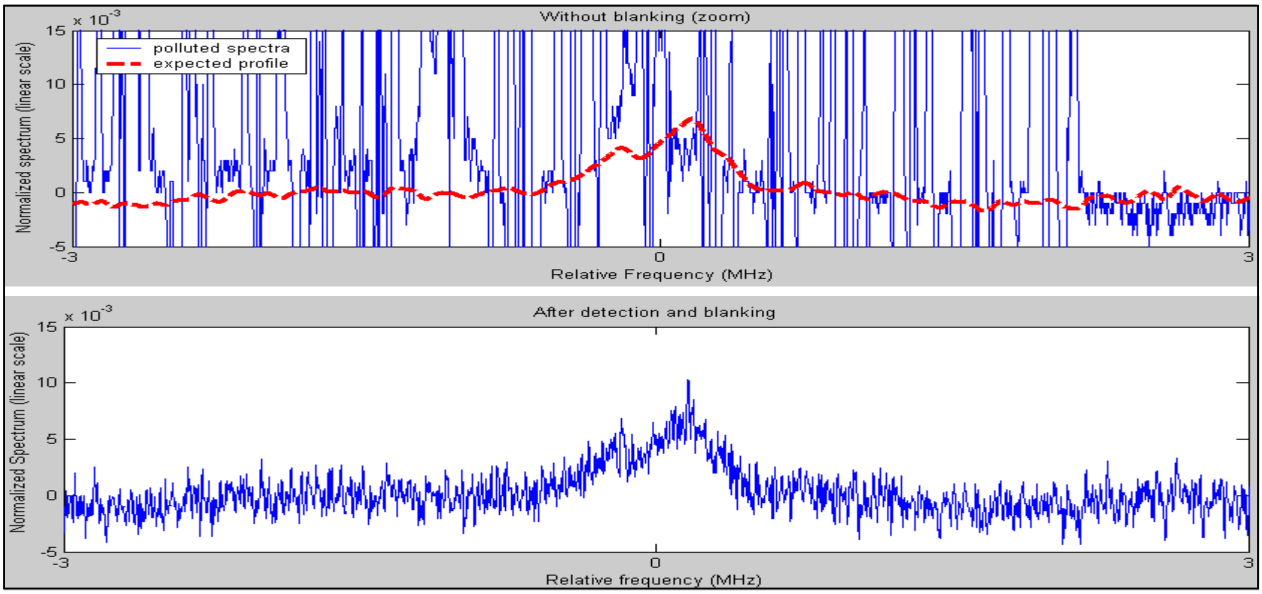

Figure 4: Spectra of IIIZW35 after a 7 minutes time integration. (a) without blanking. The Y-axis is scaled so that the SOI expected profile (in continuous red line) can be seen. Some RFI bursts are 26 dB stronger than the SOI level. (b) with real time blanking. The IIIZW35 source is clearly visible. The last detection of IIIZW35 was performed off-line with stored data in1999 [6].

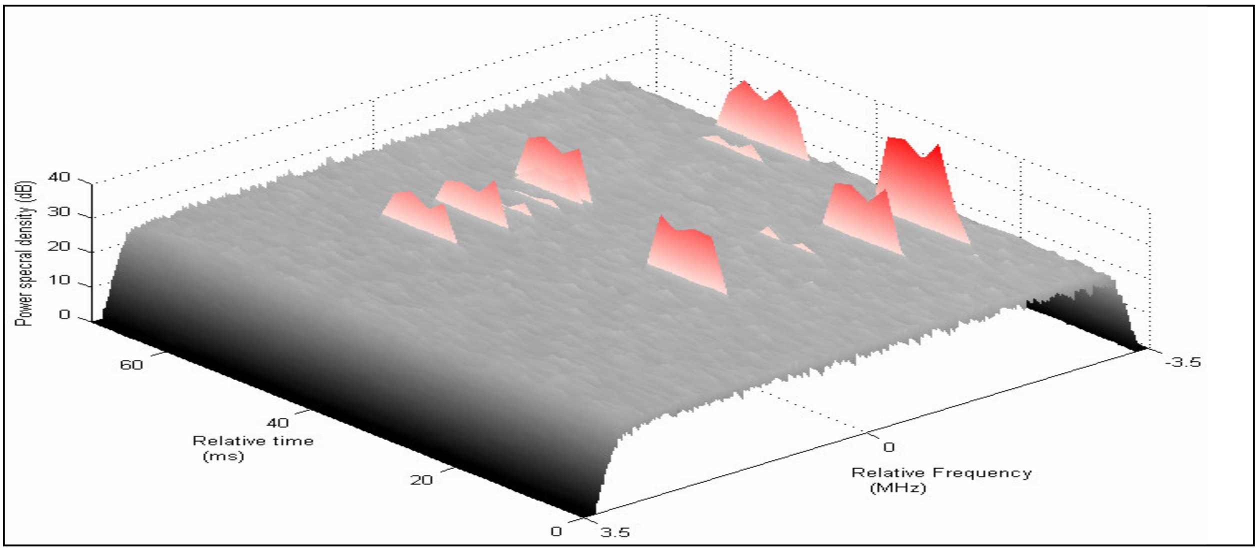

Figure 5: Time-frequency plane with the RFI bursts. The detection threshold level corresponds to mean value plus 5 times the standard deviation. The detected time-frequency areas are colored in red shaded tones. The spectrum attenuation corresponds to the receiver filter shape.