

# RADIO FREQUENCY INTERFERENCE MITIGATION WITH REAL-TIME FPGA DIGITAL SIGNAL PROCESSING

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## ABSTRACT

The sensitivity of radio astronomy telescopes is often limited by man-made radio frequency interference due to a variety of terrestrial activities. An RFI mitigation subsystem (RFIMS) based on real-time digital signal-processing is proposed for the Westerbork Synthesis Radio Telescope based on a powerful field programmable gate array (FPGA) processor. In this system the radio astronomy signals polluted by RFI are "cleaned" by the RFIMS before the routine backend correlation processing happens. The high temporal and frequency resolution of the RFIMS allows the detection and excision of RFI.

## 1. INTRODUCTION

The sensitivity and spectral performance of modern telescopes is increasingly affected by the worsening electromagnetic environment due to population density and increased spectrum use. At the same time the technology standards at modern radio telescopes have been raised and low-noise receivers have been significantly improved. However, as a result of the presence of radio frequency interference (RFI) in the data, the potential of increased sensitivity cannot be reached at all times, especially at frequencies below 1 GHz. The presence of detrimental RFI in the data translates into effective data loss and a lower observing efficiency.

Advances in digital techniques provide vast opportunities for RFI mitigation. A demonstrator RFI mitigation system has been developed at the Westerbork Synthesis Radio Telescope (WSRT) that was based on a *Signatec* PMP-8 digital signal processor (eight DSP TMS320C6201) board and 4-channel 12-bit high-speed (up to 50 Msamples/sec) analog-digital and digital-analog (ADC & DAC) converters. This system was used to operationally test several RFI mitigation algorithms.

The principal methods used in these tests were: 1) time-frequency analysis and outliers excision using thresholding, 2) RFI suppression using a "RFI estimation  $\rightarrow$  subtraction" method, 3) adaptive RFI cancellation using a reference channel, and 4) the use of higher-order statistics for analysing the data. These DSP processing efforts of the real astronomical signals resulted in considerable RFI suppression both for continuum and spectral observations.

As a follow-up to this DSP-based system a second-generation real-time RFI Mitigation System has been proposed for implementation within the existing WSRT backend infrastructure. *Real-time* processing was chosen for the RFIMS because very often RFI are unsta-

ble, rapidly changing and very strong. They may behave like bursts in temporal or frequency domains. The RFI may produce considerable distortions of averaged data at the correlator output if not "intercepted" before processing in the correlator. RFI at the antennas of such a large and sparse interferometer as the WSRT is sometimes only partly coherent and spatial processing algorithms are not always effective. Therefore, *real-time* time-frequency analysis of the signals at each antenna is a more flexible tool than post correlation processing.

The system is designed so that one of the eight 20 MHz wide sub-bands of each of the fourteen telescopes gets processed independently between the IF to video conversion ("IVC") stage and the correlation stage. The full system consists of 28 separate processors, one for each of the polarization channels per telescope (WSRT consists of 14 antennas). State-of-the-art high-performance processors implemented in FPGA's are being used for this real-time processing stage. It should be noted that this system is essentially a multi-path processing system that could be effectively applied at single-dish telescopes as well. This paper reports on the first operational results obtained with this RFIMS system.

## 2. RFI MITIGATION SYSTEM

The implementation of an RFI mitigation subsystem within an existing interferometric signal-processing backend is a delicate technical problem. In order to allow implementation, the subsystem should a) be adapted to the input-output specifications and the schematics of the backend, b) be precisely synchronized with the correlation processing, and c) keep the useful radio source signals undistorted and maintain the correct absolute and constant time relations of the multi-channel system. After the last frequency conversion stage in the IVC system, the baseband signals of bandwidth up to 20 MHz are processed in the RFI mitigation subsystem before they are applied to the radio interferometric correlator. The processed signals should be presented to the correlator as if there were no additional processing stages involved.

Using the experience obtained with the DSP-based demonstrator system, a second-generation RFI mitigation subsystem (RFIMS) has been conceived for the WSRT. The design criteria used for the RFIMS system are based on the following considerations:

1. For processing large quantities of data in a very similar manner, a high degree of parallelism, extensive pipelining, dynamic reconfigurability and the realloca-

tion of computational units, upgradability and scalability, are required.

2. High-performance processing cores (DSP, Pentium IV) provide a small benefit if the data transfer overhead reduces their processing power to unacceptable limits. Therefore, the processing power and data transfer speeds are equally important for system evaluations.

3. The signal-processing literature is full of creative solutions to real-world problems. Often these solutions are not useful to a designer because they do not map well to software-programmable DSP architectures. Similarly ASIC solutions are not an option for reasons of time-scales, economy of scale, and flexibility. On the other hand, field programmable gate arrays (FPGAs) give immediate access to a diverse range of potential solutions for high-performance digital processing systems. These devices maintain the flexibility of software-based solutions, while providing levels of performance that match ASIC solutions.

A block-diagram of the RFIMS structural buildup is presented in Figure 1. Baseband signals are digitized, processed and then transformed back to analogue form to be processed further in the correlator. The main processing unit consists of an ADC → FPGA → DAC configuration. Conversion back to analogue is necessary at the WSRT because the correlator has analogue baseband inputs and modification of this equipment is not an immediate option. This “legacy problem” is also valid for many other radio telescopes.

A 12 bit analog-to-digital converter with a maximum sampling frequency of 125 MHz is used to digitize the baseband signals at the output of the IF-to-video converter (IVC). The maximum bandwidth of the baseband signals is 20MHz. The digitized data are supplied to the signal processing engine, which contains an ALTERA STRATIX programmable logic device EP1S80B956-6 for the RFI real-time mitigation processing. The processor has 79,040 logical elements and 7,427,520 RAM bits and works with clock frequencies up to 200MHz. It also contains 176 embedded (9 x 9) multipliers. The processed data are then converted back to the analogue form using a 14-bit digital-to-analog converter, with maximum conversion frequency of 165 MHz. The RFIMS processing may be bypassed totally using a cross-point switch.

During a particular observation, a configuration of RFI mitigation algorithms is loaded in the FPGAs via the USB bus. A configuration is adapted to and optimized for the type of observations and the particular RFI environment. If the situation changes or a new observational program is to be started, a new configuration of algorithms can be loaded. The observatory staff will need to monitor the RFI environment at each of the antennas and evaluate the effectiveness of the particular RFI mitigation algorithms.

For the WSRT the minimum number of the channels is 28 with 14 antennas and 2 polarizations. In the first instance, just one of the eight 20 MHz-bandwidth frequency channels will be processed before correlation. Eventually the system could be expanded up to 224 channels to cover eight 20 MHz frequency bands from each antenna.

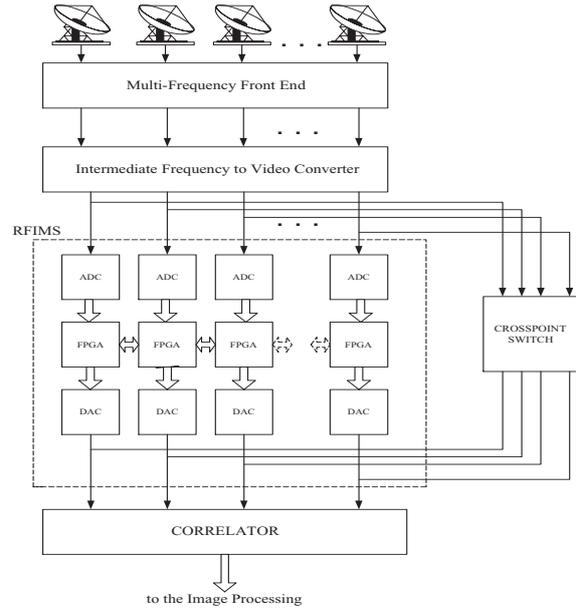


Figure 1: RFI mitigation subsystem at WSRT, ADC - analogue-digital converter, FPGA - field programmable gate array, DAC - digital-analogue converter.

## 2.1 Algorithms

Two main algorithms have been implemented in the FPGA as first trial processes.

1. *Time-frequency analysis of baseband signals and RFI excision.* Thresholding has been used in both the temporal domain and the frequency domain. After a real-time Fast-Fourier transform (FFT) in the FPGA, the running power spectrum is calculated followed by a threshold detection of the RFI in the time-frequency plane. The detection of RFI *transients* of unknown form in the time-frequency plane can be made effectively with a cumulative sum (CUSUM) procedure, which maps well onto the FPGA structure [1, 2].

However, a thresholding procedure requires knowledge of the quiescent noise variance in each of the frequency bins, which is the spectral density of the system noise in the absence of RFI. This variance could be different for each baseband due to the variability of the transfer functions of the low-pass filters in the WSRT intermediate-to-video conversion system. A nonparametric procedure is used: median filtering of the power spectrum in order to obtain a reference power spectrum, which determines the threshold level in the spectral domain. For  $i$ -th frequency channel a group of  $k = 2m + 1$  adjacent values of power spectrum  $sp_{i-m}, sp_{i-m+1}, \dots, sp_{i+m+1}$  is arranged in increasing order:

$$sp^{(1)} < sp^{(2)} < \dots < sp^{(k)}.$$

The  $i$ -th value of the power spectrum is substituted by median:  $sp^{(m)}$ . This procedure gives a more smoothed power spectrum (no “bursts” on spectrum) which may be used as a reference spectrum for thresholding.

2. *RFI suppression using adaptive noise cancellation (ANC) techniques.* The fourteen WSRT antennas form a linear sparse but regular array with separations of 144

m. Because of space constraints the installation of reference antennas and receivers near the focal region of the array elements is not feasible with the current focal configuration (a possible future focal plane array implementation may change this situation radically). Instead a combination of spatial filtering, adaptive nulling, and ANC techniques is proposed for the WSRT (see block-diagram in Figure 2). All processing is performed in the frequency domain. The signals from the IVC system, where array-based phase-rotation (fringe stopping) was done, are transformed using an FFT routine. The spectral signal function  $sp_i(f)$  of the  $i$ -th antenna at each discrete frequency  $f$  is “cleaned” using a reference signal vector  $\mathbf{r}_n$ , that is formed as a linear combination of the two “neighbor” signals from the  $i-1$ -th and  $i+1$ -th antennas. This procedure cancels the useful signal from a radio source such that:

$$\mathbf{r}_n(f) = [sp_i(f) - \overleftarrow{sp_{i-1}(f)} \quad \overrightarrow{sp_{i+1}(f)} - sp_i(f)]^T, \quad (1)$$

$$sp_i(\widehat{f})_n = sp_i(f)_{n-1} - \mathbf{w}_n^T(f) \mathbf{r}_n(f), \quad (2)$$

$$\mathbf{w}_n(f) = \mathbf{w}_{n-1}(f) + \mu \cdot \overline{sp_i(f)}_{n-1} \cdot \overline{\mathbf{r}_n(f)}. \quad (3)$$

In these formulae the functions  $sp_{i-1}(f)_n$ ,  $sp_i(f)_n$ , and  $sp_{i+1}(f)_n$  are the spectral transforms of the baseband signals  $x_{i-1}(t)$ ,  $x_i(t)$ , and  $x_{i+1}(t)$  from antennas  $i-1$ ,  $i$ , and  $i+1$ . The index  $n$  denotes the tag number of the spectrum and represents the time axis or the number of iterations of the least-mean-square (LMS) algorithm depicted in the equations (1), (2), and (3), [3]. The vector  $\mathbf{r}_n$  serves as the reference signal vector and the arrows above  $sp_{i-1}(f)$  and  $sp_{i+1}(f)$  denote the time shift (actual delay compensation) of these signals. The time shift is necessary to obtain totally coherent versions of the signal with respect to the signal of interest from the astronomical data before the actual subtraction executed in equation (1). This operation is similar to the delay compensation operation routinely done in the correlator. The determination of the delay compensation is under computer control and the values are pre-calculated for each particular “source - array” geometry. Therefore, the useful signal from the radio source is not present in the vector  $\mathbf{r}_n(f)$ . On the other hand, the “clean” signal  $sp_i(\widehat{f})_n$  (with hat) for each iteration  $n$  is determined as an *error signal* using an LMS algorithm with a gain factor  $\mu$  and the weight column vector  $\mathbf{w}_n(f)$ . The overline bar in  $\overline{\mathbf{r}_n(f)}$  denotes a complex conjugation, the superscript  $T$  denotes a transposition.

The number of antennas taking part in the formation of the reference channel can be larger than two, using the method described above. The vector  $\mathbf{r}_n$  may therefore contain more differences of the kind of  $sp_i - sp_{i-1}$ . A more accurate vector  $\mathbf{r}_n$  would increase the level of RFI suppression, but the effectiveness of such steps depends on the degree of RFI correlation at the array’s antennas. Thus, for radio interferometry using longer baselines, RFI at widely separated antennas may be considerably uncorrelated.

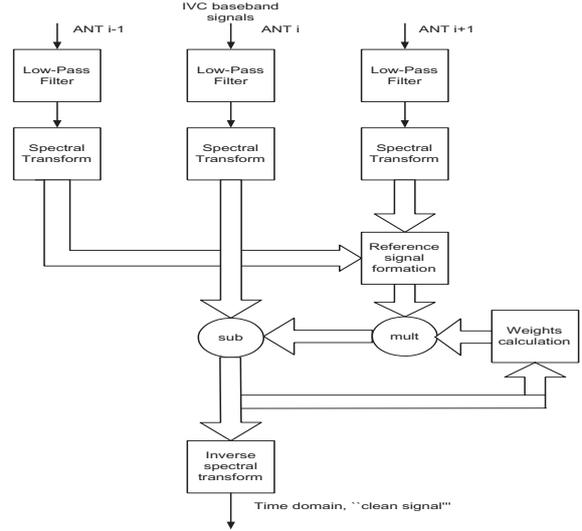


Figure 2: Block-diagram of the adaptive RFI cancellation.

## 2.2 Observational examples

An RFIMS pilot system for 4 channels is being completed for the WSRT and we present some results of the test observations. WSRT is a 14-element (radio telescope, RT) correlation interferometer and the correlator output is the primary data for further processing. Fig. 3 shows the cross-spectrum amplitude as a function of time, corresponding to the antenna’s combination RT5-RT7 with and without RFI mitigation. Radio source 3C286 was observed at frequency 355 MHz with the bandwidth equal to 20 MHz. Integration time for each spectrum (record) is 60 sec and the figure is built with 98 records. Therefore, the time evolution of the cross-spectrum amplitudes during  $\approx 1.6$  hours is shown in the figure. There are eight baseband channels at each RT, and two of them were used for this experiment: signals at RT5 and RT7 in the 2 were processed with RFIMS and then applied to the correlator, while signals in band 3 were applied directly to correlator (no RFIMS). Both bands were tuned to the same frequency. The upper panel in Fig. 3 shows the effect of RFI mitigation comparing to the lower panel - no RFI mitigation.

The corresponding cross-correlation amplitude plots are shown in Fig. 4 as a function of time, in the same way as in Fig. 3.

The RFI mitigation system was also tested at the single dish 100m Effelsberg (Germany) radio telescope. Fig. 5 illustrates the effect of RFI mitigation at 1625MHz: the RFI is from Iridium communication satellites. The integration time is 1 min and the bandwidth is 12.5 MHz. The upper panel shows the power spectrum (calculated from the autocorrelation function) at the spectrum analyzer output with implemented RFI mitigation while the lower panel shows the spectrum obtained simultaneously without RFI mitigation.

## 2.3 Conclusions

First results obtained with the real-time RFI mitigation system based on FPGA are encouraging. Application of

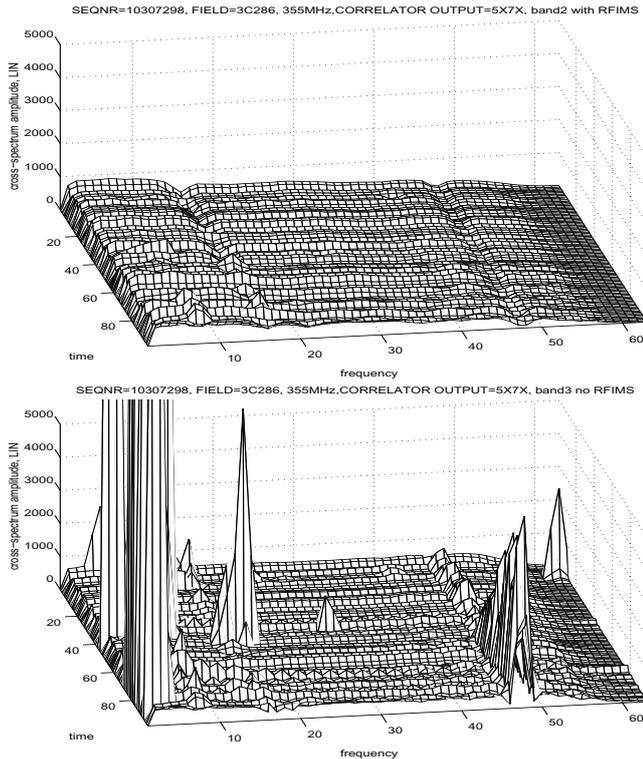


Figure. 3: Observation at WSRT, source 3C286, central frequency 355 MHz, bandwidth 20 MHz, integration time 60 sec for each of the 98 records ( $\approx 1.6h$ ). RFI were suppressed at band 2 of channels RT5 and RT7 and not suppressed at band 3 of these channels, band 2 and 3 tuned to the same frequency. The time-frequency presentations of the **cross-spectrum amplitudes** are given: band 2 -upper panel, band 3 - lower panel.

modern FPGA's allows implementing signal processing algorithms with sufficient complexity to get significant RFI mitigation effects.

The FPGA's are reprogrammable devices, and this feature may be used to implement different algorithms, depending on the nature of RFI and on the type of observation being done. The use of this kind of adaptability represents innovation in radio astronomy signal processing.

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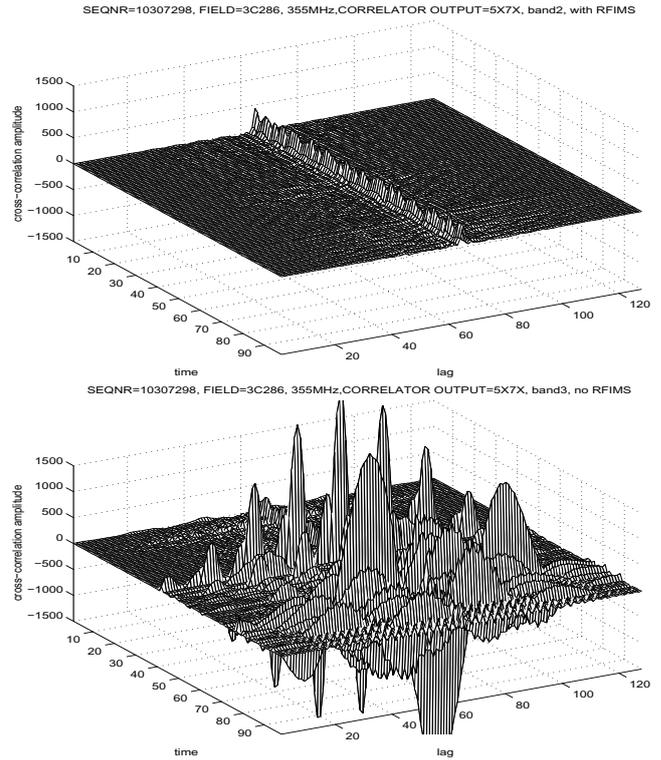


Figure. 4: Observation at WSRT, source 3C286, central frequency 355 MHz, bandwidth 20 MHz, integration time 60 sec for each of the 98 records ( $\approx 1.6h$ ). RFI were suppressed at band 2 of channels RT5 and RT7 and not suppressed at band 3 of these channels, band 2 and 3 tuned to the same frequency. The time-frequency presentations of the **cross-correlation amplitudes** are given: band 2 -upper panel, band 3 - lower panel.

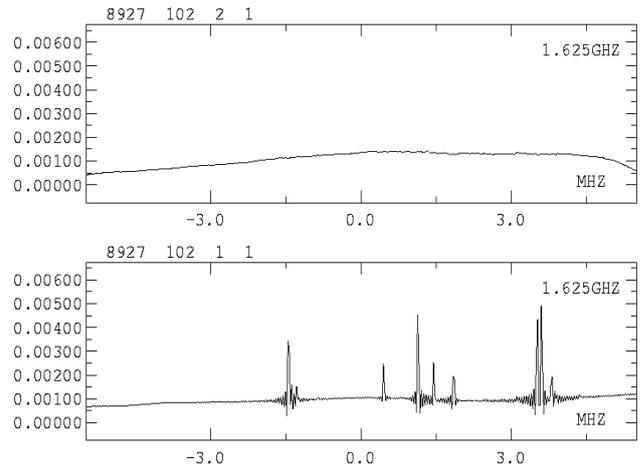


Figure. 5: Observation at 100 m Effelsberg radio telescope, central frequency 1625 MHz, bandwidth 12.5 MHz, integration time is 60 sec. Upper panel: power spectrum with RFI mitigation, lower panel: power spectrum without RFI mitigation.