PROCEEDINGS OF SCIENCE

The RFI Mitigation System at WSRT

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Imaging results are presented to show the effectiveness of the real-time RFI mitigation system (RFIMS) implemented at the Westerbork Synthesis Radio Telescope. Thresholding of RFI signals in the time and frequency domains is applied to 28 separate FPGA-based signal paths to independently handle two polarized 20 MHz bands from fourteen telescopes. Comparisons between processed and non-processed data show that the system can effectively remove both the weak and destructive RFI without doing damage to the remaining data.

RFI mitigation workshop - RFI2010
March 29-31, 2010
Groningen, the Netherlands

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PoS(RFI2010)024

1. Introduction - Objectives

The increased sensitivity and spectral performance of existing radio telescopes make them vulnerable to the ever deteriorating electromagnetic environment that results from population density and intensified spectrum use. The presence of radio frequency interference (RFI) in data and the resulting data loss already limit the return on investment from existing instruments. While current standards for unwanted emission do not sufficiently protect bands allocated to the passive services, observations made with broadband receivers and backends outside these allocated bands will encounter the ever increasing emissions of active users of the spectrum. The spectrum available for passive use by radio astronomy will thus be severely limited.

Managing the presence of RFI signals in radio astronomy data requires mitigation strategies that remove the damaging effects on the data. While manual flagging has served this purpose, advances in computing and data processing now make it possible to implement real-time, automated, mitigation strategies. These are particularly needed for large bandwidth observations (partially) outside the allocated RAS spectrum bands. In the absence of a preferred and universal RFI mitigation method, successful mitigation can be achieved by deploying a sequence of measures at various stages of the data acquisition path. Traditionally these measures include scheduling observations at radio quiet times, filtering, and some form of pre-processing and post-processing excision. Nevertheless, all of these methods result in some data loss and some reduction in observing efficiency.

Advances in digital techniques provide many new opportunities for RFI mitigation using high performance processors. This paper describes the successful results of a second generation, multi-path, real-time, RFI Mitigation System (RFIMS), which was implemented within the existing back-end infrastructure of the Westerbork Synthesis Radio Telescope (WSRT) [1, 2, 3].

2. System Implementation

The RFIMS sub-system is based on real-time, pre-detection & pre-correlation, baseband processing of one IF band from each of the fourteen telescopes. Real-time multi-path processing is desired for the WSRT because (1) the RFI environment is often quite variable; (2) the fringe stopping and delay properties of the interferometer need to be retained to add to the baseline-length dependent attenuation (decorrelation) of the RFI; and (3) the tied-array observational mode needs to be preserved. Implementation within the existing interferometric signal-processing backend is achieved (1) by adapting to the input-output specifications and schematics of the backend; (2) by precisely synchronizing with the correlation processing; and (3) by maintaining undistorted radio-source signals and correct absolute and constant time relations within the multichannel system.

RFIMS independently processes one of the eight 20 MHz (or 10 MHz) subbands of the intermediate-frequency (IF) band between the IF conversion stage and the correlation stage. The full system services 28 separate signal paths required to independently handle two polarizations from 14 telescopes. Each signal path consists of (1) a 12-bit ADC (maximum frequency 125 MHz) that digitizes the analog input, (2) a digital processing component, which occupies half of an Altera Stratix S80 processor chip, and (3) a 14-bit DAC (maximum frequency 165 MHz) that converts the digital signal back to analog for input into the DZB correlator system. The RFIMS is composed of off-the-shelf VME modular components and operates under VME control at 40 Msamples/sec.

The RFIMS processing may be bypassed completely using a cross-point switch. The system design requires 224 processing paths to cover all eight IF frequency bands provided by each antenna.

The main algorithms implemented in the FPGA for the purpose of this paper incorporate time-frequency analysis of the baseband signals and RFI excision. Thresholding has been used in both the time and frequency domains. 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 [1]. The detection of RFI transients in the time-frequency plane is done using a cumulative sum (CUSUM) procedure within the FPGA. 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 is different for each baseband because of the variability of the transfer functions of the low-pass is used to obtain a reference power spectrum, which determines the threshold level in the spectral domain. The removal of outliers by thresholding does not affect the mean value of the data accumulation for a spectral channel, only its variance. Therefore, thresholding does not affect subsequent bandpass and gain calibration. On the other hand, setting the affected channel values to zero will affect the mean, the variance, and the calibration.

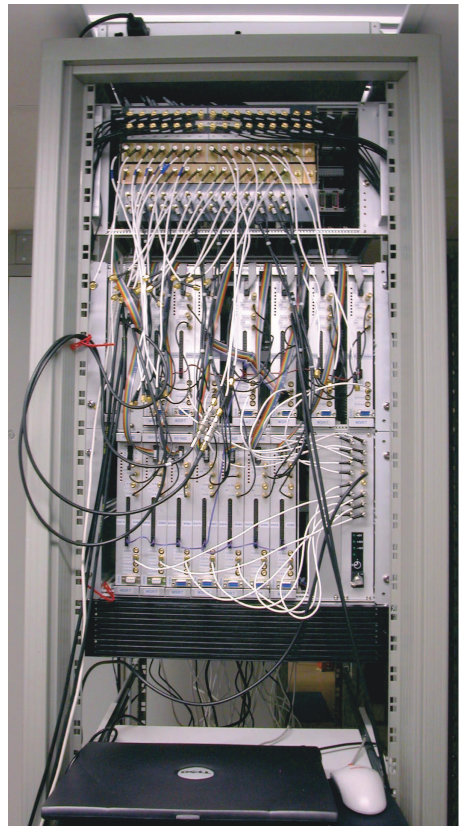

Figure 1: The RFIMS system for 28 20 MHz baseband signals using 14 FPGA processors.

3. Imaging Results

The thresholding algorithms and an algorithms for Adaptive Noise Cancellation using the (reference) signals of adjacent telescopes have been extensively tested using an earlier version of the system using four telescopes [2]. The time evolution of the cross-correlation products were used to display the effectiveness of these methods on the spectrum amplitudes. The effect of mitigation is most easily seen in the (u, v)-data.

In this paper we present imaging results for two of the eight IF bands of the WSRT using identical frequency settings and experiencing the same RFI environment. One of these IF bands (IF5) is processed by RFIMS before being passed to the correlator, while the other band (IF4) is passed directly to the correlator. The IF4 and IF5 band data may thus be used for directly evaluating the mitigation operation. The image reconstruction and the rms in the maps serve as indicators of the effectiveness of the method and its toxicity, i.e. the damage done to the data by the process itself.

The double radio source 3C390.3 has been mapped at 1625.58 MHz in the Iridium operation band (anno 2005). The total power spectra for IF4 and IF5 clearly show the presence of RFI (Figure 2). No post-correlation editing (flagging) was done for the IF4 data. A comparison of the maps (Figure 3) shows that the large majority of the RFI striping in the IF4 map (left) has been removed from the IF5 map (right). Weak RFI residuals remain in the IF5 map and bandpass.

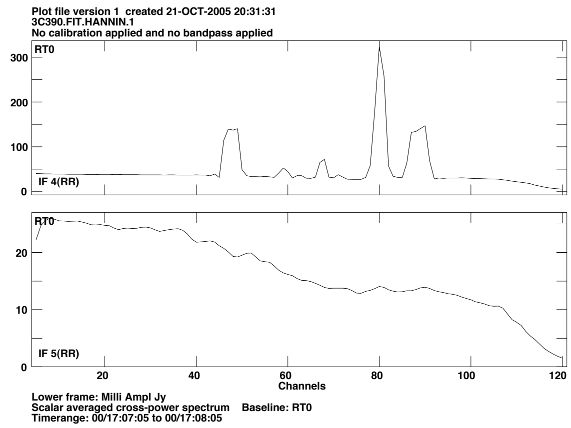

Figure 2: The cross-power spectrum of 3C390.3 at 1625 MHz without (IF4 top) and with (IF5 bottom) RFI mitigation. The interference is caused by the Iridium system operating between 1621.35-1626.5 MHz.

The well known giant radio galaxy DA240 was observed at 357 MHz using a 10 MHz bandwidth. Strong interference was encountered from aeronautical radio navigation signals. The maps presented in Figure 4 show a very distorted map for the un-processed IF4 data (left) and clear resemblance of the giant (double-lobe) radio galaxy for the RFI-mitigated IF5 map (right). No additional processing has been applied to either map. There is no evidence of residual interference in the mitigated map.

The maps of NGC891 display two prominent sources and many background sources (Fig. 5). The IF4 and IF5 maps were produced by post-correlation (manual) flagging plus self-calibration (left) and by automated RFI mitigation plus self-calibration (right). Differences between the maps are minimal except for more extended contours in the mitigated map. There is no evidence of weak remnants of interference in either map.

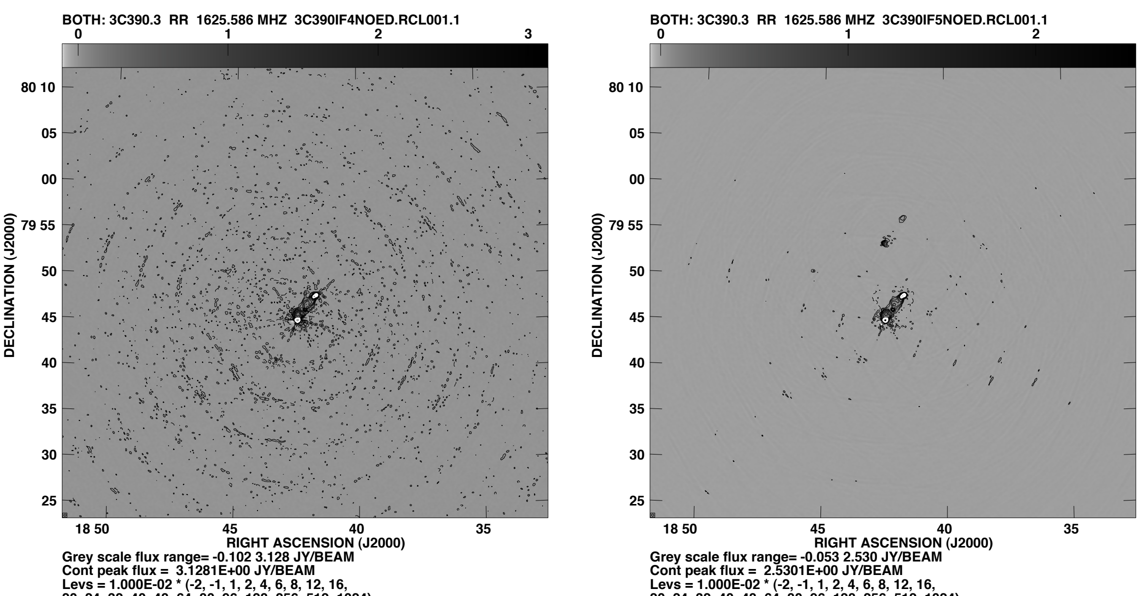

Figure 3: The double radio galaxy 3C390.3 at 1625.6 MHz. Iridium signals cause radial striping in the unedited IF4 map because of multiple moving satellites. Incomplete removal of the strongest signals in the IF5 data leave weak residuals in the cleaned map (right).

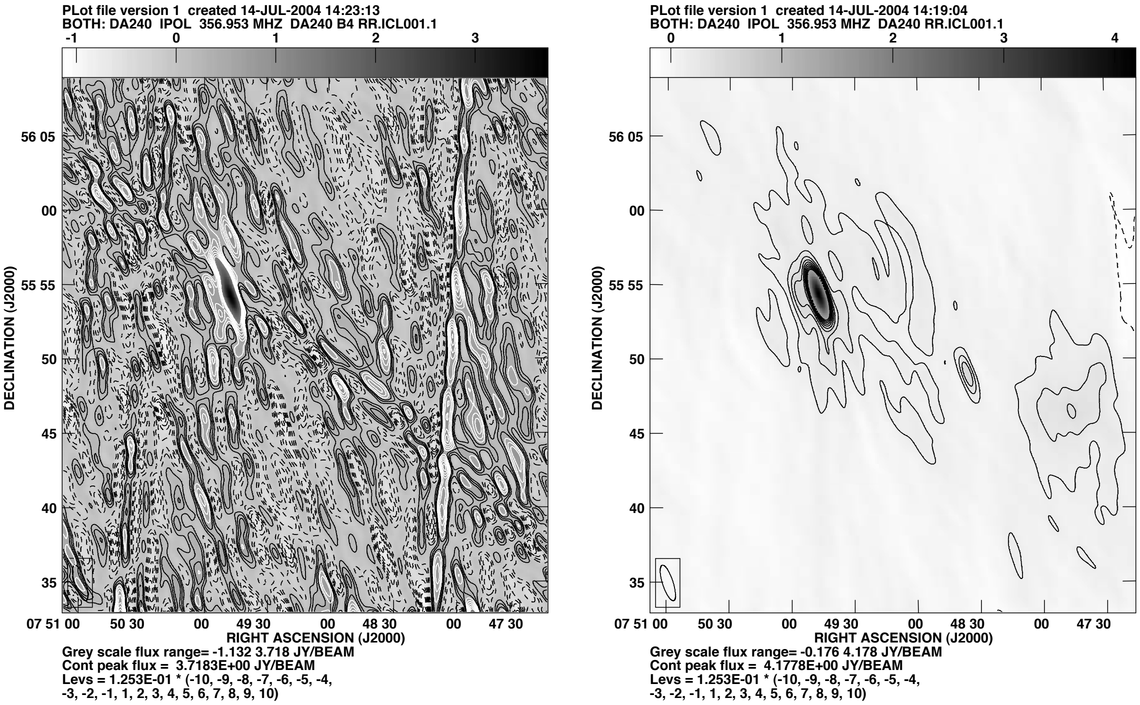

Figure 4: Continuum structure of the giant double radio galaxy DA240 at 357 MHz. The interference from aeronautical radio navigation systems in IF4 (left) completely dominates the data. The RFI mitigated IF5 (right) map reveals the double radio galaxy, with the nuclear source between the two lobes and with a prominent jet hotspot in the eastern lobe.

4. Project Evaluation

The real-time RFIMS at WSRT performs as expected and removes all detectable RFI from the data. In general, the rms values of the cleaned maps are equal or slightly better than those from manually-cleaned version of the same data. No evidence of toxicity or damage to data was found from the thresholding algorithm.

In the case of 3C390.3 some RFI residuals are found in the (u, v)-amplitudes (Figs. 3, 2); RFI cleaned data may also retain an RFI signature in the phases. Since the efficiency of RFI-mitigation processes depends strongly on the type of RFI and its signal-to-noise ratio, weak RFI signals will not always be removed completely, which will leave residuals in the (u, v)-data and the maps. The insertion of digital components into an analog data path renders accurate bookkeeping of the RFI mitigation process difficult. This is not an issue for RFI mitigation by thresholding because it does not affect the mean of the channel data, or the gain & bandpass calibration.

5. Conclusions

The hardware and software designs of RFIMS allow expansion to all eight bands of the WSRT system. In addition to thresholding, RFIMS can accommodate mitigation methods, such as adaptive noise cancellation and higher-order statistical methods, that remove the RFI without damaging the data. A decision-making sub-system could be used to control the applied mix of algorithms,

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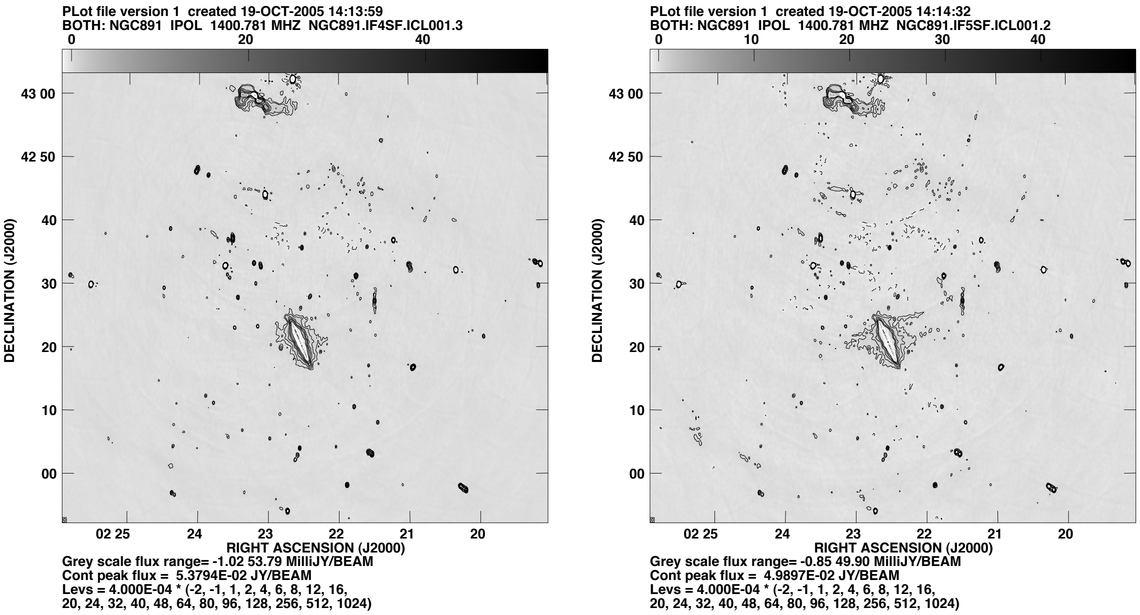

Figure 5: Radio continuum structure of NGC891 at 1400 MHz. The galaxy is located at the image center with radio galaxy NVSS J022302+425749 to the north. Self-calibration was done for both maps after manual data flagging of IF4 (left) and RFI mitigation processing of IF5 (right). The maps are very similar and show no evidence for residual RFI, except that the right map shows some more extended structure.

depending on the type of interference encountered. Different algorithms can be implemented at different stages in the data taking process in order to optimize the cumulative effect of mitigation.

RFIMS has shown that real-time, pre-correlation mitigation can work successfully for both single-dish and interferometry systems. RFIMS also shows that retro-fitting existing and complex telescope backends with automated mitigation hardware is possible. Because the effectiveness of mitigation algorithms varies with the RFI situation encountered, the systems need to be flexible enough to adjust their algorithms. New-generation and other newly-built radio telescopes should be designed to incorporate multiple mitigation methods. The performance of computing platforms will make automated real-time mitigation a standard procedure for radio astronomy.

The impact of RFIMS has been very limited because of the disinterest on the part of astronomers. This well-engineered and proven system has not been used at WSRT because of unfounded concerns about 'black box' automated flagging and because the few remaining clean parts of the spectrum suffice for current research interests. It is anticipated that this condition will change when the observing bands (data volumes) become larger and the RFI conditions deteriorate.

References

[1] Baan, W.A., Fridman, P.A. & Millenaar, R.P., *Radio frequency interference mitigation at the Westerbork Synthesis Radio Telescope*, AJ, 128, 933, 2004

[2] Fridman, P.A., *DSP Experimental System for Radio Frequency Interference Mitigation at WSRT*, ITR-221 (Dwingeloo: ASTRON), 2000

[3] Fridman, P. A. & Baan, W. A., *RFI mitigation methods in radio astronomy*, A&A, 378, 327, 2001