

Real-time RFI Excision for the GMRT Wideband Correlator

Kaushal D. Buch,
Yashwant Gupta, Shruti Bhatporia, Swapnil Nalawade,
Kishor Naik, Ajithkumar B.

Digital Backend Group,
Giant Metrewave Radio Telescope (GMRT), NCRA-TIFR,
Pune, India
kdbuch@gmrt.ncra.tifr.res.in

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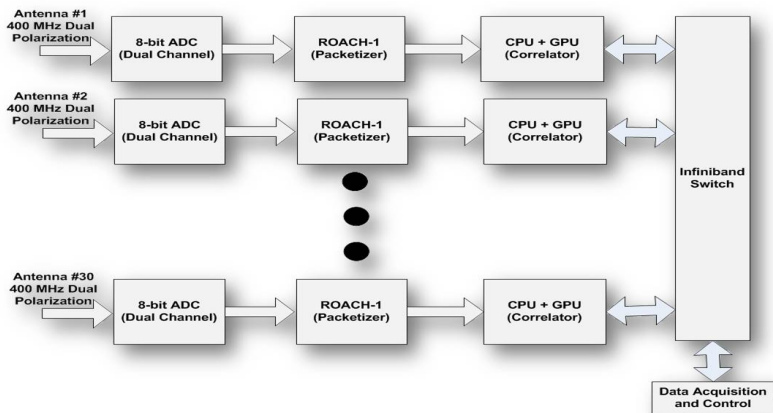
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Giant Metrewave Radio Telescope (GMRT)

- Sensitive instrument for observing astrophysical phenomena at low radio frequencies (150 - 1450 MHz)
- 30 antennas each a 45 m diameter prime-focus parabolic reflector
- 12 antennas in one square kilometer (central square), 18 antennas in Y-shape (three arms)
- Shortest baseline $\sim 100\text{m}$, Longest baseline $\sim 25\text{ km}$
- Upgraded GMRT (uGMRT) - undergoing upgrade to achieve better sensitivity
 - Needs real-time broadband and narrowband RFI excision

GMRT Wideband Correlator



400 MHz bandwidth, 8K-16K spectral-channel FX correlator built using FPGAs and CPU-GPUs

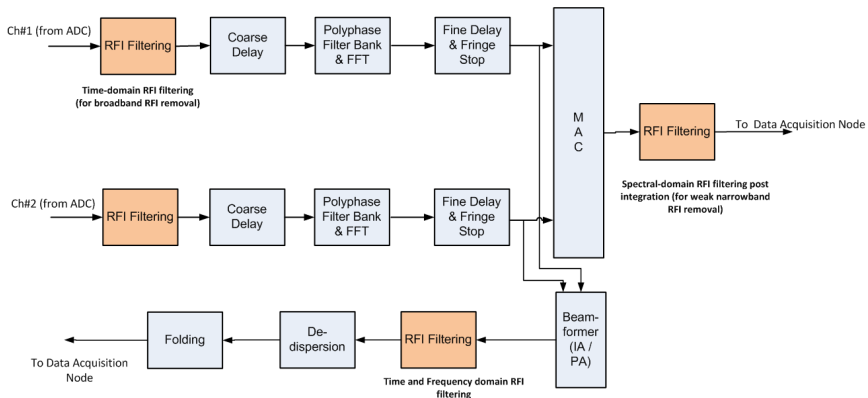
Broadband RFI at GMRT

- Primary cause: sparking on high-power transmission lines
- Observed at lower radio frequencies (up to 700 MHz)
- Leads to off-source correlation in GMRT central square antennas
- Period - 10 ms or lower, typical ON time - few microseconds
- Broadband RFI mitigation is challenging because linear filters cannot be used

Why real-time excision ?

- Temporally impulsive RFI: Energy spreads post-FFT hence excision needed before the FFT
 - Power-line RFI: low duty cycle but high spectral occupancy
 - RFI is correlated in closely spaced antennas
- Spectrally impulsive RFI: excision useful for low time occupancy
- Reduction in the artifacts due to RFI
- Best possible time resolution: reduced loss of astronomical data
- Leads to improvement in the receiver sensitivity

RFI Excision in the GMRT backend



Multiple instances of RFI excision are required in the processing chain to remove diverse types of RFI

MAD Estimation and Non-linear Filtering

- Interference is strong and additive - Signal (Gaussian), Noise (Gaussian), Interference (Non-Gaussian)
- Detection using Median Absolute Deviation (MAD) as a robust estimator of dispersion of data. Breakdown point: 50%
- Threshold τ can be controlled using n

$$\tau = M(x_i) \pm n * (1.4826 * (M(|x_i - M(x_i)|)))$$

where x_i is the input data set and M is the median operator, 1.4826 is scaling factor for Gaussian distribution

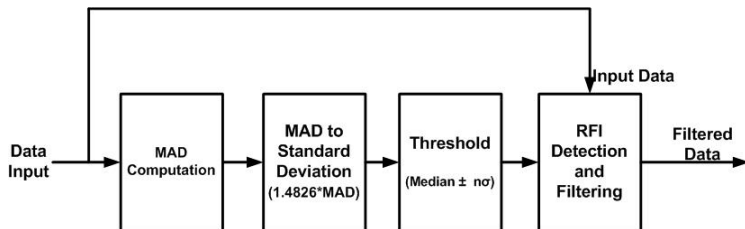
- Detection followed by non-linear filtering on each sample x_i

$$y_i = K; \text{ for } x_i \geq \tau_U \text{ or } x_i \leq \tau_L = x_i; \text{ for } \tau_L < x_i < \tau_U$$

- K - threshold value or constant value or a noise sample

MAD Estimation and Non-linear Filtering (contd.)

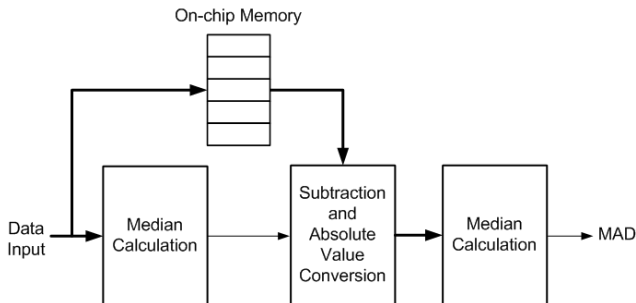
- Window size is $2 * (T_R/T_S)$ samples where T_R is the (worst case) duration of RFI and T_S is the sampling interval
- Excision on individual samples causes lower loss of data than non-normality detectors



Real-time Implementation

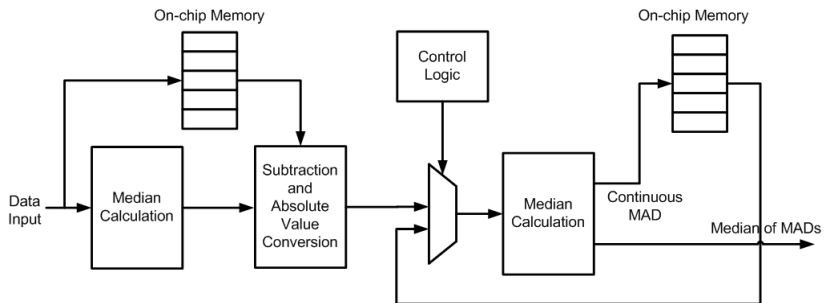
- Computational requirement: MAD for consecutive windows on integer data (8-bit) Nyquist-sampled digital time-series and moderate to large window sizes (1K to 8K)
- MAD requires two consecutive median operations and each median computation typically takes $N/\log N$ operations
- Better approach : Histogram based median computation
 - Parallel approach: bin the data and locate the median
 - Complexity scales as 2^q (q is the number of inputs bits)
 - Amenable for implementation on FPGAs and CPU-GPU platforms

Real-time Implementation on FPGA



- Two median computations, initial latency of $2W$ clock cycles (window size)
- Real-time implementation on Xilinx Virtex-5 FPGA (ROACH-1 board)
- 15-20% resource utilization for 8-bit, 4K window size block
- Basic design available in the CASPER repository

Long lasting RFI: Median of MADs



- Hold MAD values from consecutive windows in a memory buffer
- Compute the median (M) i.e. median of MAD values (M_m)

$$M_m = M(MAD_1, MAD_2, \dots, MAD_n)$$

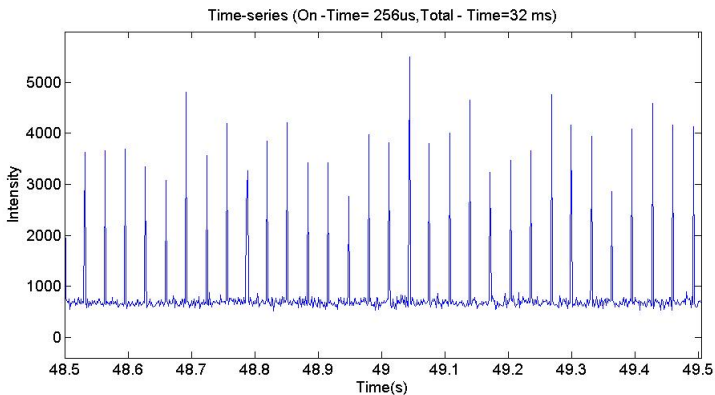
Test Results from the GMRT wideband correlator

- Two inputs - RFI Emulator and Antenna (Sky) signals
- High Time Resolution: Single spectral channel plot over time at 1.3 ms integration period for filtered and unfiltered outputs
Improvement (dB)

$$\text{Improvement}(dB) = 10 * \log(MR_F / MR_U)$$

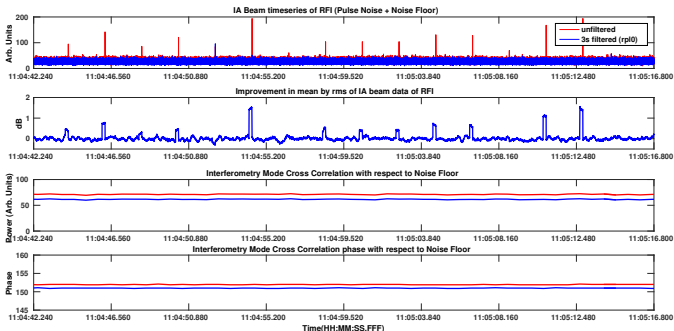
- Where MR_F and MR_U are the mean/rms ratio for filtered and unfiltered signal respectively. Running mean/rms calculated over 1024 samples of beam output
- Coarse Time Resolution: Cross-correlation magnitude (unnormalized) and phase at 0.671s integration period: options are filtered vs filtered, filtered vs unfiltered and unfiltered vs unfiltered for a short baseline

RFI Emulator



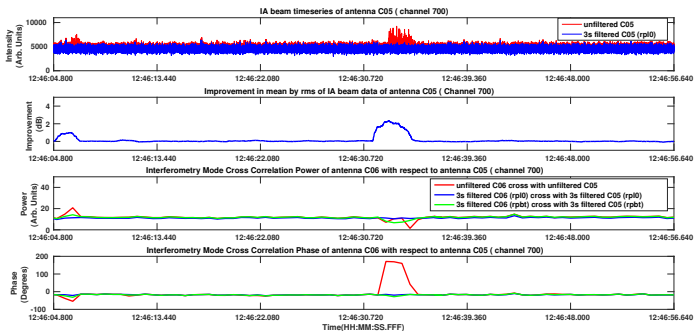
- Programmable analog unit developed to emulate broadband and narrowband RFI of desired strength and duty-cycle
- Used for radiation at RF or direct baseband input to ADC
- Helps in accurate characterization of RFI excision system

Test results (RFI Emulator)



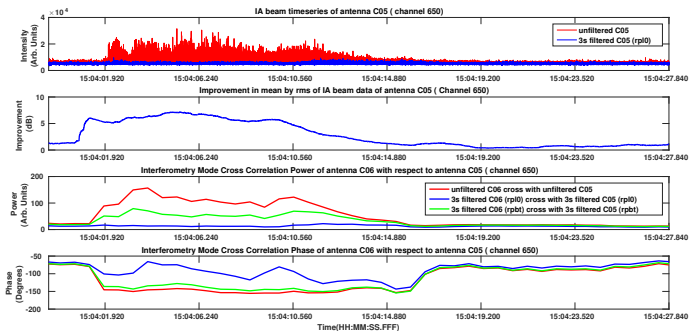
Time series of a spectral channel showing filtering (for beam and correlator outputs) at 3σ threshold computed for busy RFI : replacement with *zero*

Test results (Antenna Signal)



Time series of a spectral channel (651 MHz) showing filtering (for beam and correlator outputs) at 3σ threshold computed for isolated bursts of RFI

Test results (Antenna Signal)

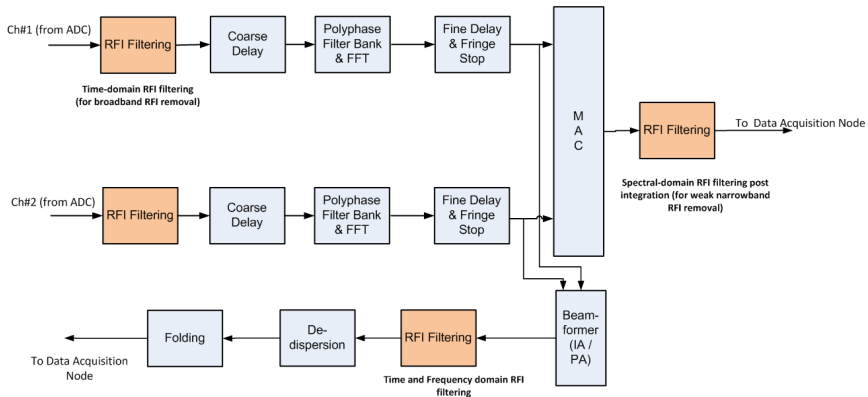


Time series of a spectral channel (651 MHz) showing filtering (for beam and correlator outputs) at 3σ threshold computed for continuous bursty RFI

Book-keeping of flagged samples

- The final number of data points filtered can be reflected in terms of weights for each visibility output
- Since the flagging would also happen earlier in the signal processing chain, this information has to be passed on to the later stages to take appropriate action (e.g. remove the block while performing FFT or MAC etc.)
- Challenge: how to carry out book-keeping when multiple types of RFI are being filtered simultaneously ?

Narrowband RFI Excision

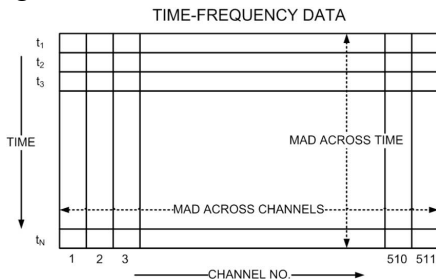


Real-time Narrowband RFI Mitigation is carried out post-integration (depending on the strength of the RFI relative to the overall noise).

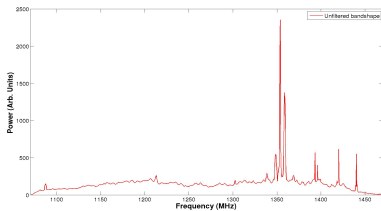
Two Approaches to Narrowband RFI Filtering

- 1 Estimation and filtering each channel over time: MAD filtering across time (MFAT)
- 2 Estimation and filtering across the spectral channels: MAD filtering across channels (MFAC)

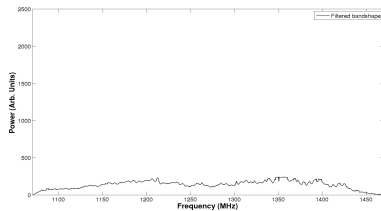
Estimation and filtering across channels is more suitable for real-time applications with additional correction required for across-the-band gain variations



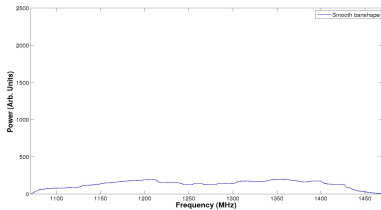
Normalization of the Spectrum



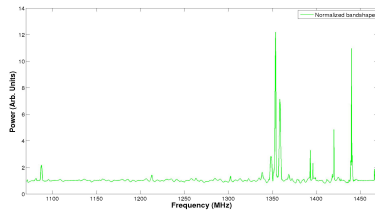
Unfiltered Spectrum



Filtered Spectrum

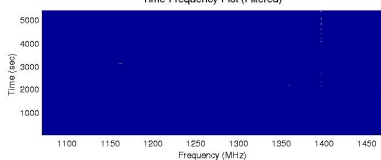
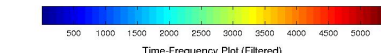
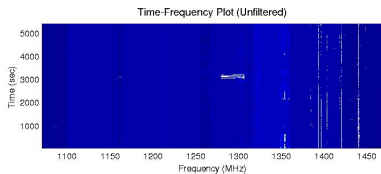
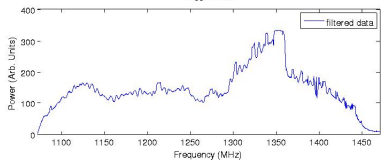
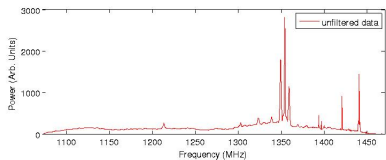


Smooth Spectrum



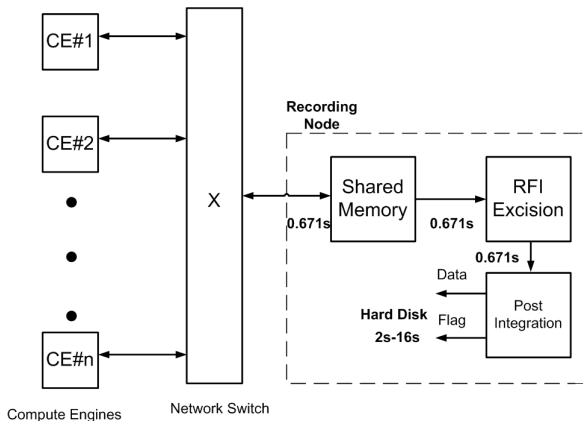
Normalized Spectrum

Narrowband RFI Excision on GWB data



Narrowband RFI filtering on recorded GMRT correlator data (L-band) 5000 s data single-antenna plot

Towards real-time implementation



RFI Excision will be carried out on auto-correlation outputs at base-integration time of the correlation (671 ms)

Summary and Future Plans

- Real-time broadband RFI excision is available for the uGMRT user community
- Various tests carried so far show an improvement of 10-12 dB in the post-filtering signal-to-noise ratio
- Long-term RFI filtering tests which are needed to understand the effect of filtering on power spectrum and cross-correlation are being carried out
- RFI Emulator designed for carrying out controlled tests for testing and fine-tuning RFI filtering designs
- Narrowband RFI mitigation demonstrated on recorded correlator output, real-time implementation in progress

Acknowledgements

- Sanjay Kudale
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Thank You!

