Implementing and Characterizing Real-time RFI Excision for the GMRT Wideband Backend

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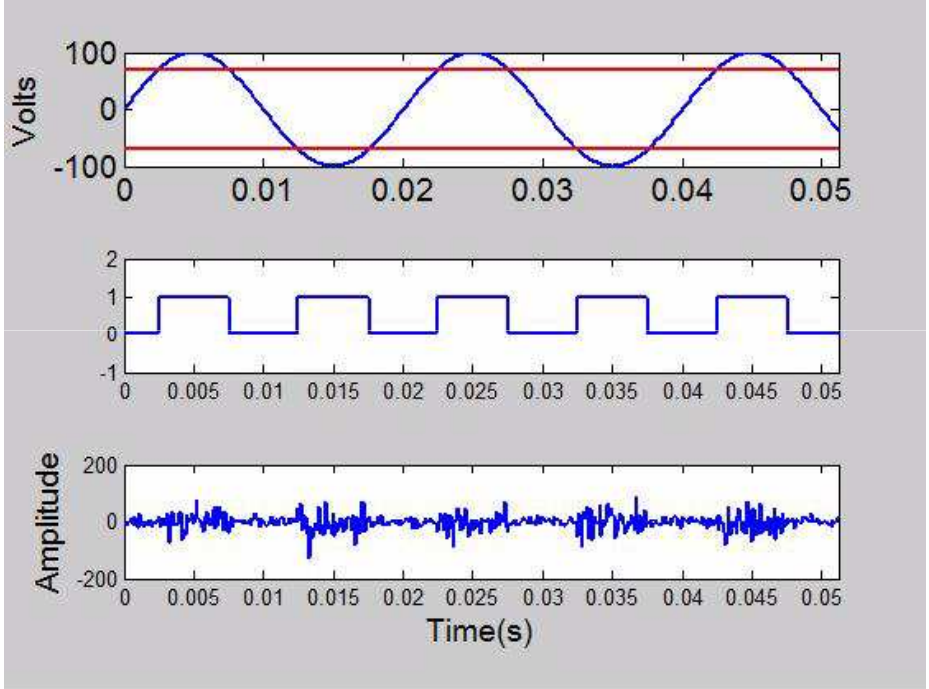
The (Upgraded) GMRT

- Giant Metrewave Radio Telescope (GMRT) is an array consisting of thirty 45m diameter parabolic reflector antennas, is a highly sensitive radio receiver system for observing astrophysical phenomena at low radio frequencies
- The upgraded GMRT (uGMRT) will provide nearly seamless frequency coverage from 50 to 1450 MHz, along with an increase in the maximum instantaneous receiver bandwidth from 32 MHz to 400 MHz
- With increased bandwidth and receiver sensitivity, the uGMRT will encounter increasing levels of man-made radio frequency interference (RFI)

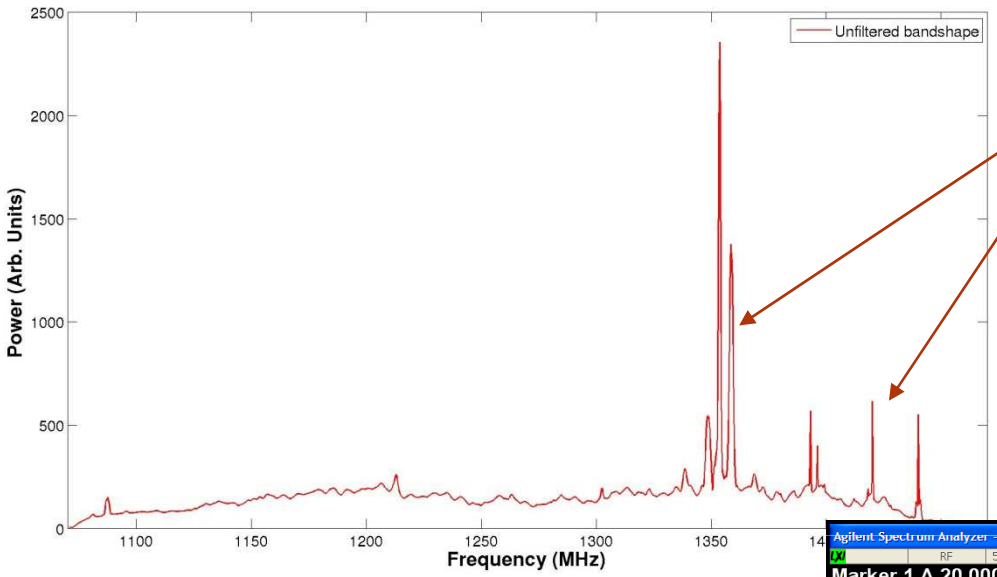
Radio Frequency Interference (RFI)

- Electromagnetic radiation from manmade (electronic/electrical equipments etc.) & natural (lightening etc.) sources
- RFI is typically 30 to 40 dB stronger than the astronomical signal
- RFI has a non-random distribution; astronomical signals have a random distribution
- RFI mitigation – very important problem (challenge) for contemporary radio telescopes



Matlab simulation showing the power-line sparking and its effects

RFI at GMRT

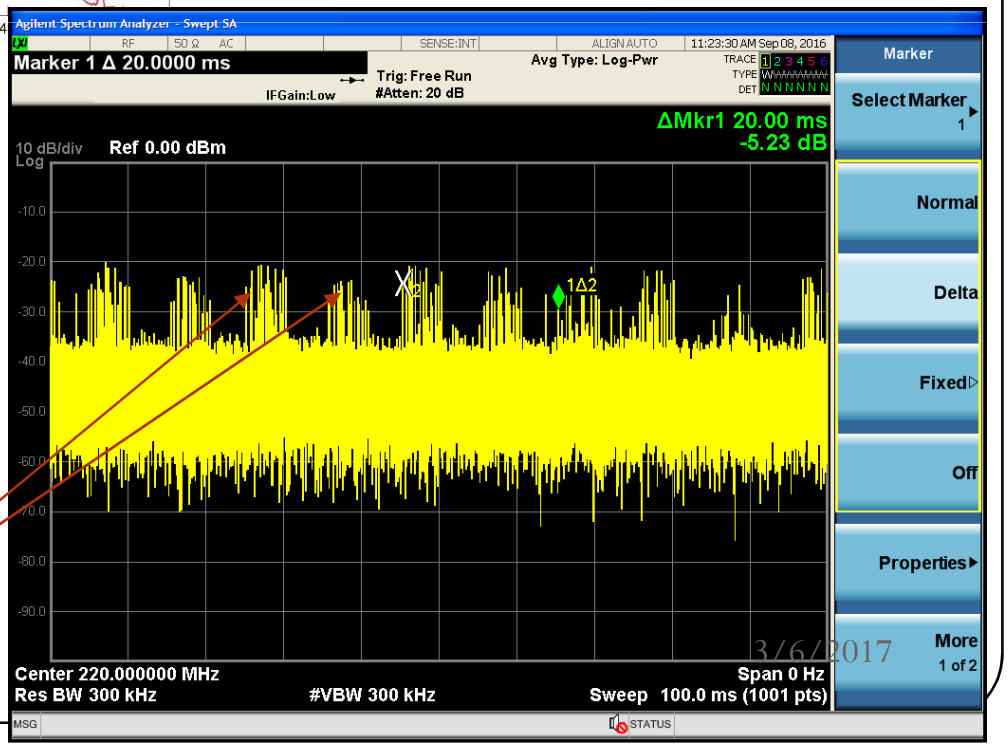


Narrowband RFI

RFI

Broadband RFI is stronger at lower radio frequencies

Broadband RFI

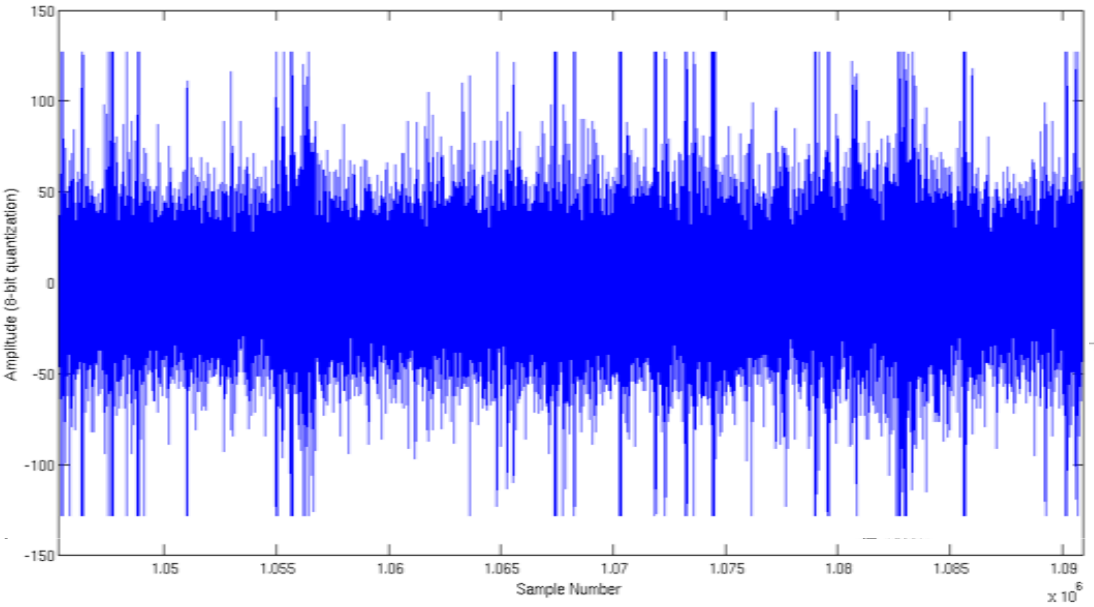


Examples showing impulsive time and frequency domain RFI observed at the GMRT

RFI is usually 30-40 dB stronger than the system noise

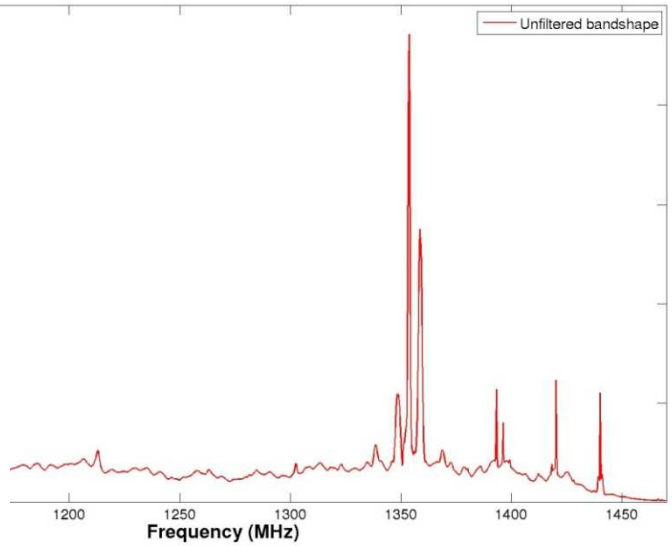
RFI

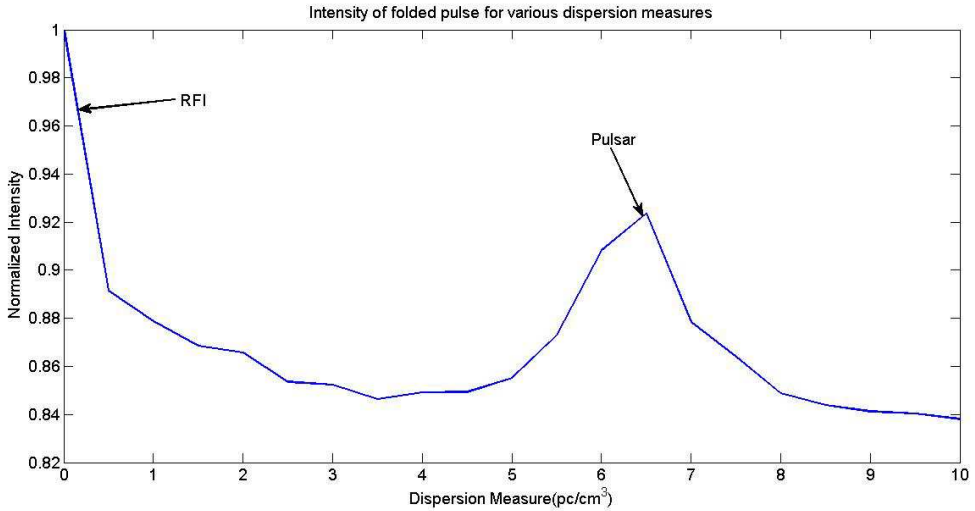
RFI Excision in three domains



Time

Frequency





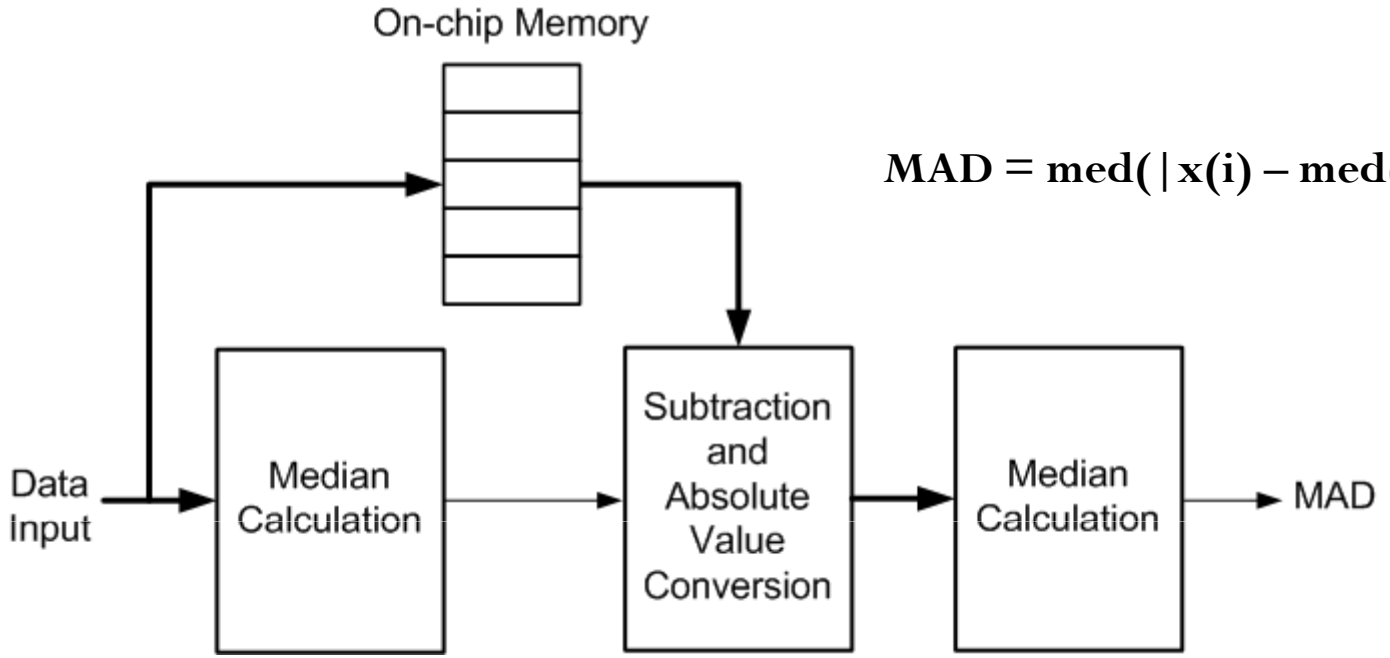
Dispersion

RFI Excision for uGMRT

- RFI in astronomical data – outliers make Gaussian distribution heavy-tailed (Fridman, 2008)
- Excision (Baan, 2001, 2010) assumes that RFI is much stronger than the astronomical signal
- Robust threshold using Median Absolute Deviation for RFI detection (Fridman, 2008) $MAD = med(|x(i) - med(x)|)$
- Excision by replacing the RFI affected samples by constant value or noise or threshold Robust threshold: median $\pm n^{*}\sigma_{MAD}$
    - Implemented in temporal and spectral domains

Buch et. al, "Towards Real-time Impulsive RFI Mitigation for Radio Telescopes", JAI Special Issue, 2017 http://www.worldscientific.com/doi/abs/10.1142/S225117171641018X
Buch et. al, "Real-time RFI excision for the GMRT wideband correlator", RFI-2016 conference proceedings, 2016 http://ieeexplore.ieee.org/abstract/document/7833523/

Real-time Implementation



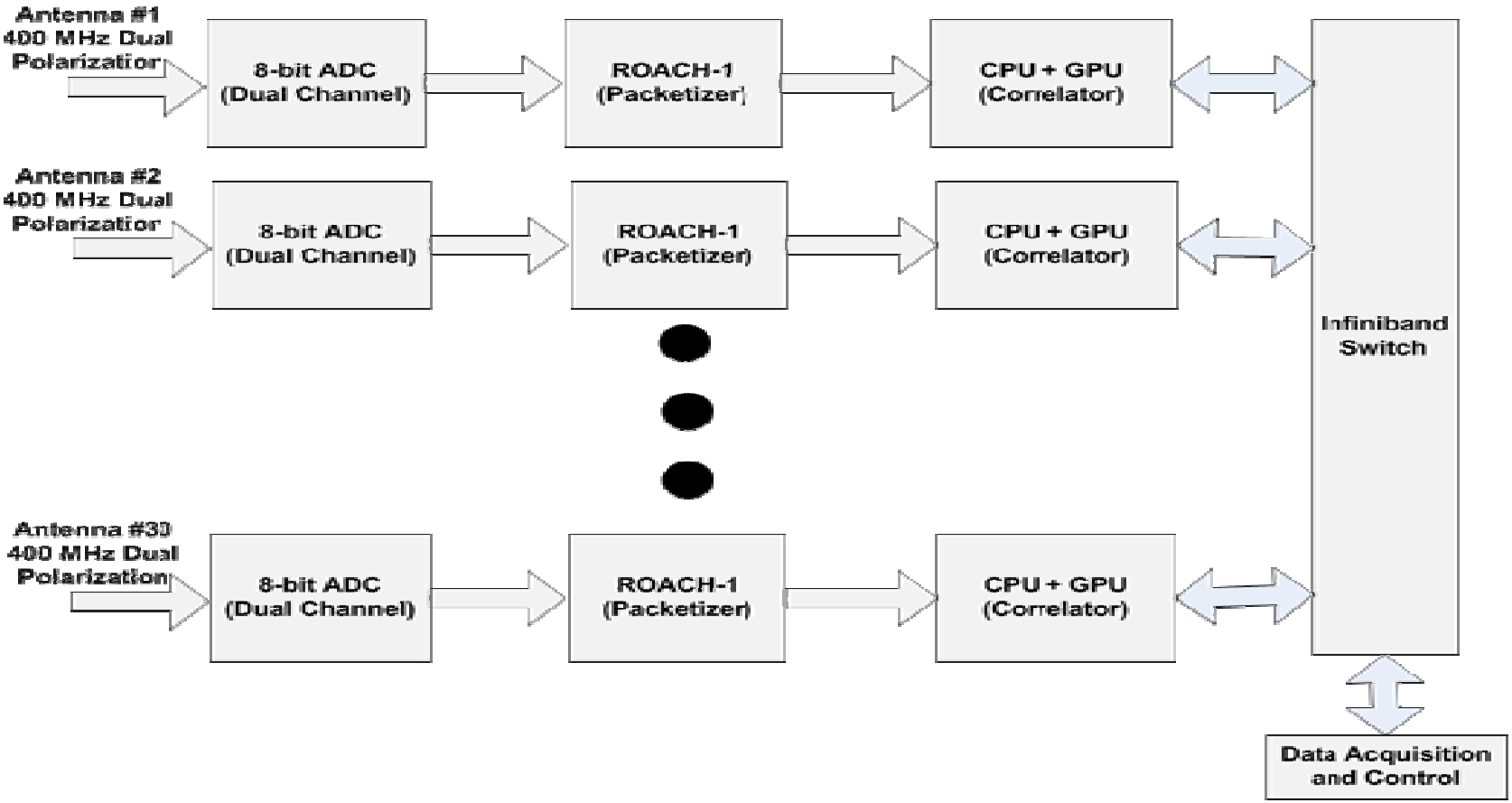
- Uses the histogram method for median computation – explores parallelism on FPGA
- Window size is $2*(T_R/TS)$ samples where T_R is the (worst case) duration of RFI and T_S is the sampling interval

Long-lasting RFI:

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

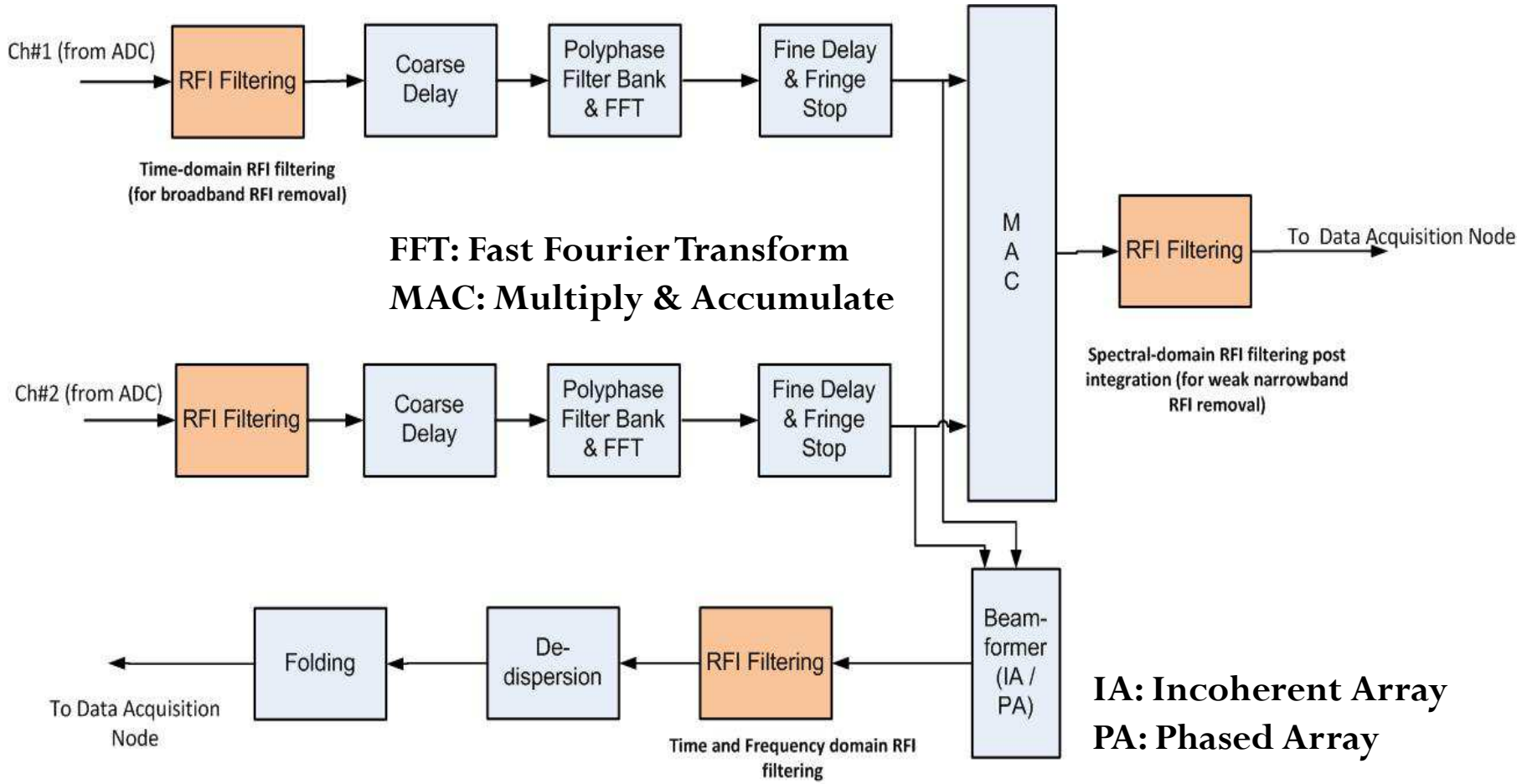
$$M_m = M(MAD_1, MAD_2, \ldots, MAD_n)$$

GMRT Wideband Digital Backend

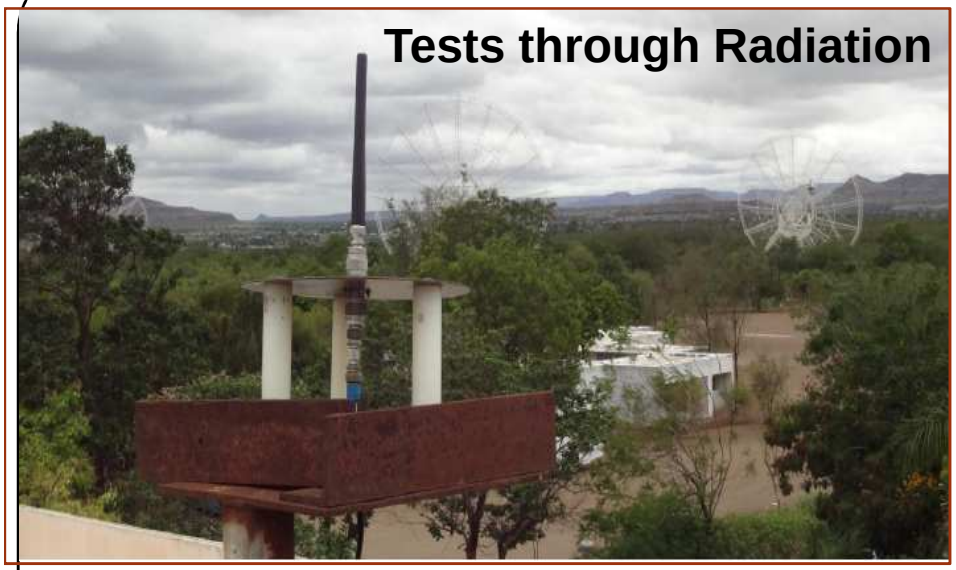


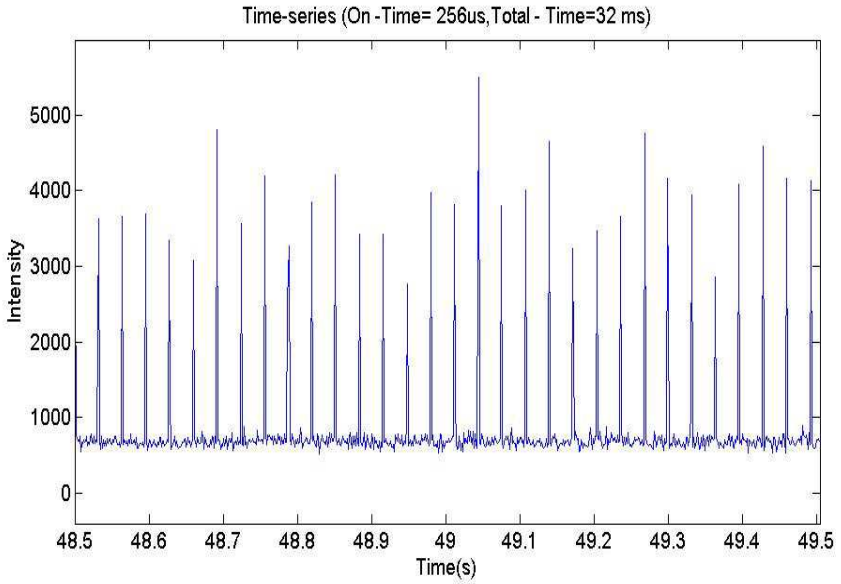
Real-time broadband RFI Mitigation is implemented on ROACH-1 FPGA board

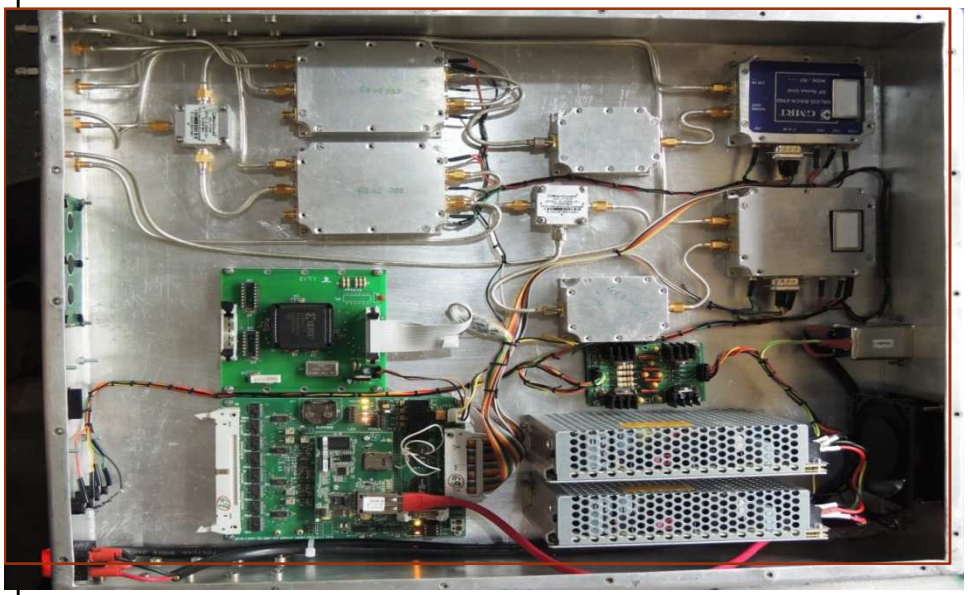
RFI Mitigation in GMRT Wideband Backend

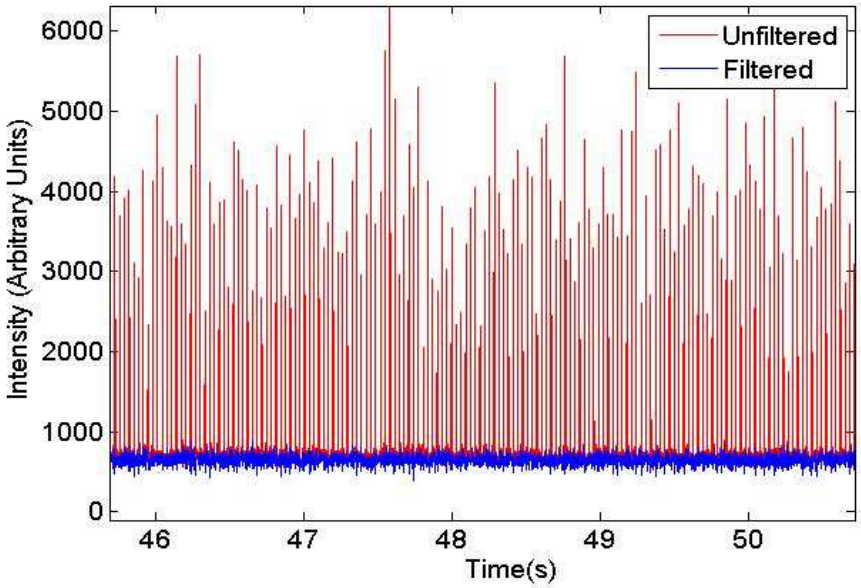


- Requires implementation at multiple locations in the processing chain to remove diverse types of RFI
- Broadband RFI filtering is carried out in real-time on Nyquist-sampled digital time-series (for each antenna) at 800 MHz



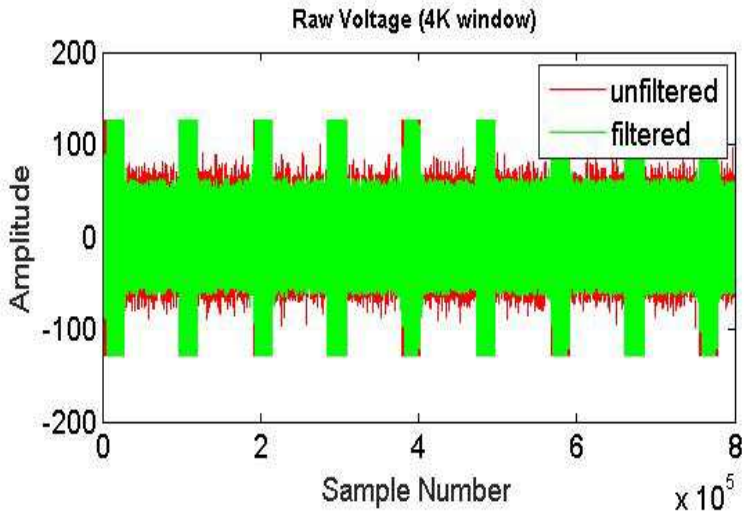


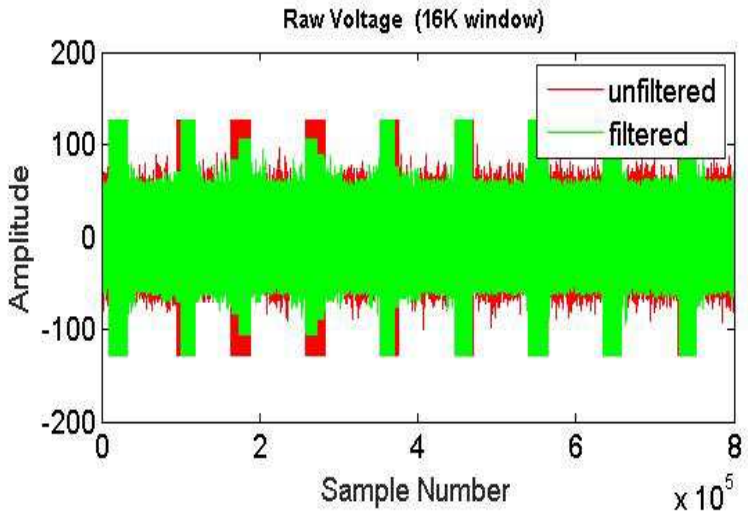


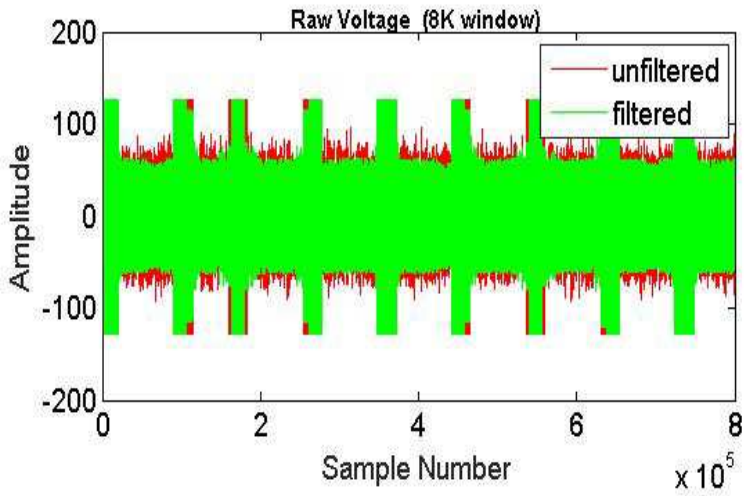


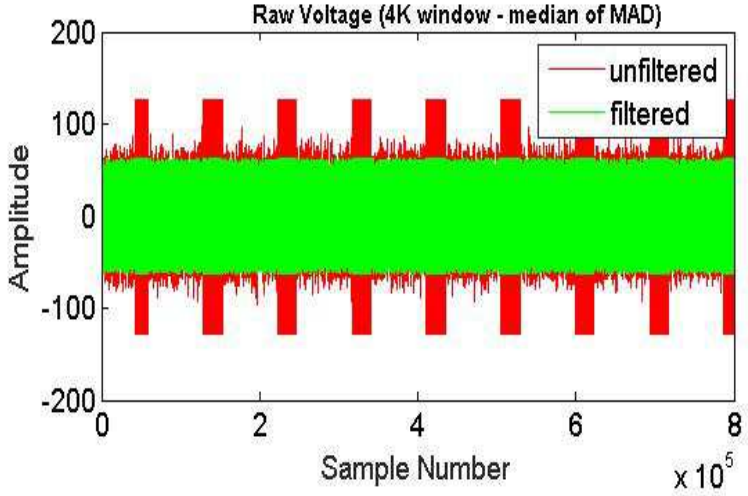
RFI Emulator unit

RFI filtering in time-domain

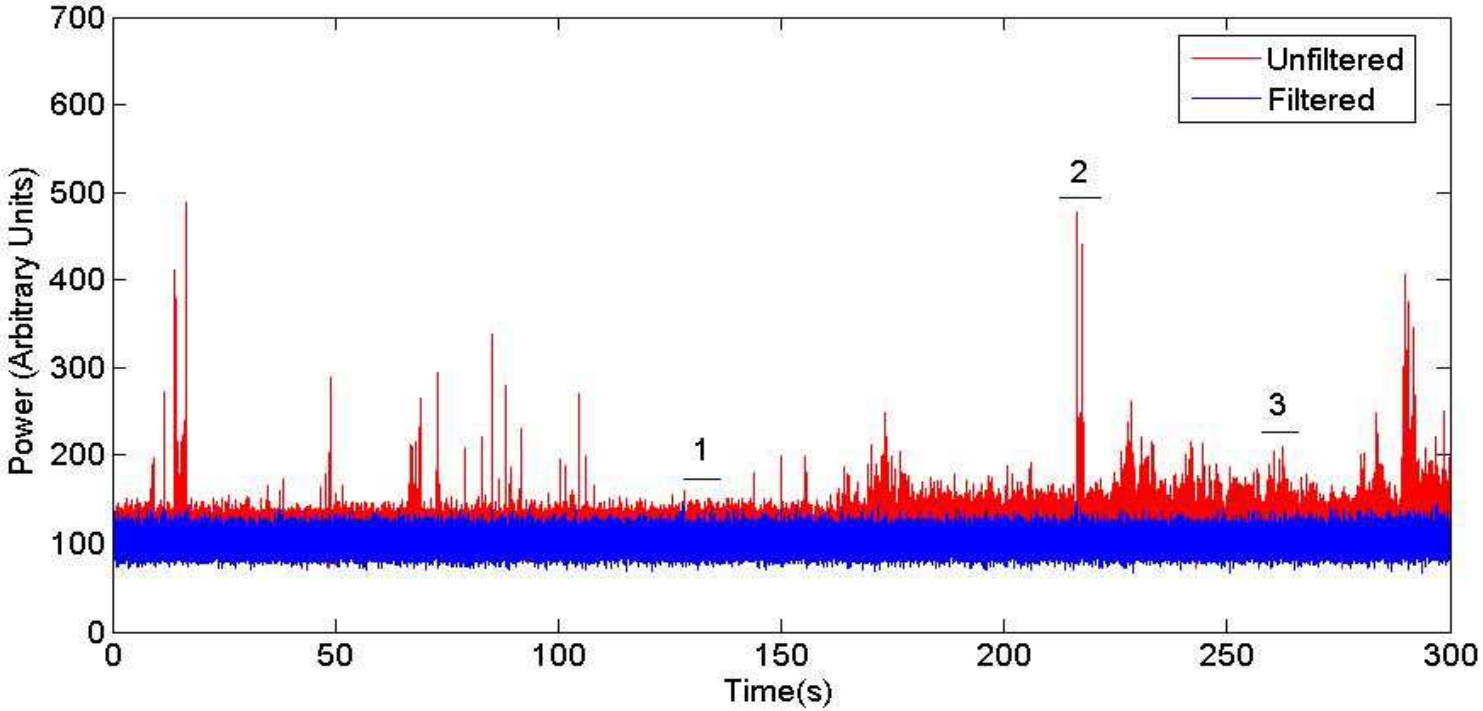








Quantitative Metric for filtering



Parameter	Unfiltered Output			Filtered Output		
	Region 1	Region 2	Region 3	Region 1	Region 2	Region 3
Mean / RMS ratio	10.89934	4.7044	8.5987	11.9863	11.9689	10.9659

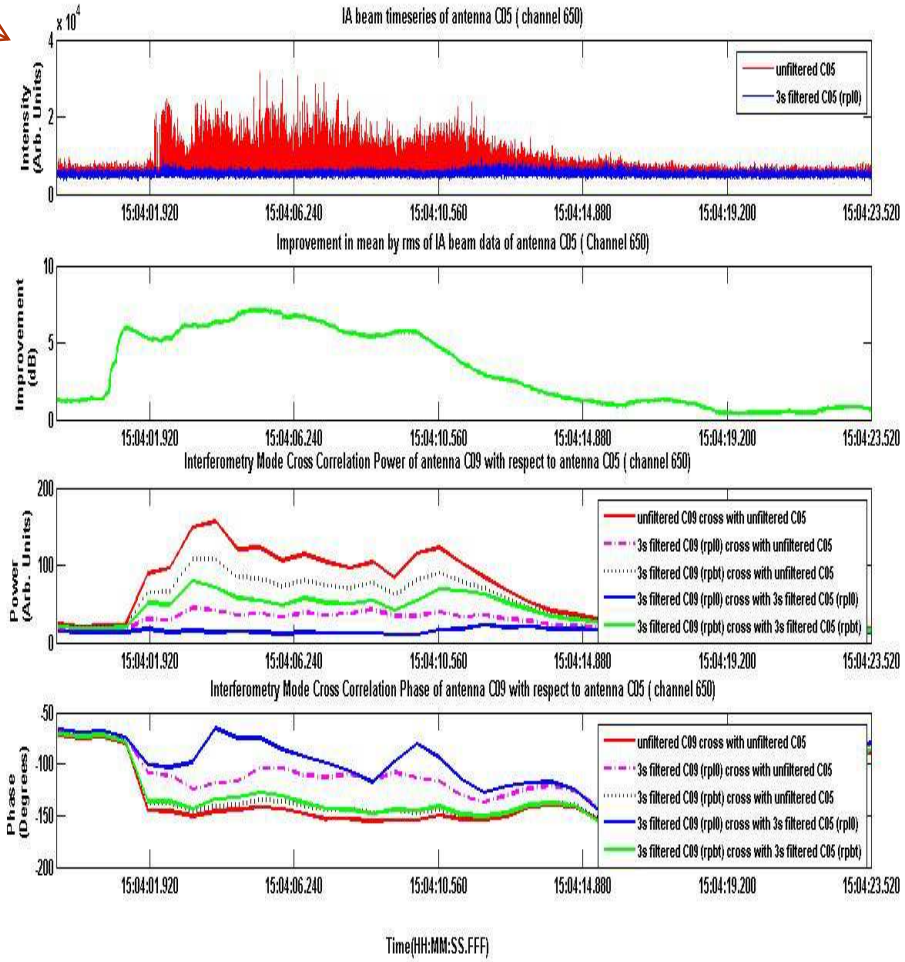
Theoretical: √(B*T) =√ ((200e6/2048)*1.31ms) = 11.31

Test Results

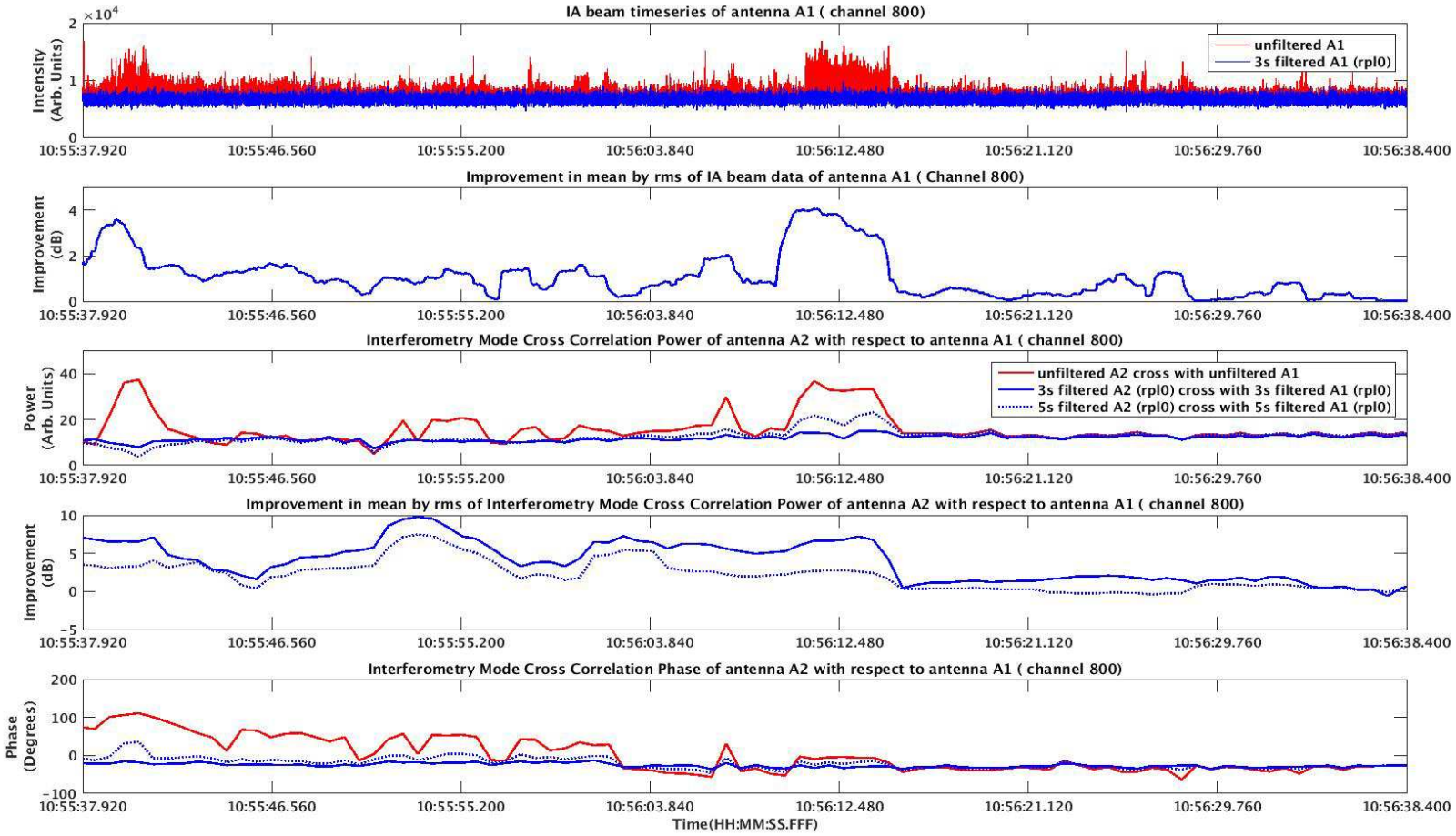
- **Single spectral channel plot over time (IA mode) from the GWB at 1.3 ms time resolution for filtered and unfiltered outputs**
- **Improvement (dB)**

  I = 10log(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 IA beam output
- **Cross-correlation magnitude (unnormalized) and phase – options – filtered vs filtered, filtered vs unfiltered and unfiltered vs unfiltered**



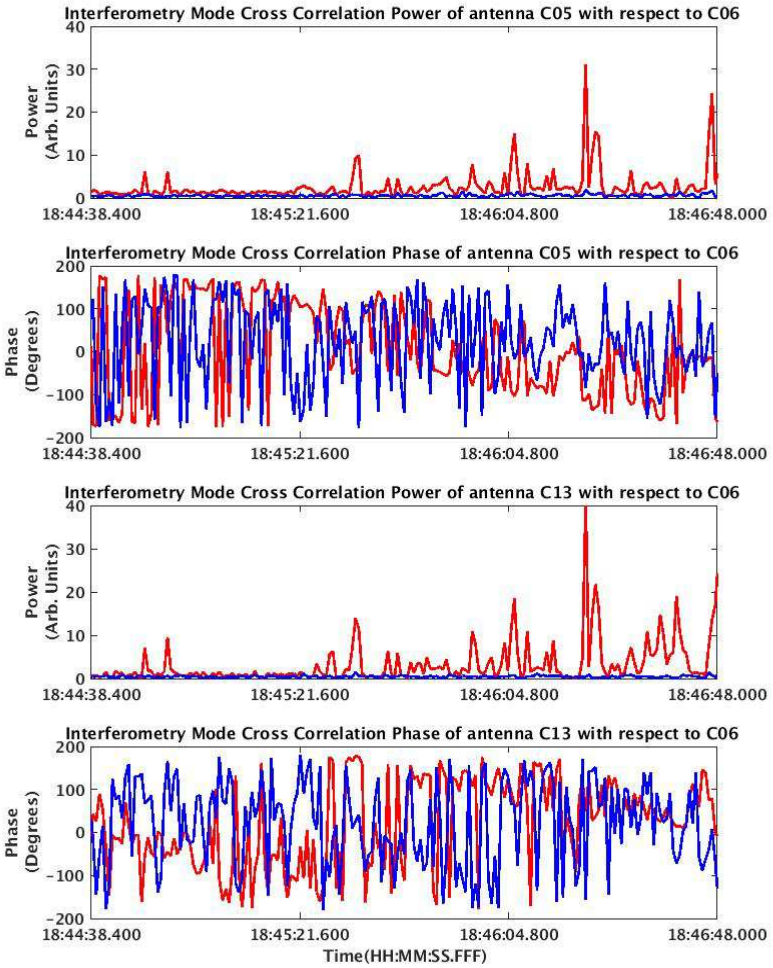
Test Results from GWB



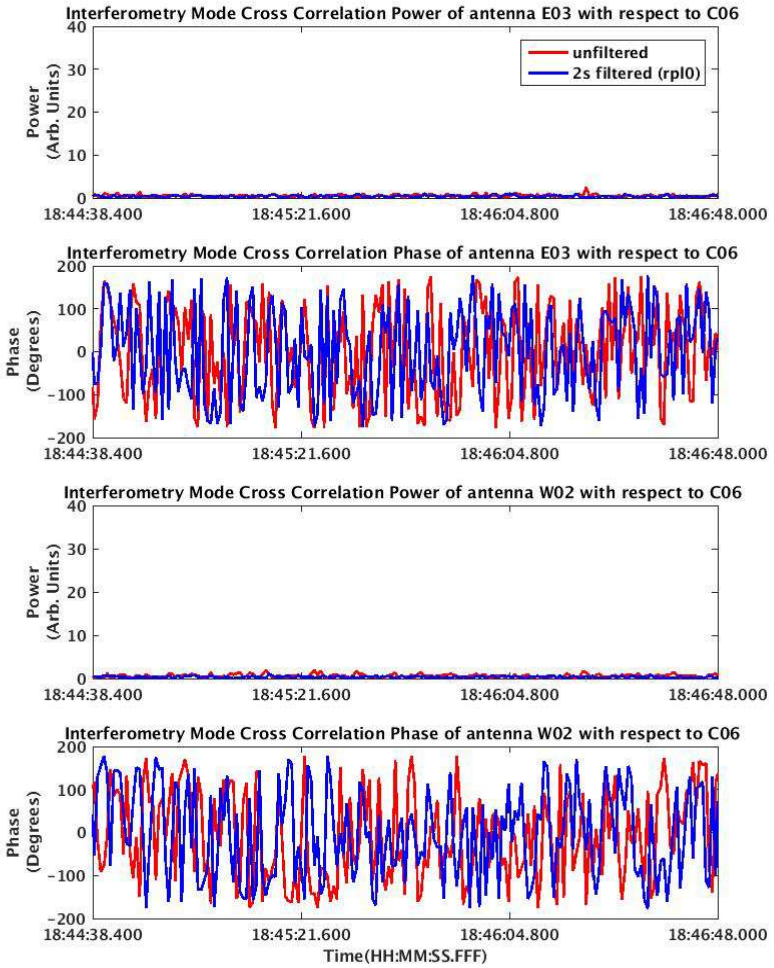
Simultaneous Recording of beam mode (1.3 ms) and interferometry mode (0.6 ms). RFI outside 3 sigma threshold is replaced with zeros.

Off-source tests (250-500 MHz)

Shorter Baselines (magnitude and phase)



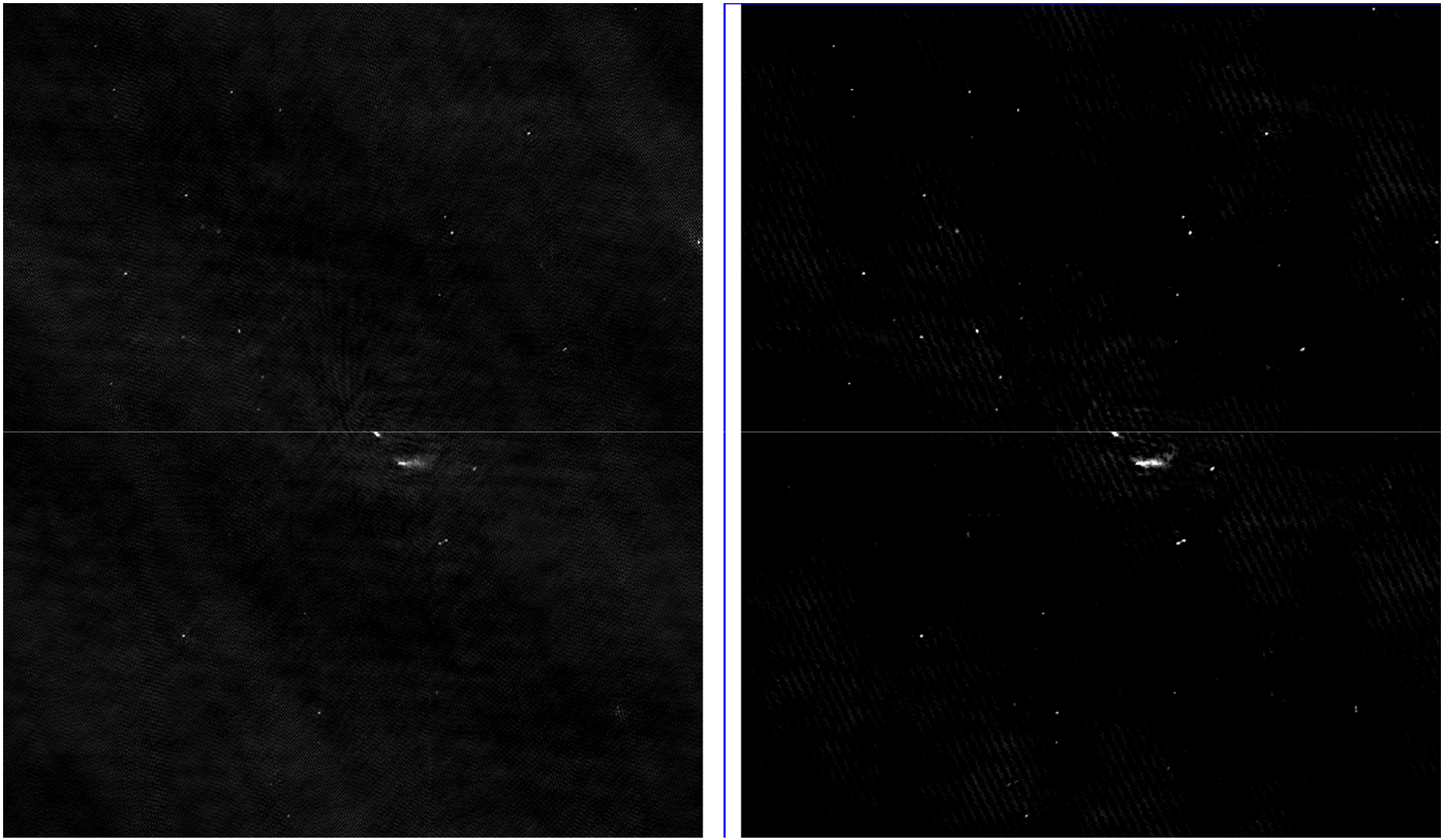
Longer Baselines (Magnitude and phase)



5 degrees off-source, shows correlated RFI, Filtering at 2 sigma threshold (replaced by zero), unfiltered in red color, filtered in blue color

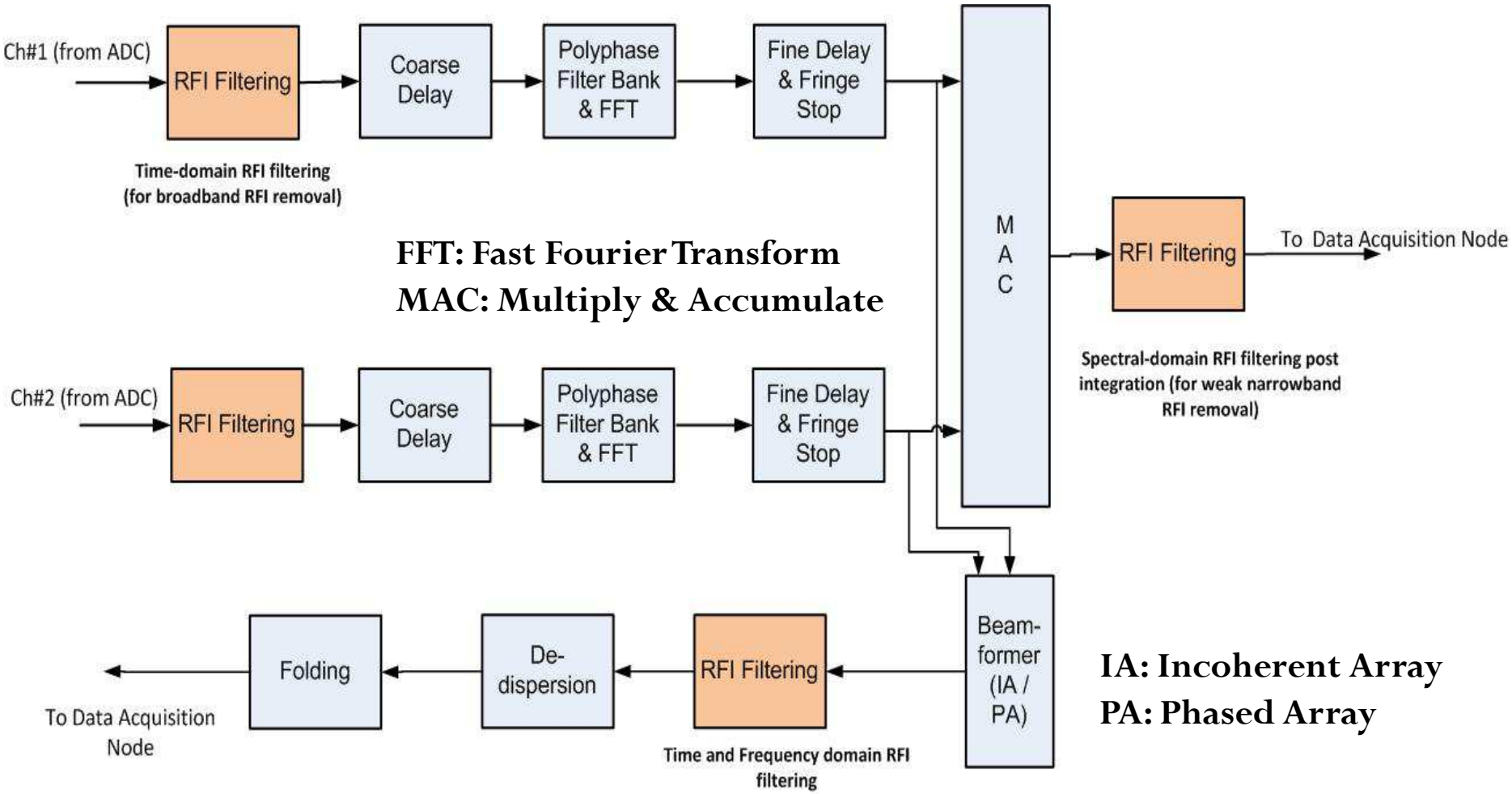
First Image

Image Courtesy: Dharam Vir Lal



250-500 MHz, 16 antennas, Pol.-1 (left, without filter) & Pol.-2 (right, with broadband RFI filter), factor of two improvement post-filtering

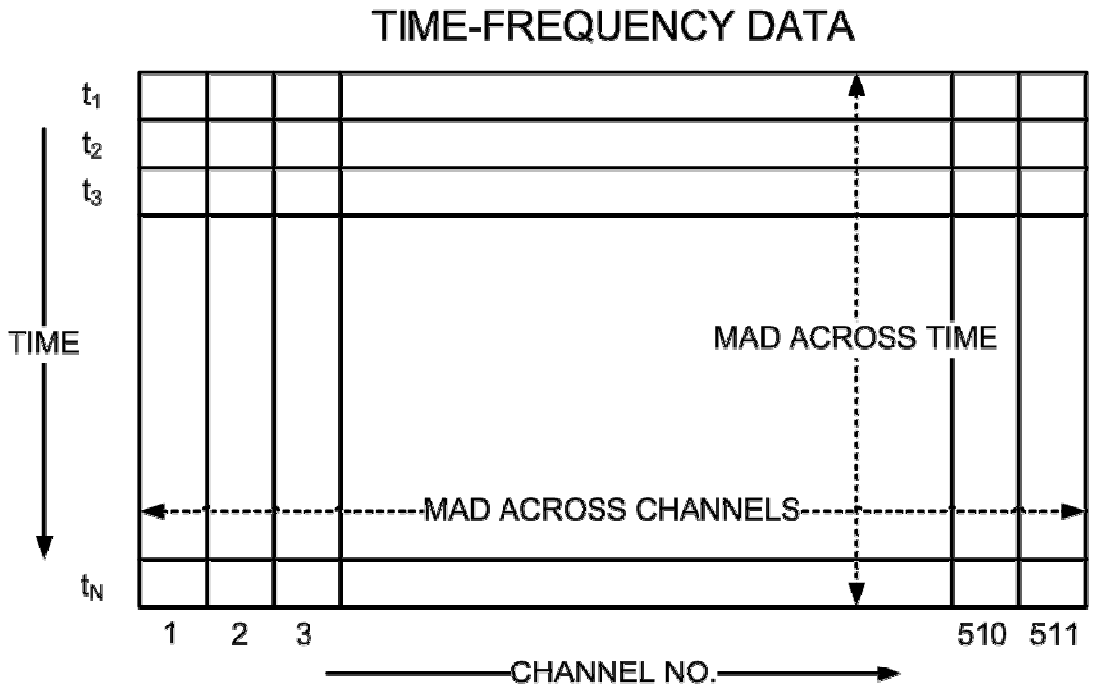
Spectral Domain RFI Filtering



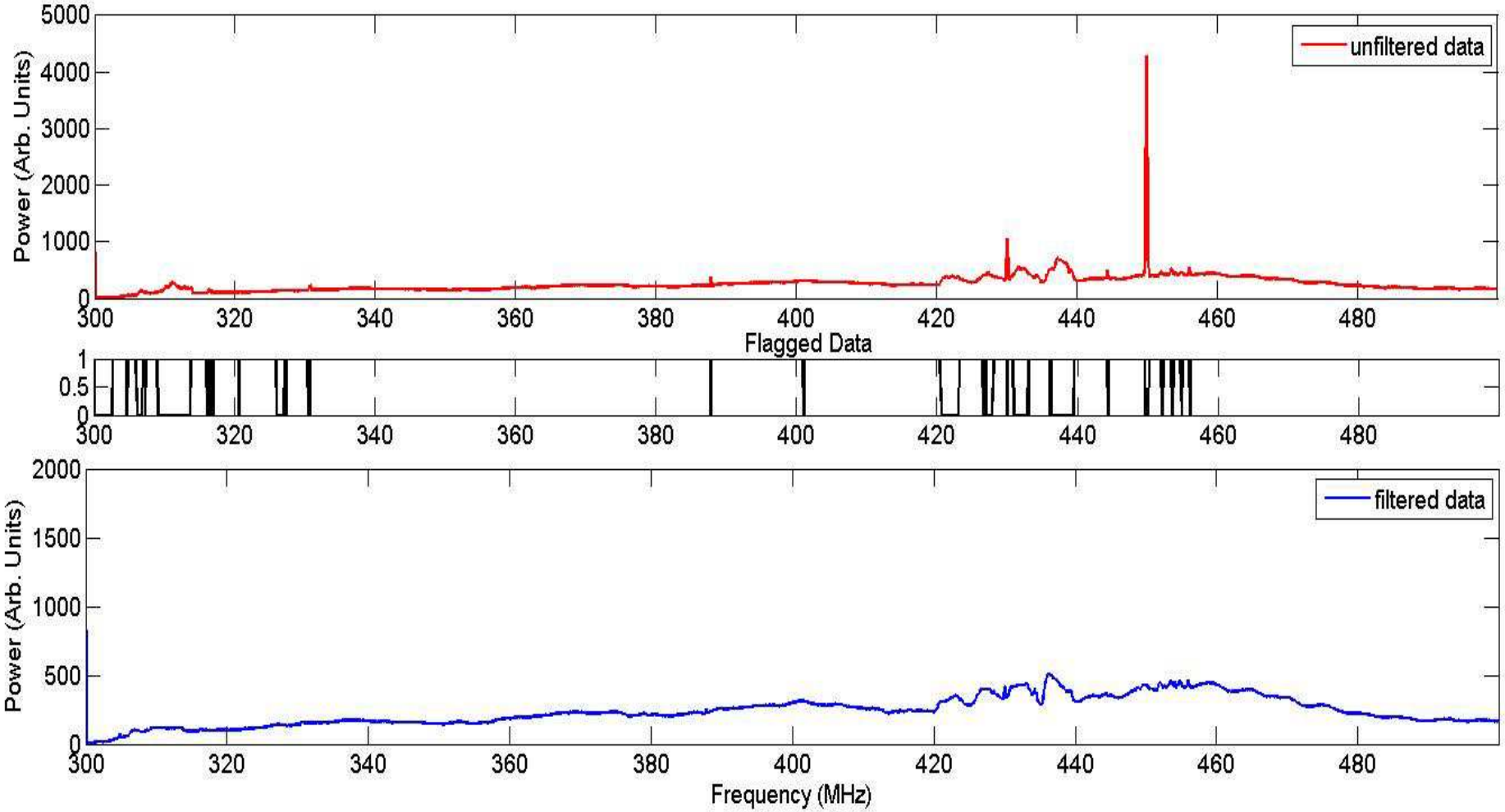
Real-time Narrowband RFI Mitigation is carried out post-integration at 0.671s integration on visibilities

Two Approaches to Spectral RFI filtering

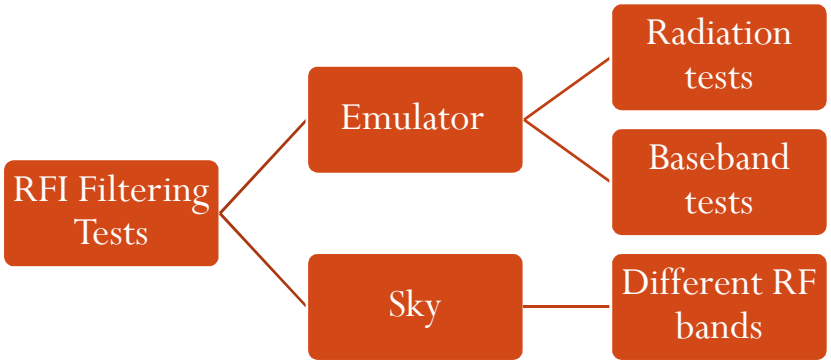
- Two approaches to Spectral MAD filtering – 1. Estimation and filtering each channel over time (MFAT) and 2. Estimation and filtering across the spectral channels (MFAC)
- Estimation and filtering across channel is more suitable for real time applications – with additional correction required for across the band gain variations.



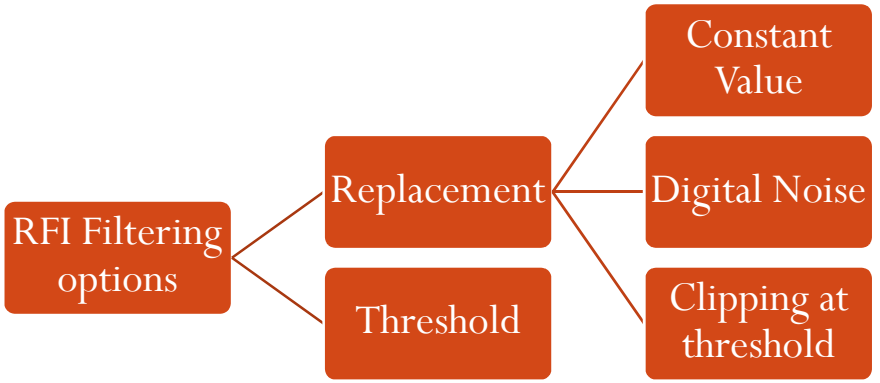
Narrowband RFI filtering (250-500 MHz)



Test Strategy: Characterization



Regular tests



Long-term tests

Current Status & Plans

- Long-term experiments show about 10-12 dB improvement in signal-to-noise ratio; work going on to find the best sample replacement strategy for filtering
- Broadband RFI filtering – released and available for testing for uGMRT observations
- Facility to keep track of flagged samples (broadband RFI filtering) – March 2017
- Real-time narrowband RFI filtering along with weights per spectral channel for each visibility output – April 2017

Antenna	Timestamps	Total Count	Flag Count
C09	Mon 06-02-17 10:36:43:034387 IST	400000000	200000000
C09	Mon 06-02-17 10:36:43:054802 IST	0	0
C09	Mon 06-02-17 10:36:43:075124 IST	2458736	1762648
C09	Mon 06-02-17 10:36:48:668962 IST	400000000	200000000

Example window showing the total count and flag count for a particular antenna at a given time instance (zero in the count indicates a 'reset' to the counter)

Acknowledgements

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GMRT Backend Team

GMRT Control Room and Operations Group

NCRA Astronomers

GMRT Telemetry Group

Short-term Engineering Interns

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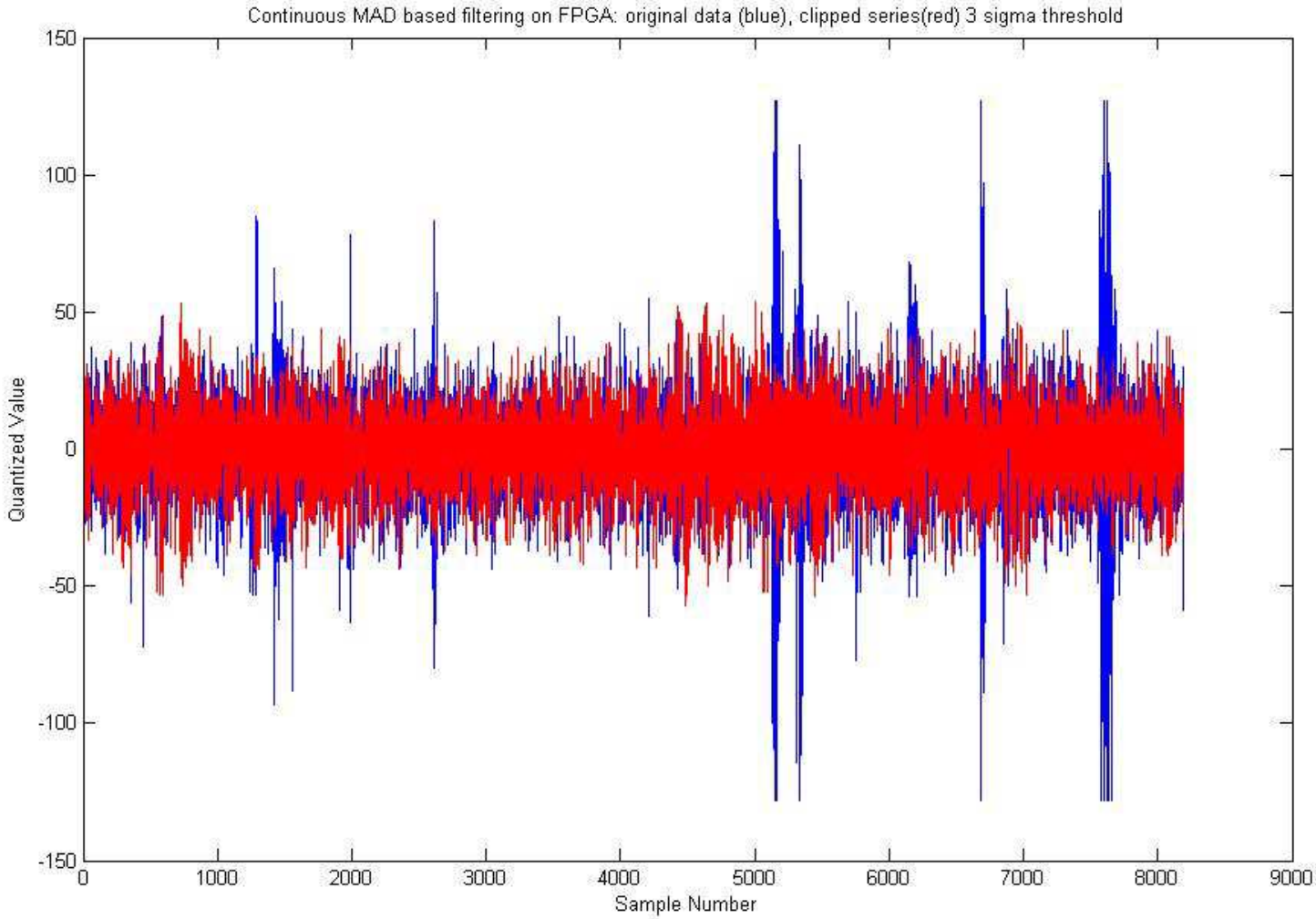
Thank You!
For queries, suggestions or comments, email:
kdbuch@gmrt.ncra.tifr.res.in

Effects of RFI

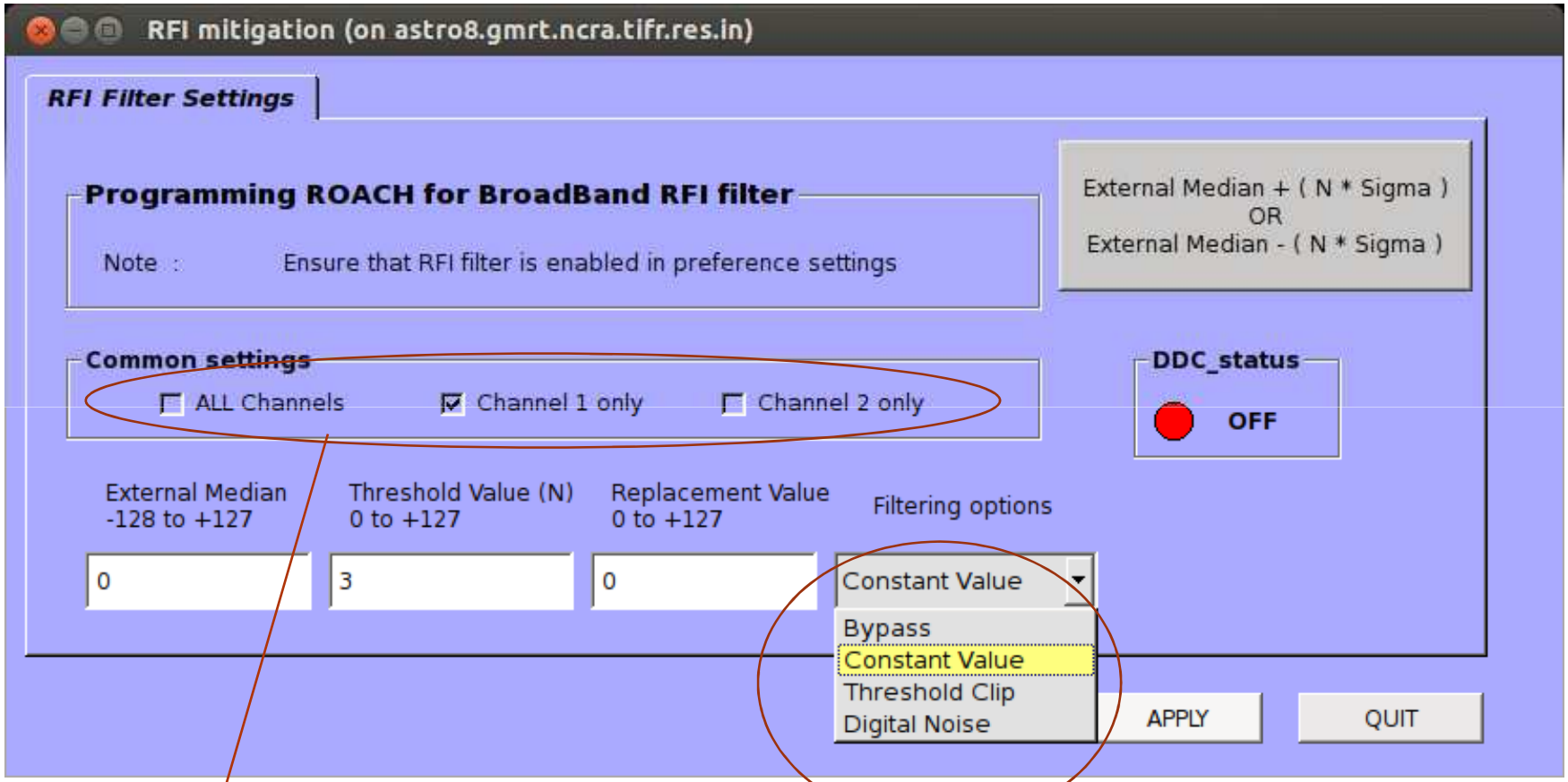
- Presence of RFI
  - Signal fluctuations do not integrate down as $t^{-0.5}$ upon temporal averaging
  - Leads to reduced signal to noise ratio (SNR) and sensitivity
- Strong narrowband RFI lines
  - Produces harmonics
  - Pronounced effects due to spectral leakage
    - Increased side-lobe levels
    - Reduced dynamic range
- Limits detection and analyses of weak radio sources, temporal events and transients

Time-series from Antenna Tests



GMRT 150MHz time series with RFI (blue) and 3σ filtered time series (red)

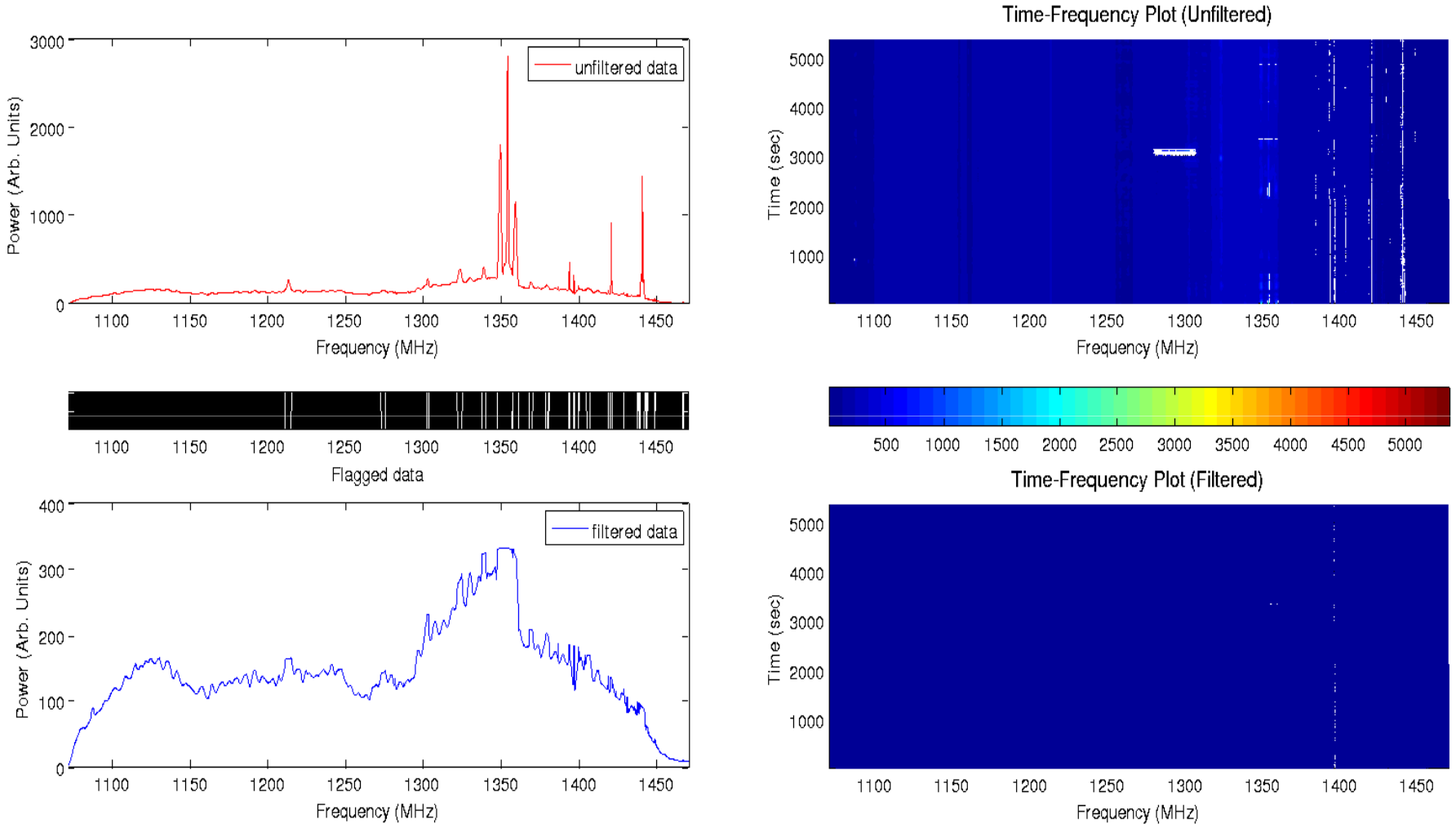
Real-time RFI Filtering: Features



Can filter one or both polarizations

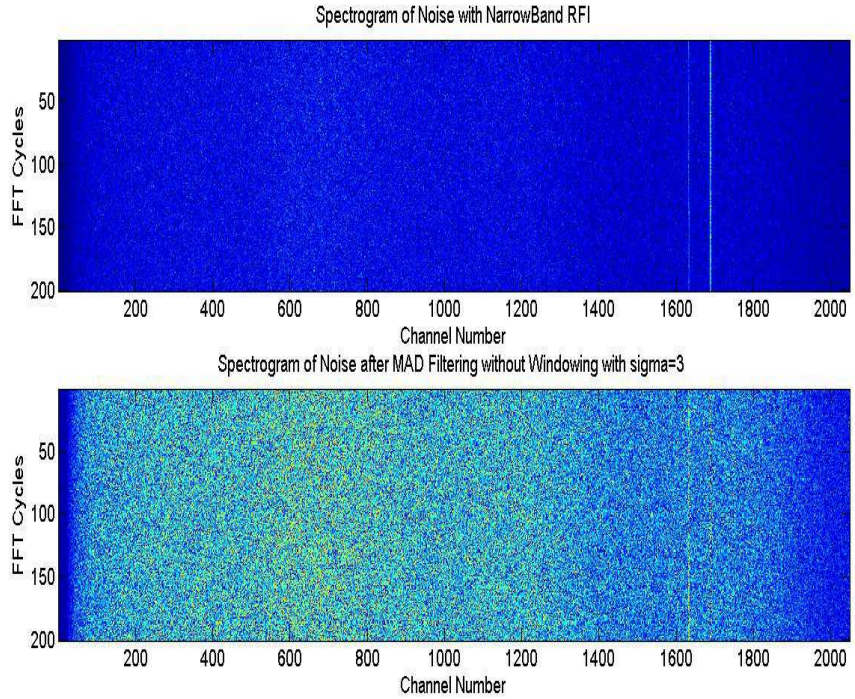
Includes option to bypass the filter

Narrowband filtering on GWB data

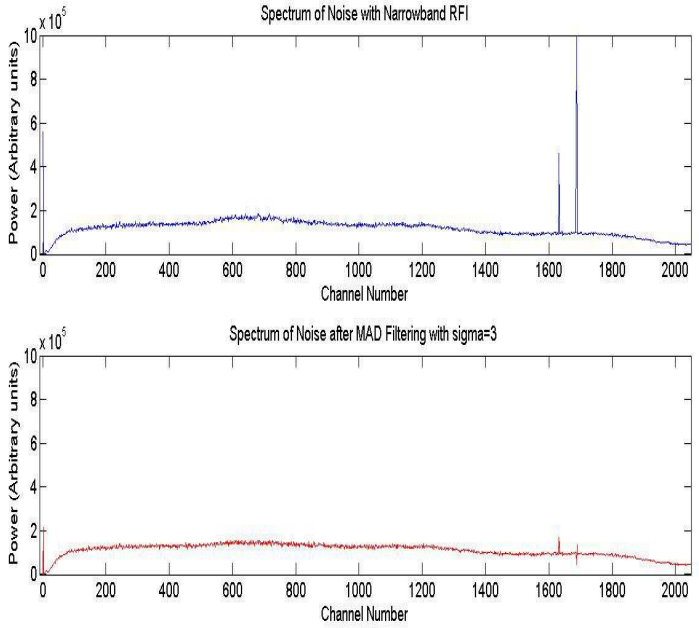


Narrowband RFI filtering on GWB-3 recorded data (L-band)
5000 s data single-antenna plot

Spectral RFI – across channel filtering



Two distinct interference lines (from broadcast TV transmission) removed using across the MFAC filtering ~ 8-10 dB improvement in the SNR.

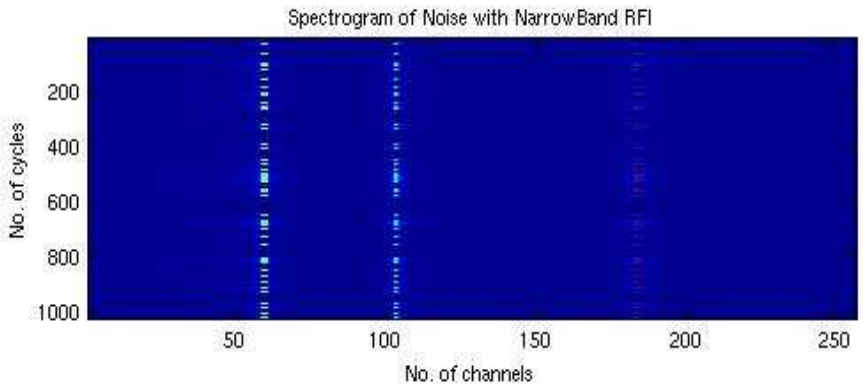


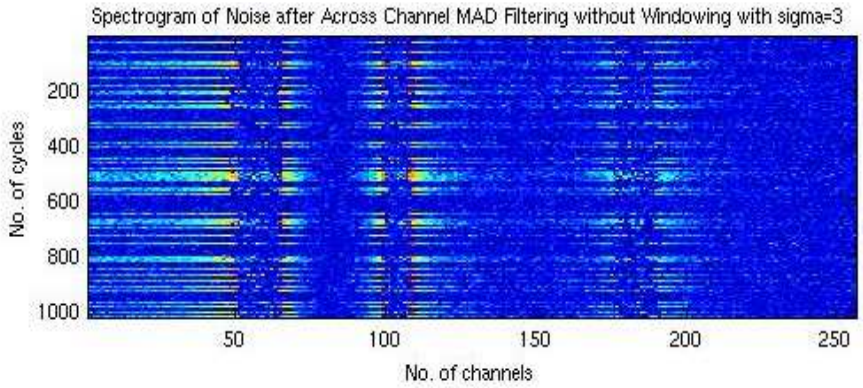
GWB Spectrum Output – Pre & Post RFI filtering
RF: 250-500 MHz, BW: 200 MHz

Removes Strong Persistent RFI
Dependence on the signal bandshape

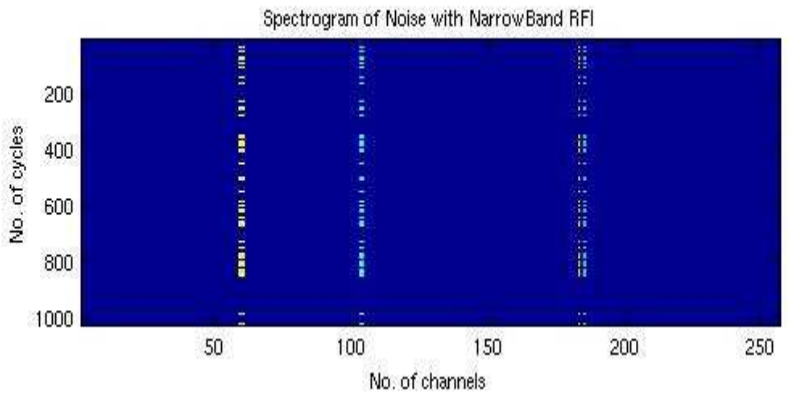
Spectral RFI – across channel filtering

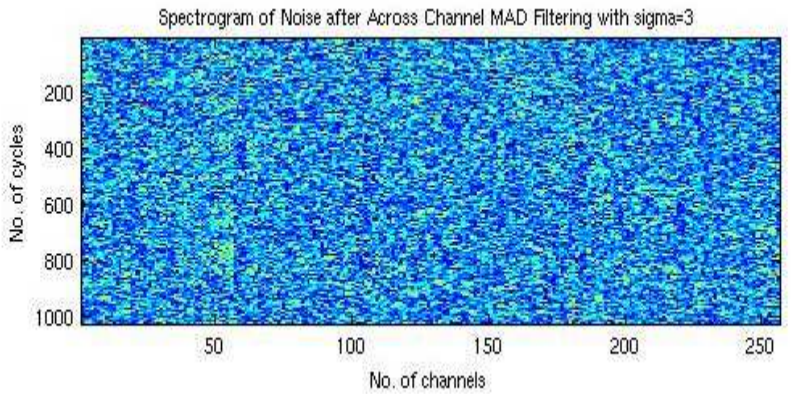
Without windowing





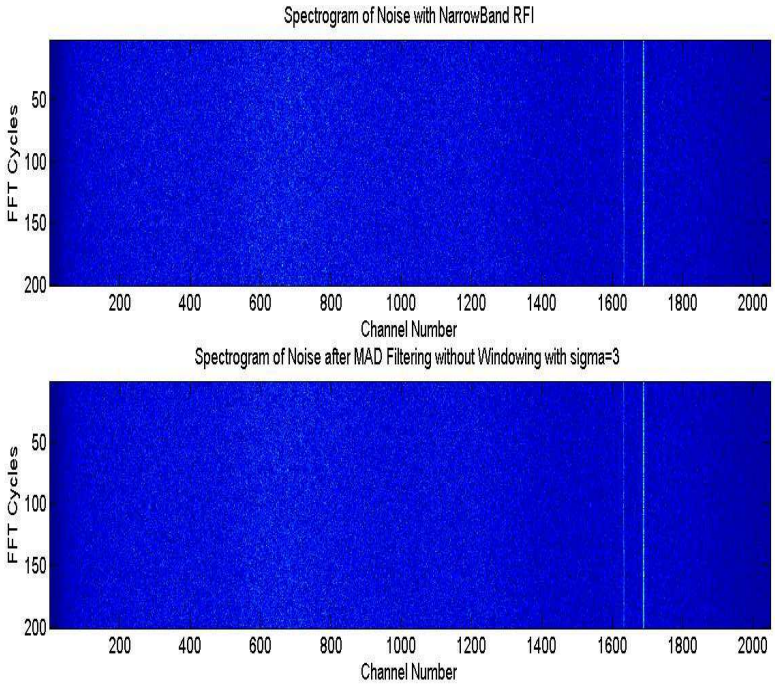
With windowing



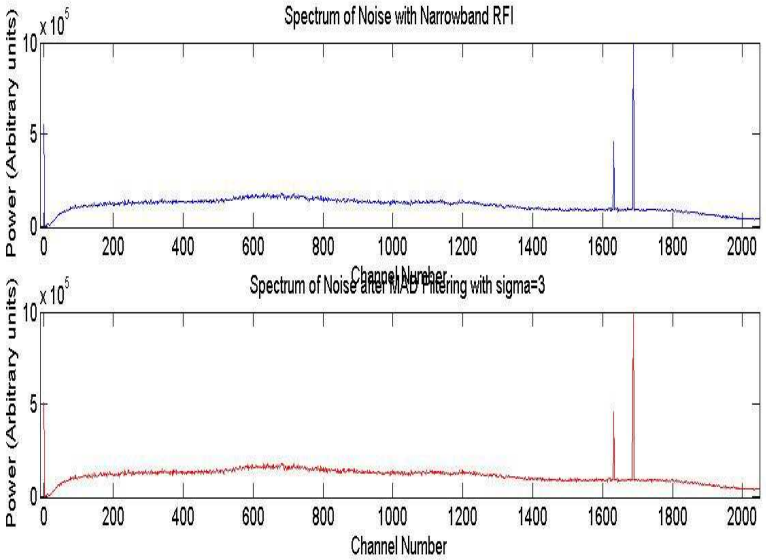


- Windowing reduces spectral leakage – prevents strong narrowband RFI to leak into adjacent channels.
- Filtering on windowed data gives better results !

Spectral RFI – channel over time filtering



Two distinct interference lines (from broadcast TV transmission) present constantly –not removed using MFAT filtering

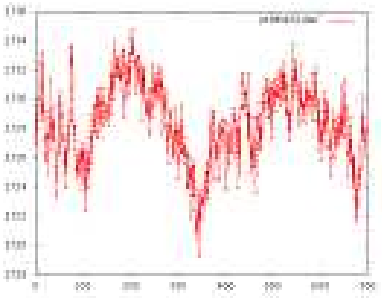


GWB Spectrum Output – Pre & Post RFI filtering
RF: 250-500 MHz; BW: 200 MHz

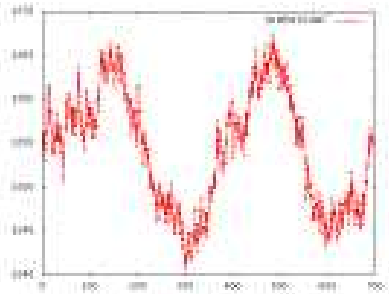
Independent of the signal bandshape
Removes Strong Bursty Narrowband RFI

Results

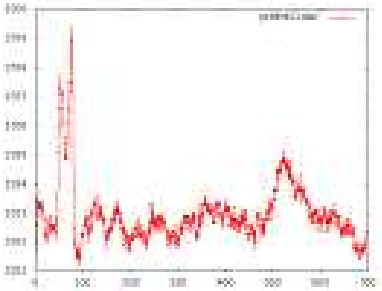
- Pulsar J1652+2651
- GWB 250-500 MHz; 2048 spectral channels; 1.3 ms integration time
- Spectral and temporal filtering applied to spectral time-series



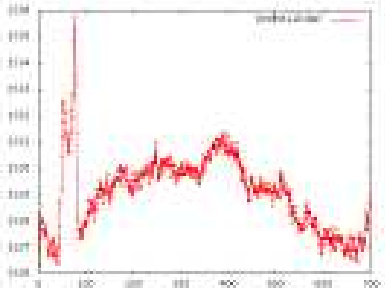
(a) Unfiltered profile



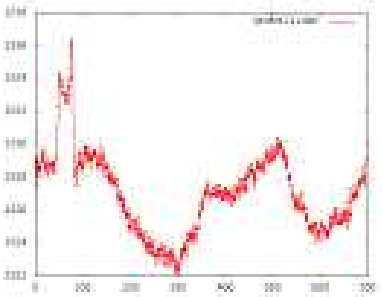
(b) Only time filters applied.



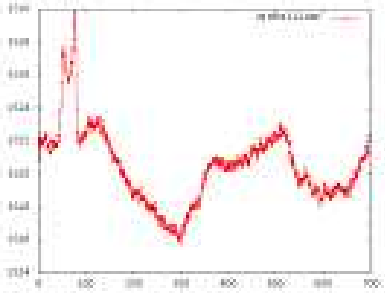
(c) Only channel filters applied.The peak is visible.



(d) Channel and time filters, channel applied first.The baseline is cleaner than (b) and (c)

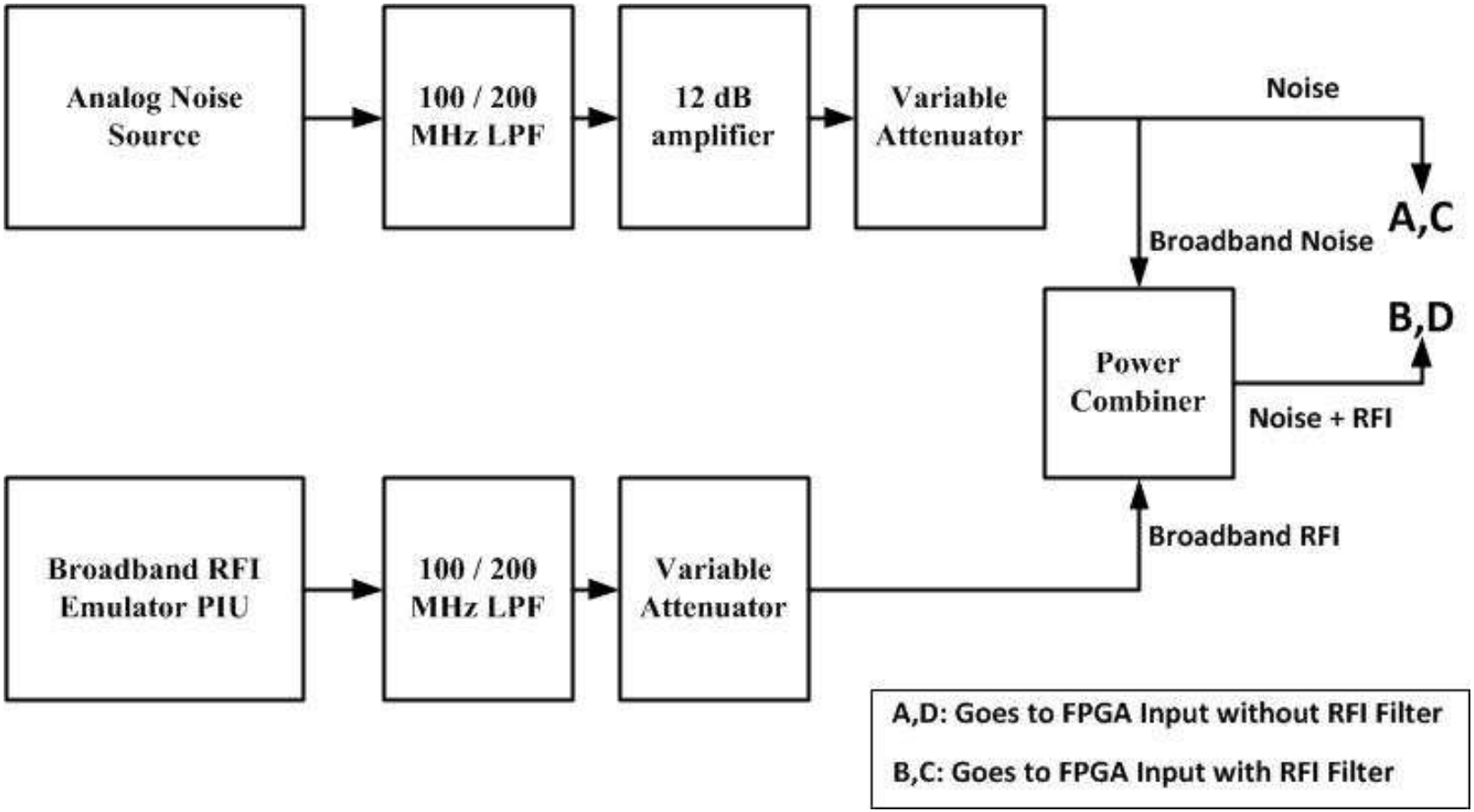


(e) Channel and time filters, time applied first



(f) Channel and time filters, independent of each other. Not much different from (b)

Plans for further testing

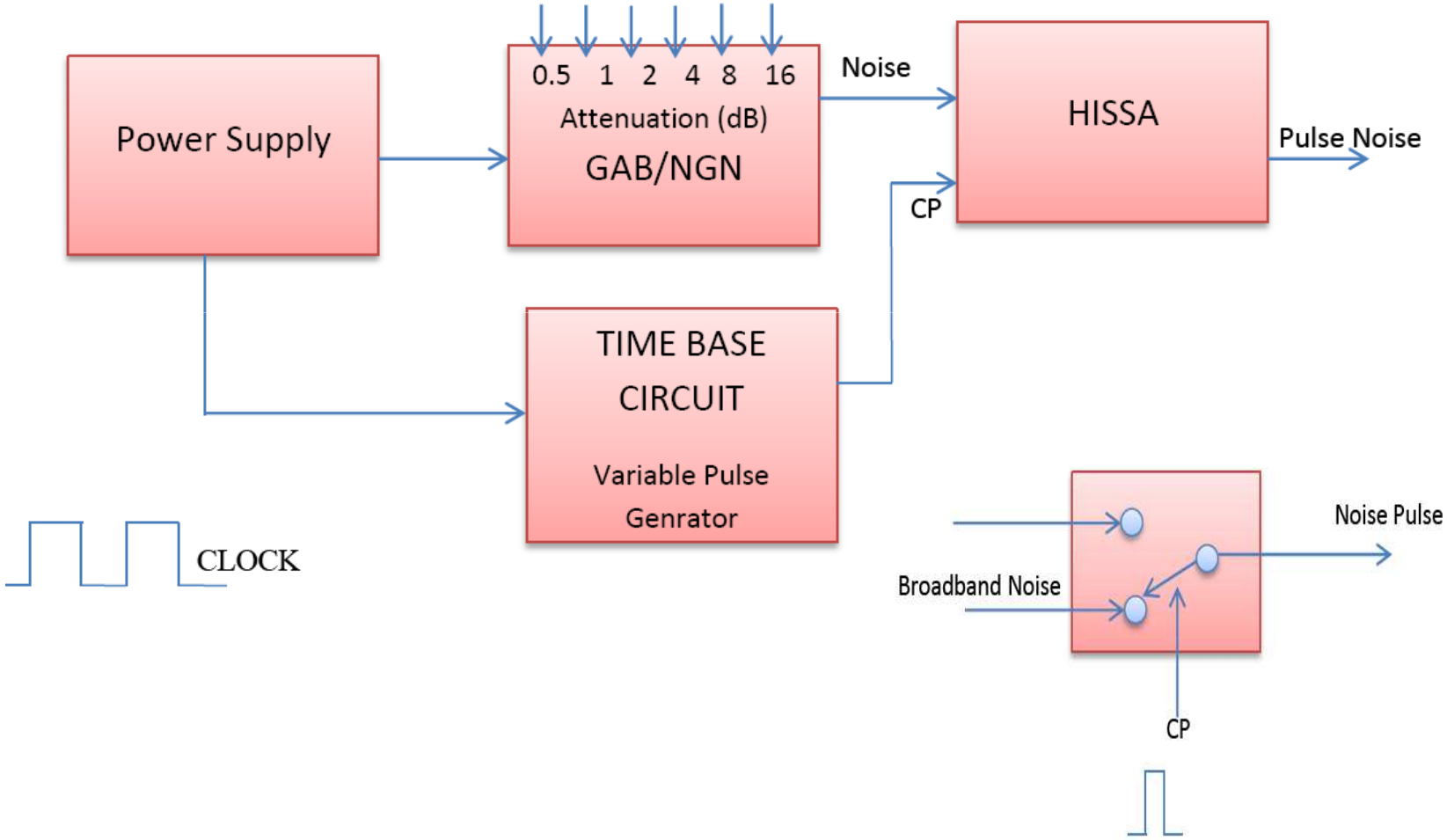


RFI Excision for uGMRT

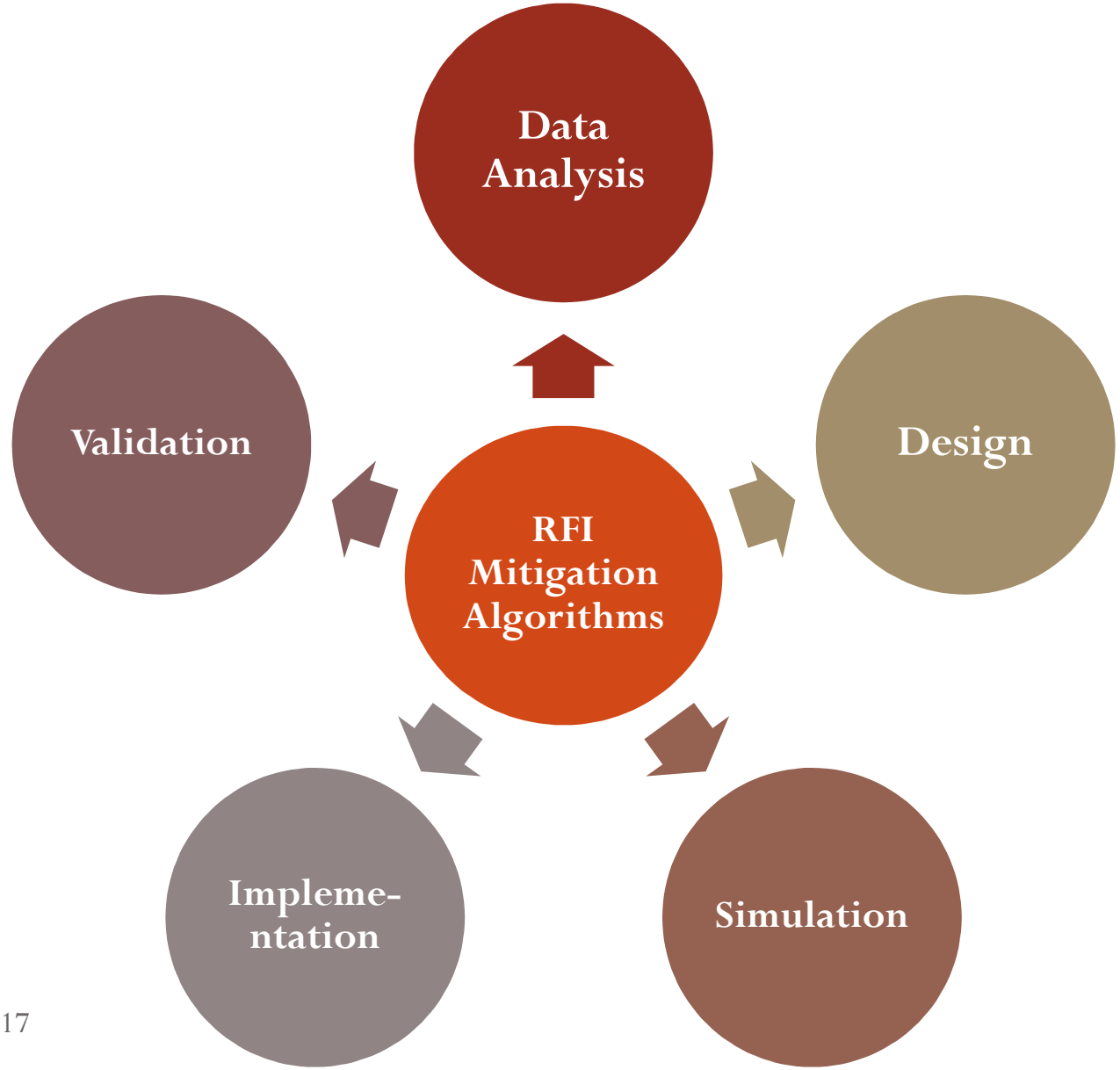
- RFI in astronomical data – outliers make Gaussian distribution heavy-tailed
- Excision assumes that RFI is much stronger than the astronomical signal
- Robust threshold using Median Absolute Deviation for RFI detection
- Excision by replacing the RFI affected samples by constant value or noise or threshold
    - Implemented in temporal and spectral domains

Buch et. al, "Towards Real-time Impulsive RFI Mitigation for Radio Telescopes", JAI Special Issue, 2017 http://www.worldscientific.com/doi/abs/10.1142/S225117171641018X
Buch et. al, "Real-time RFI excision for the GMRT wideband correlator", RFI-2016 conference proceedings, 2016 http://ieeexplore.ieee.org/abstract/document/7833523/

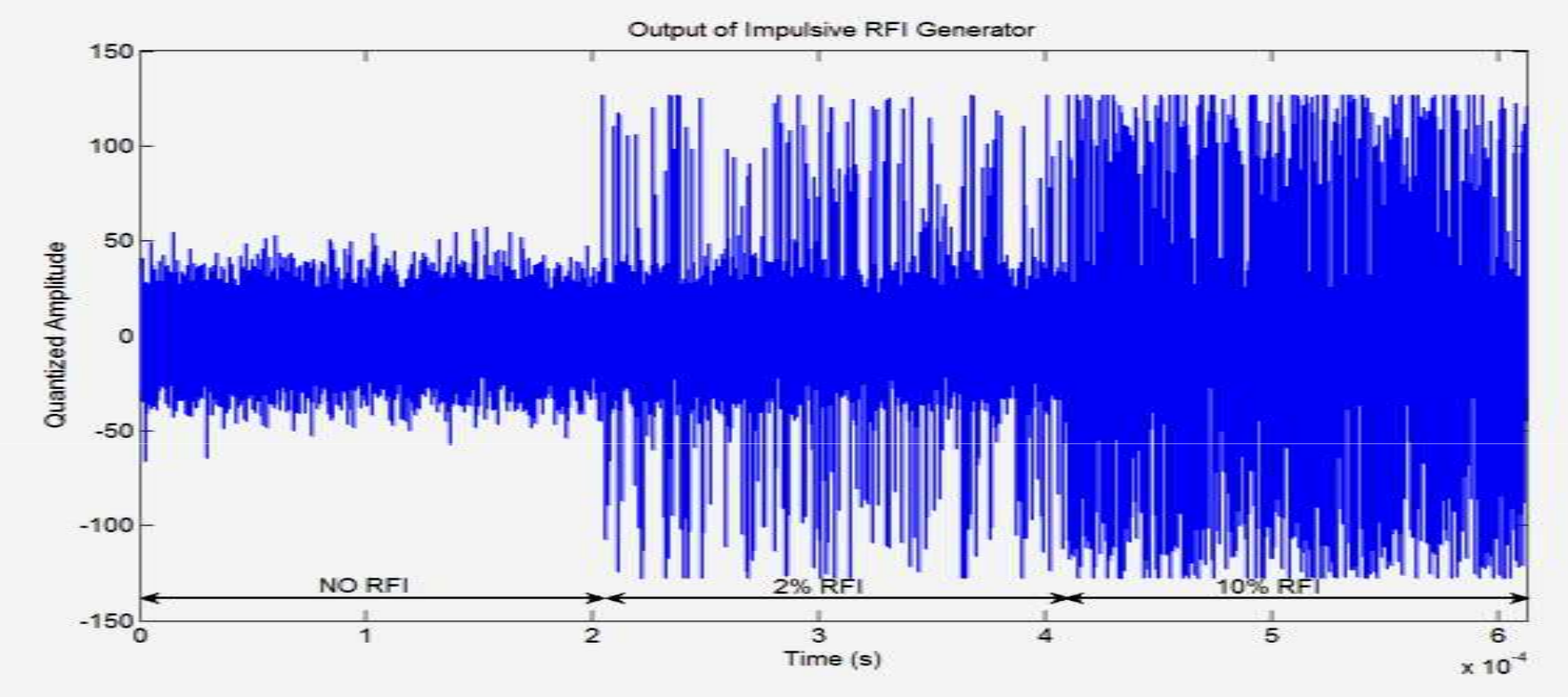
Block Diagram of Broadband RFI Emulator



Development Cycle

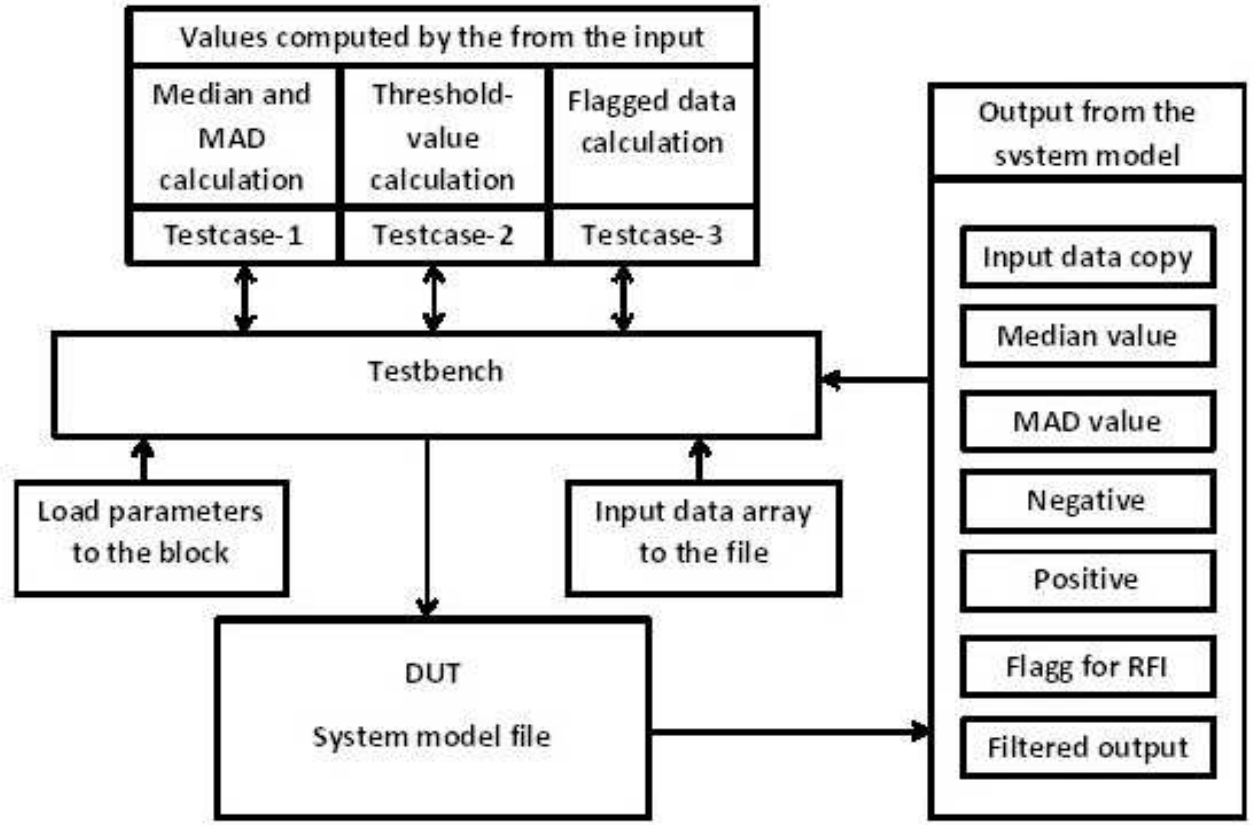


Functional Verification

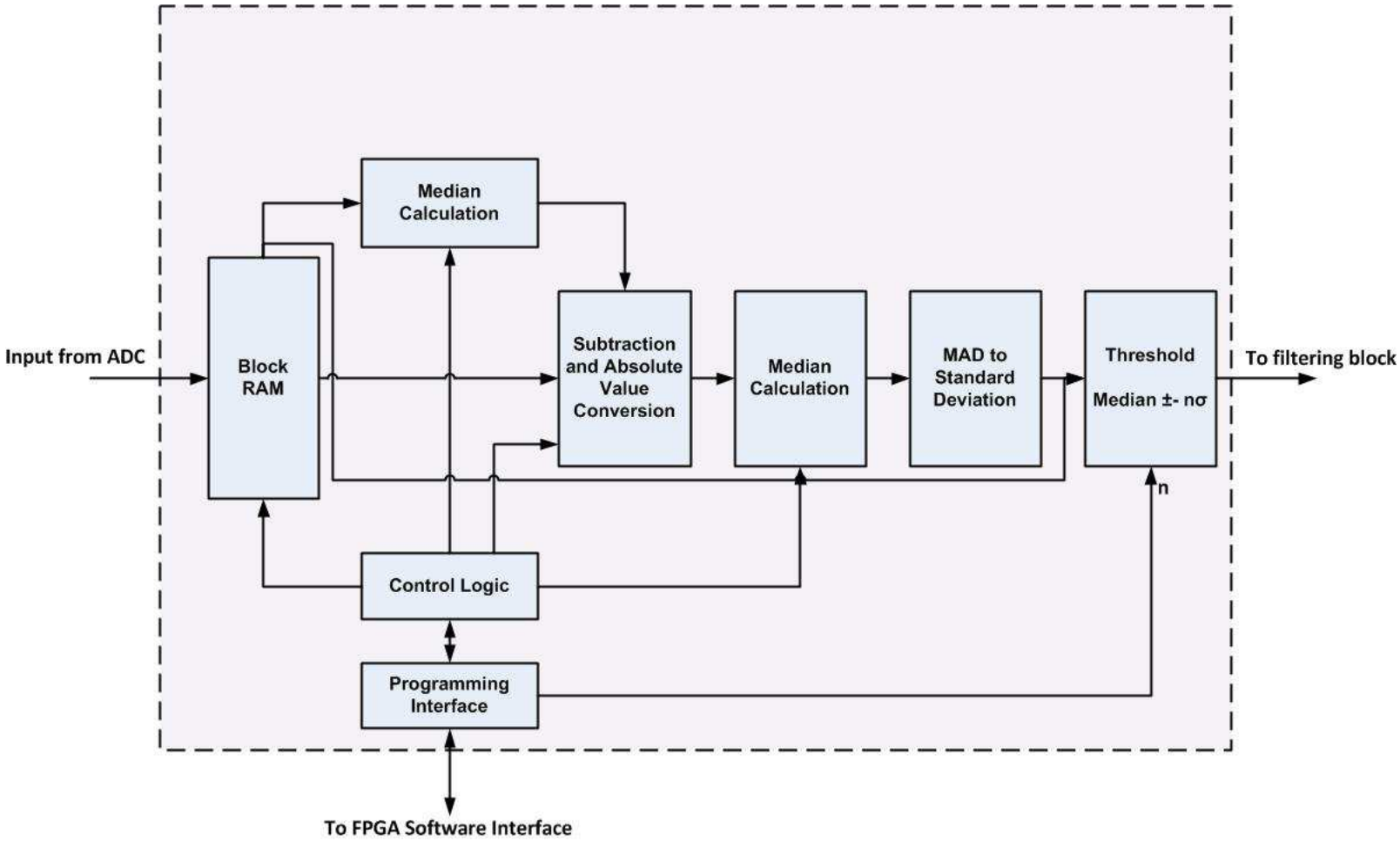


- RFI with different types of RFI was emulated using Matlab. This is required for validation of RFI mitigation algorithms.
- Example shows impulsive RFI of varying degree used as a test-bench for quantifying the efficacy of the RFI algorithm.

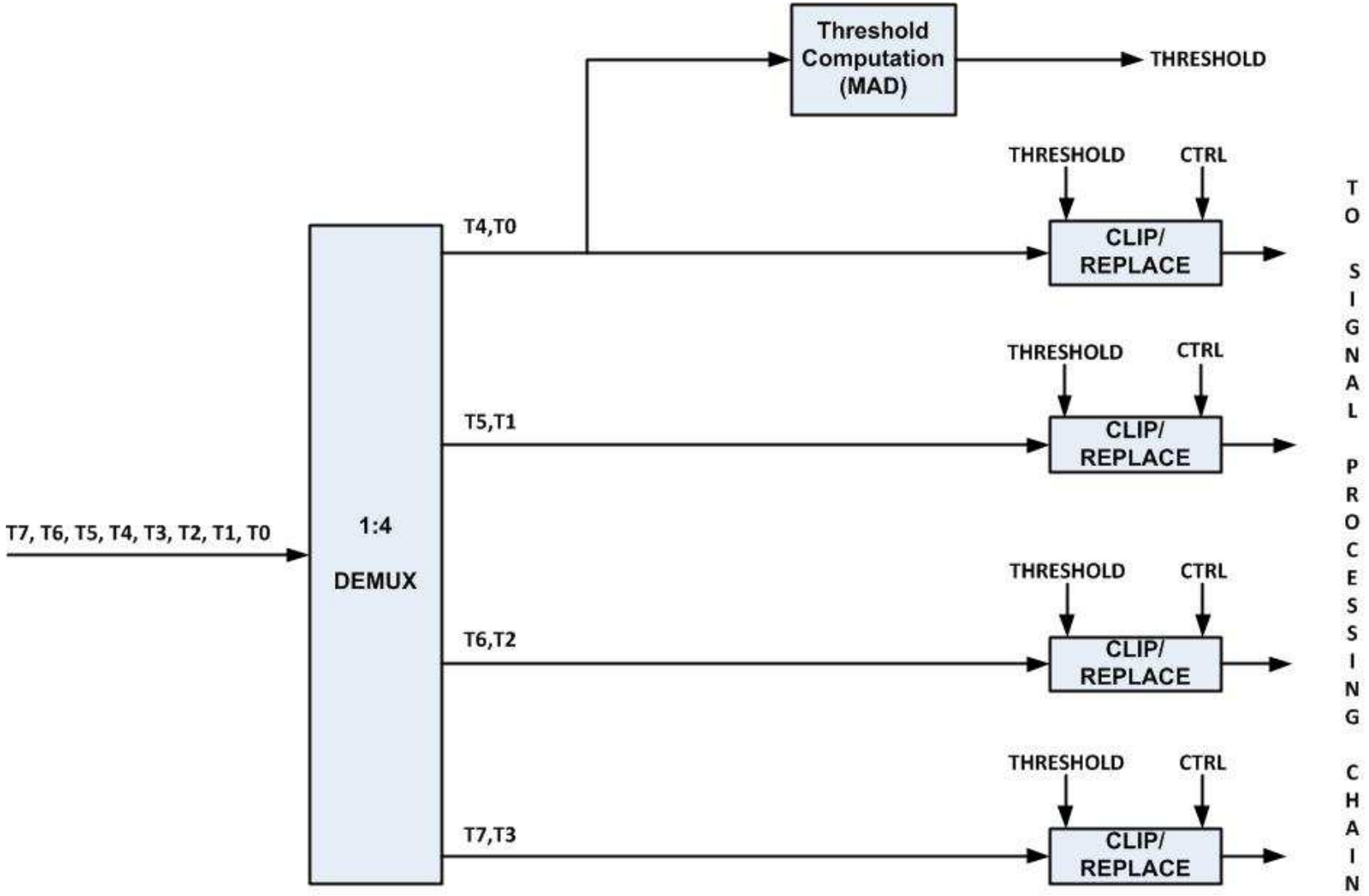
Automated Verification Environment in Matlab-Simulink



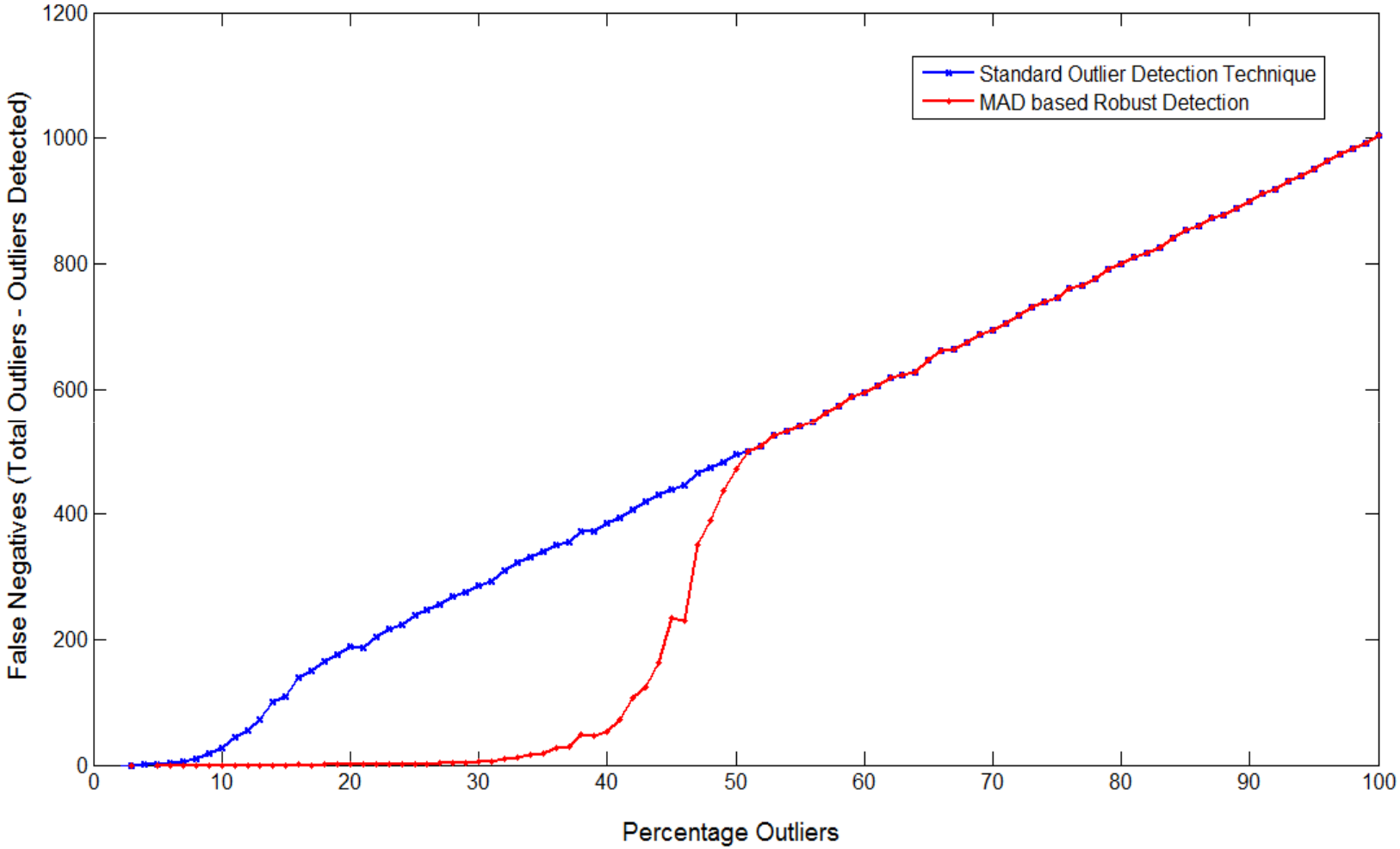
Block Diagram – MAD Computation



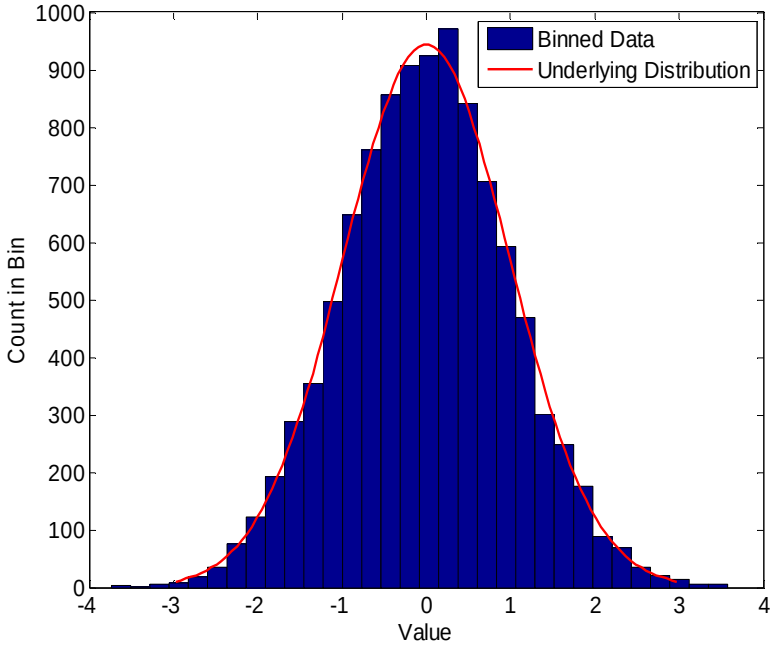
Real-time RFI Filtering : Block Diagram

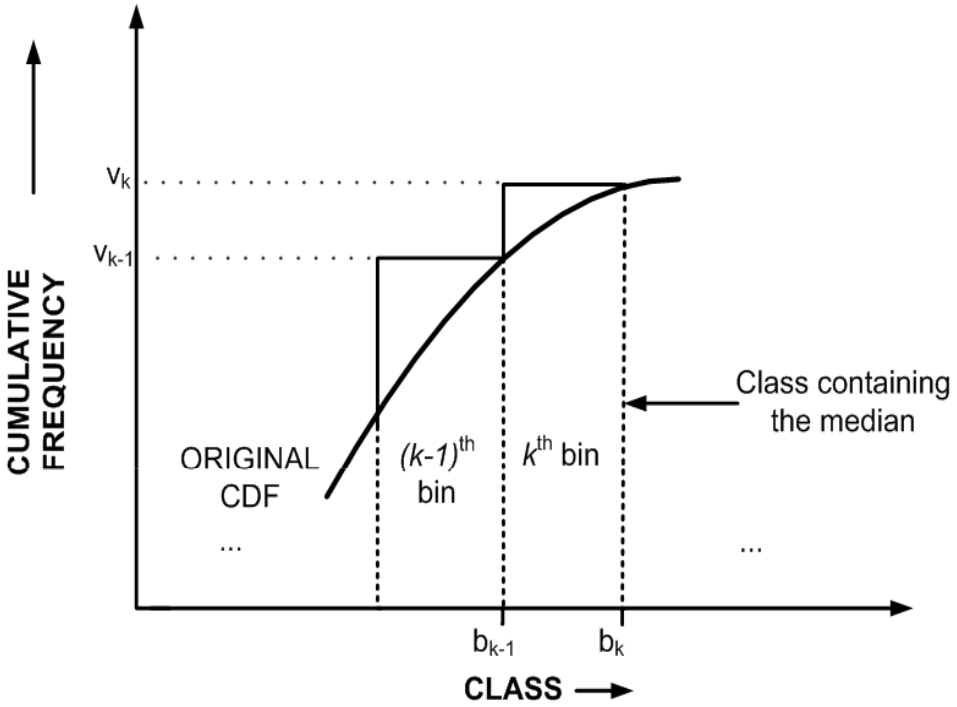


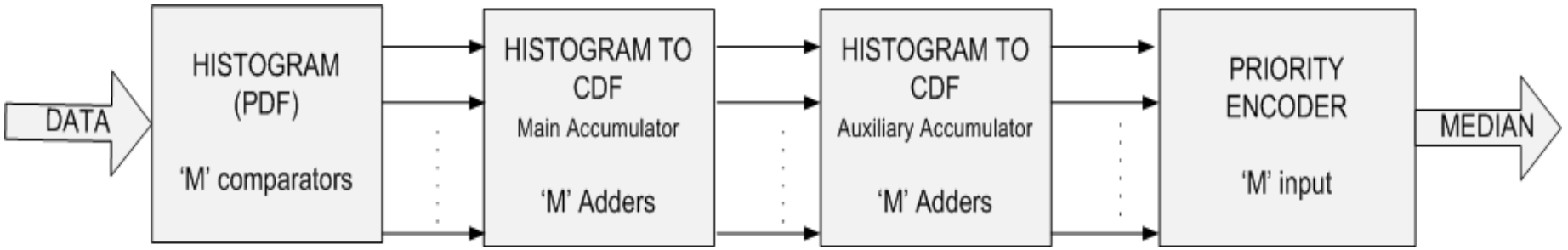
Outlier Detection



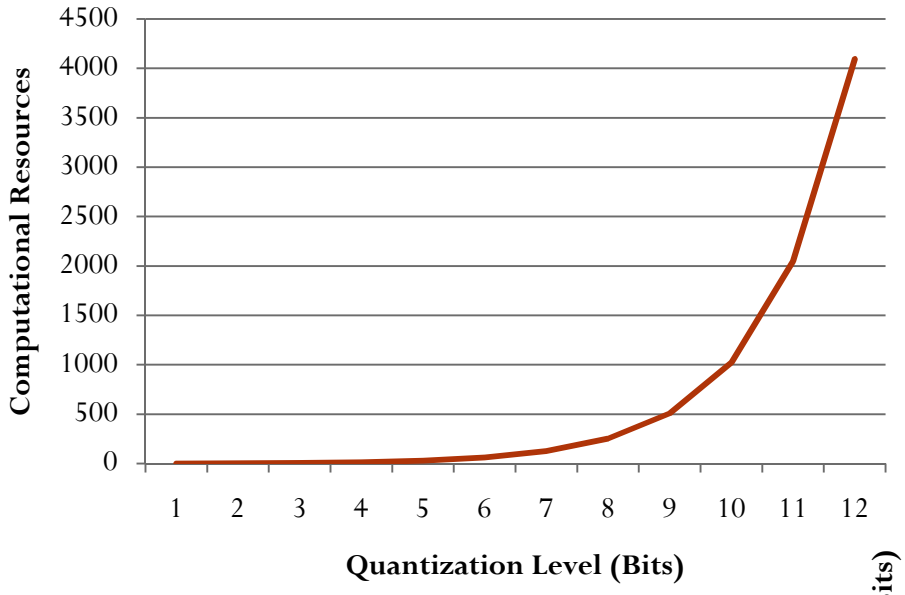
Histogram approach





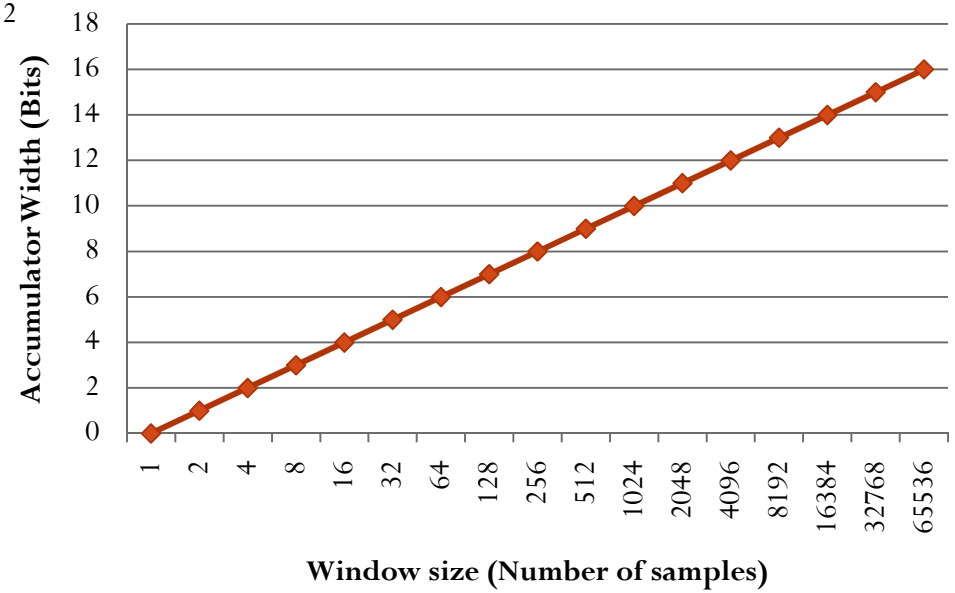


Resource Utilization – Histogram Method

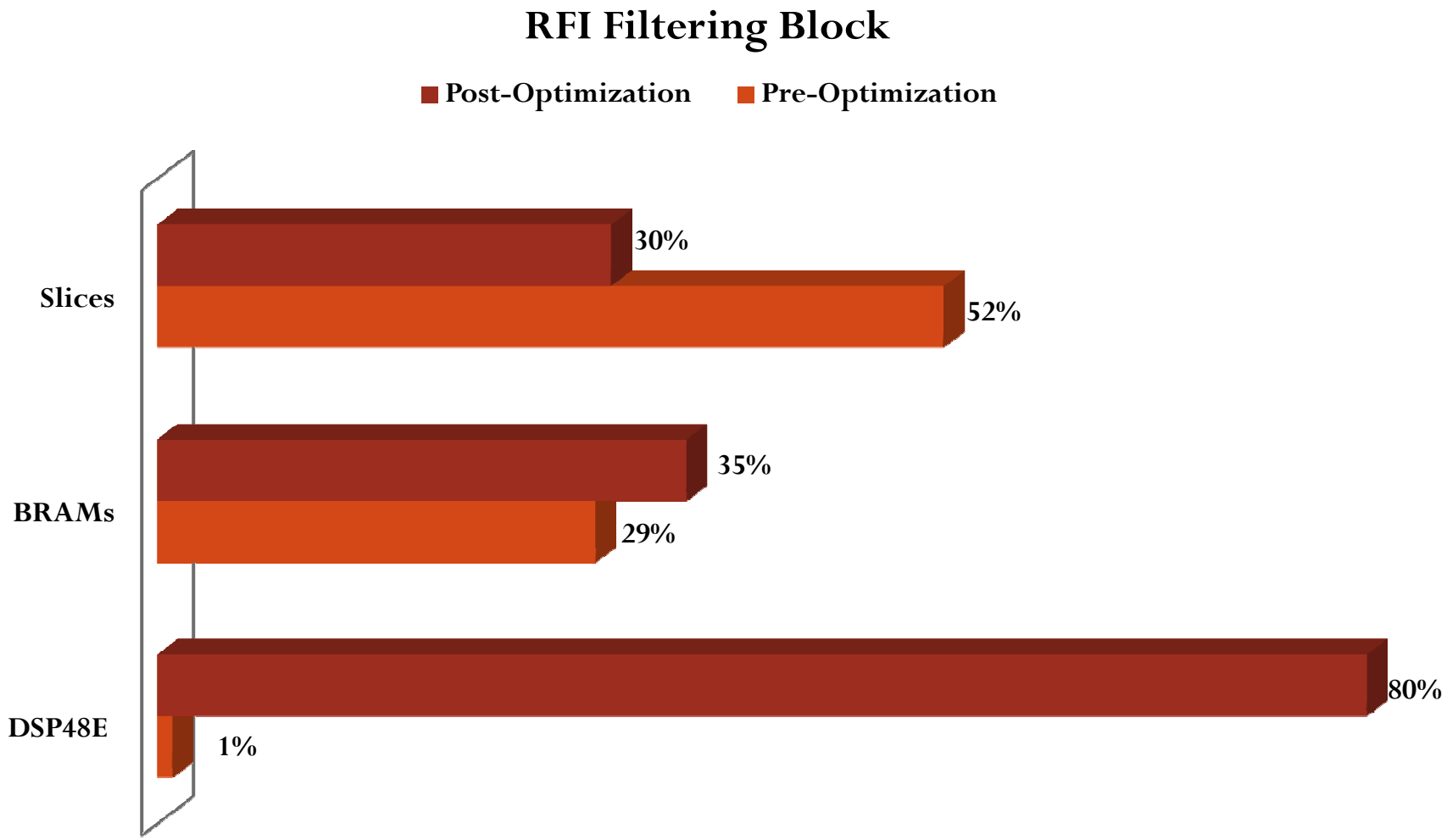


Computational Resources scale as 2^N for 'N' quantization levels (bits)

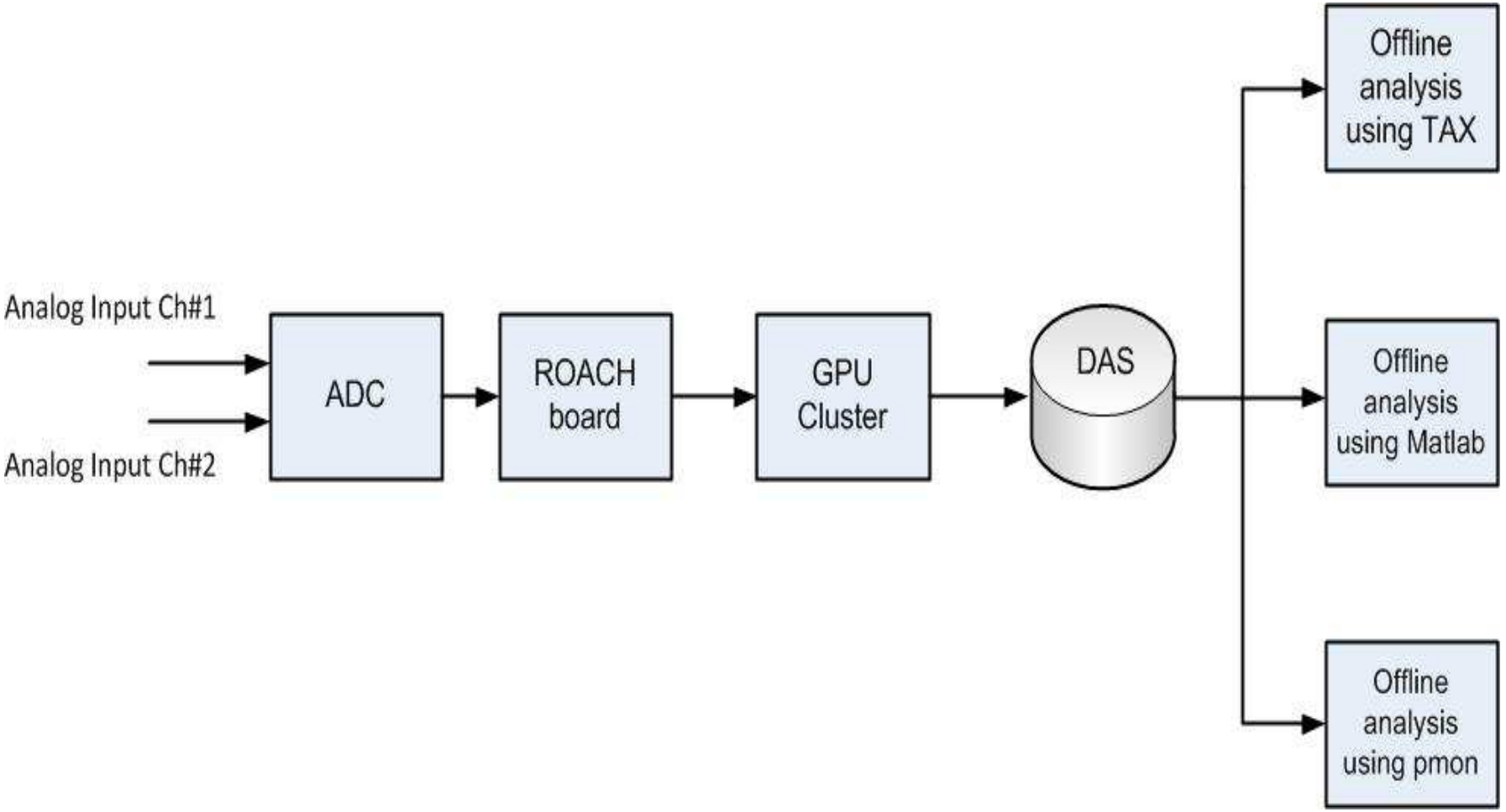
Accumulator Width (bits) scale as $\log_2 W$ for 'W' window size (samples)



RFI Filtering Block – Resource Optimization

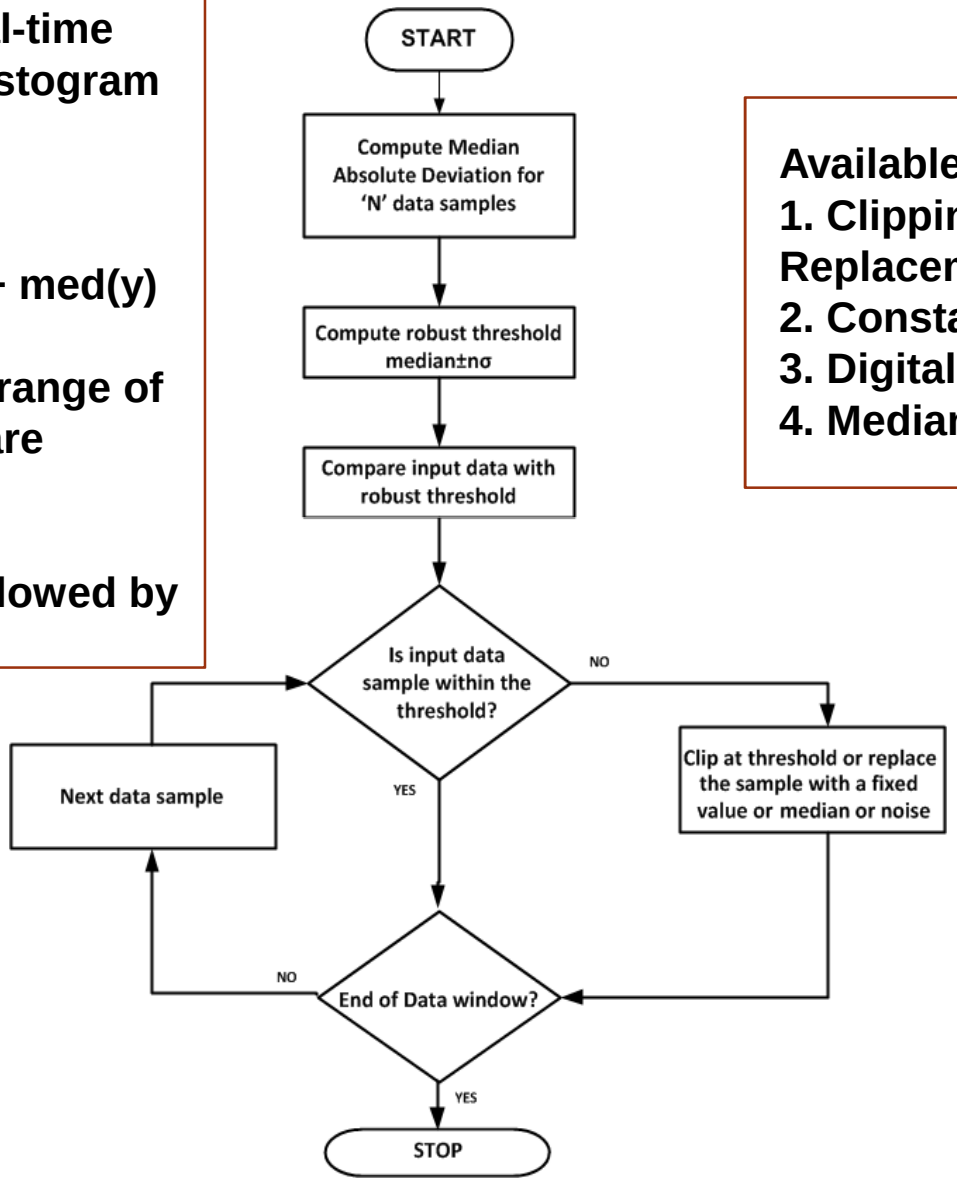


GWB Testing – Block Diagram



MAD based RFI Detection and Filtering

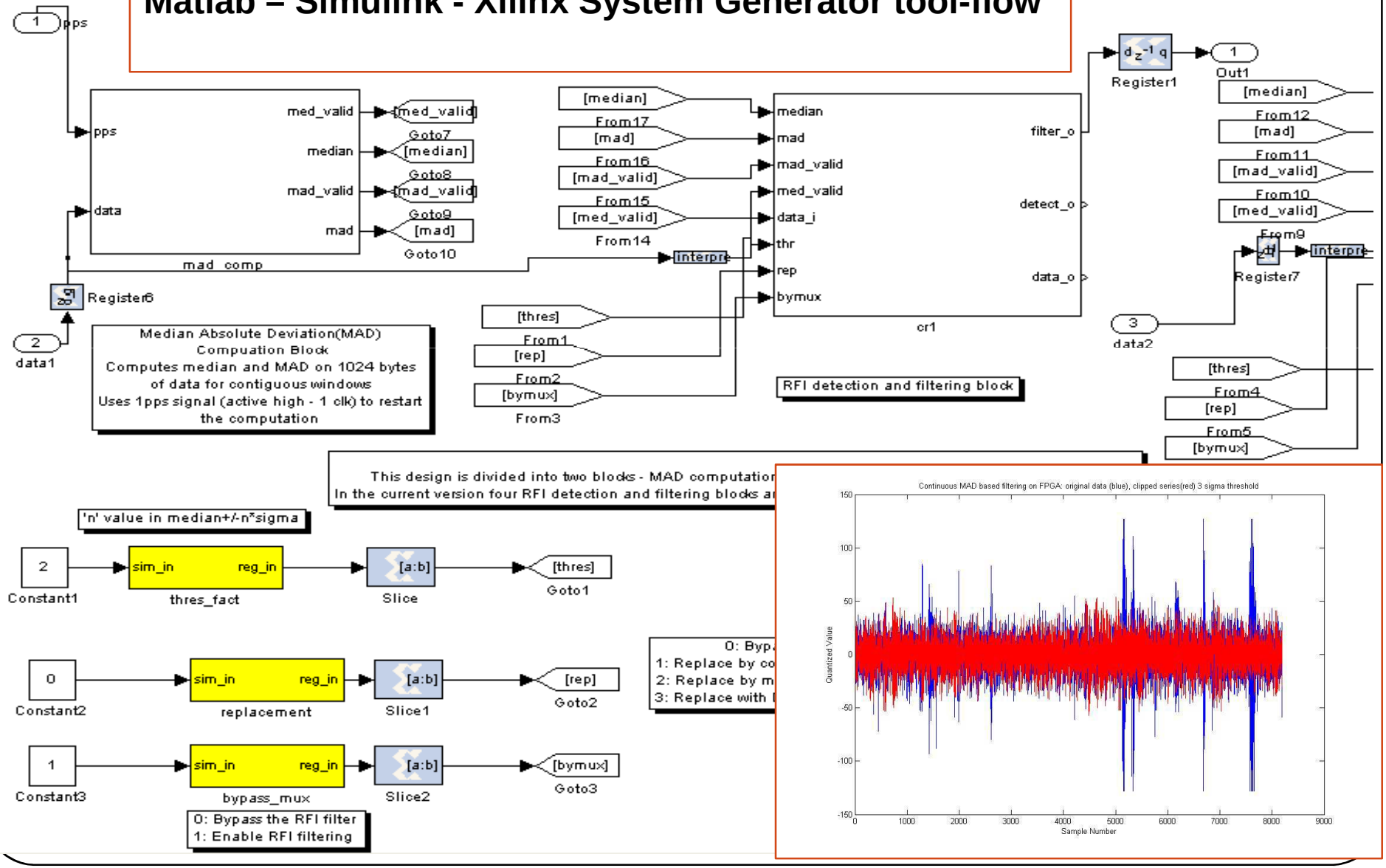
- **Computation of real-time Median using the histogram method**
- **Non-linear filtering med(x+y) ≠ med(x) + med(y)**
- **Values outside the range of [median ± n*σ_{MAD}] are treated as RFI**
- **RFI Detection is followed by filtering**



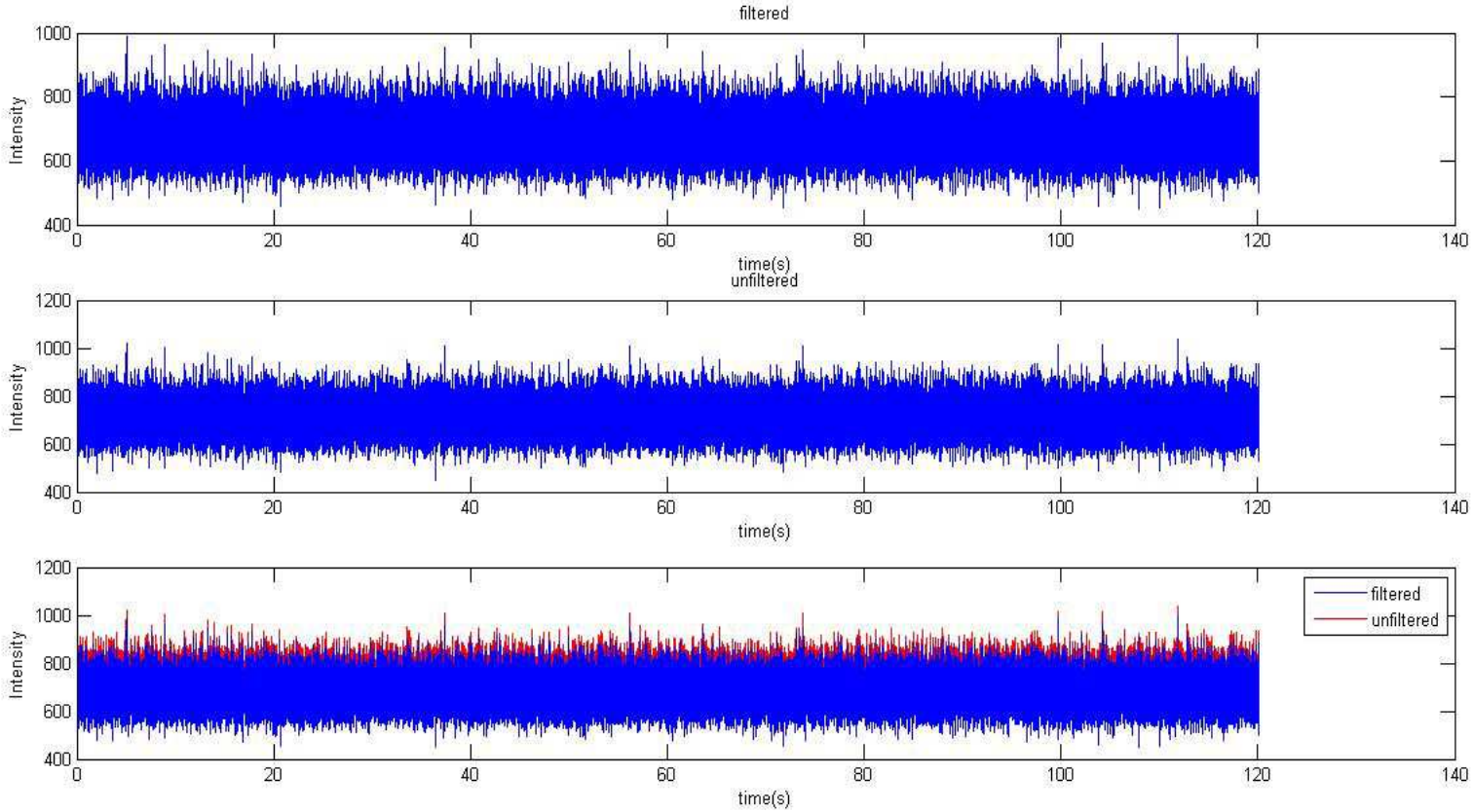
Available filtering options:
1. **Clipping**
Replacement with
2. **Constant value**
3. **Digital noise**
4. **Median**

FPGA Design

Matlab – Simulink - Xilinx System Generator tool-flow

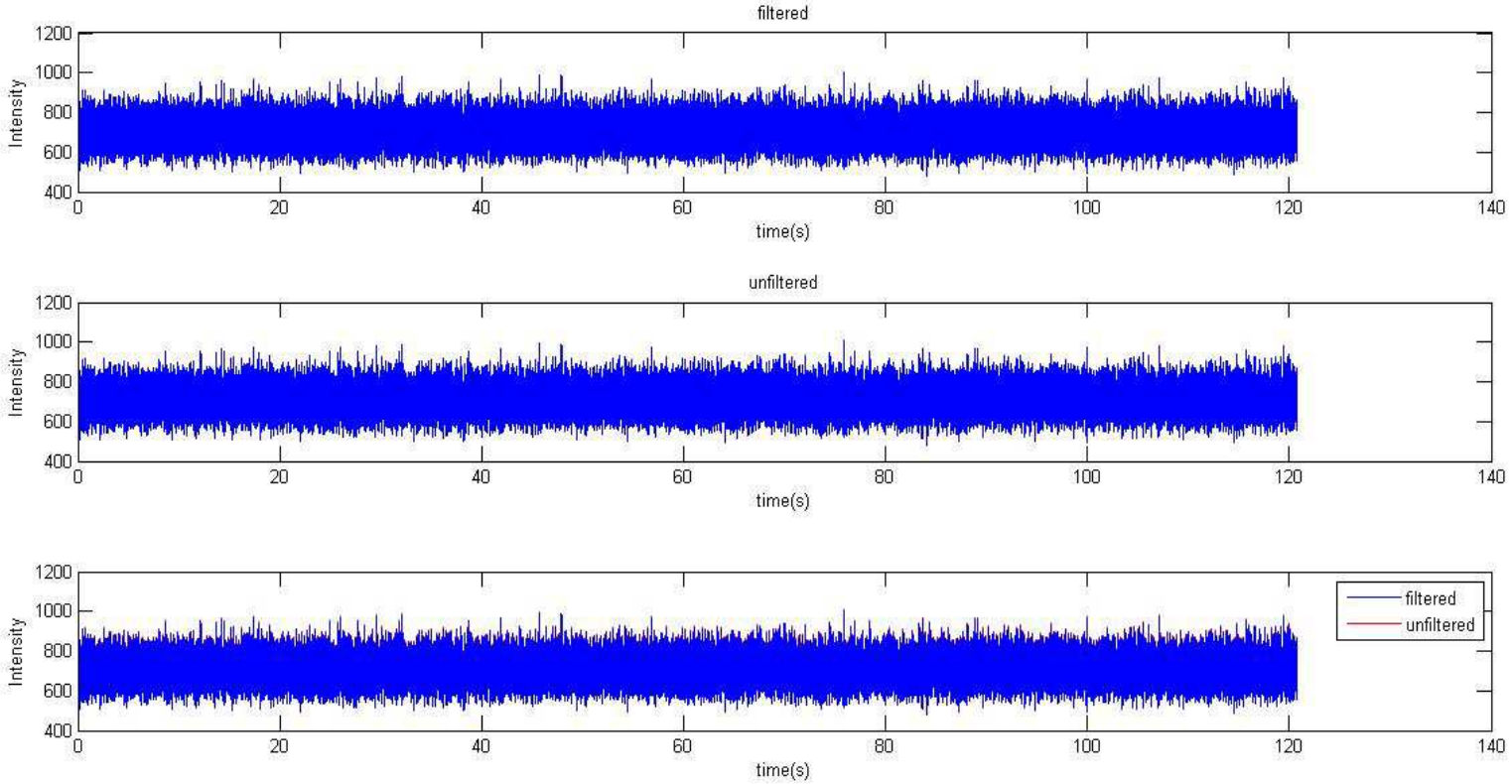


Post-filtering reduction in mean noise value



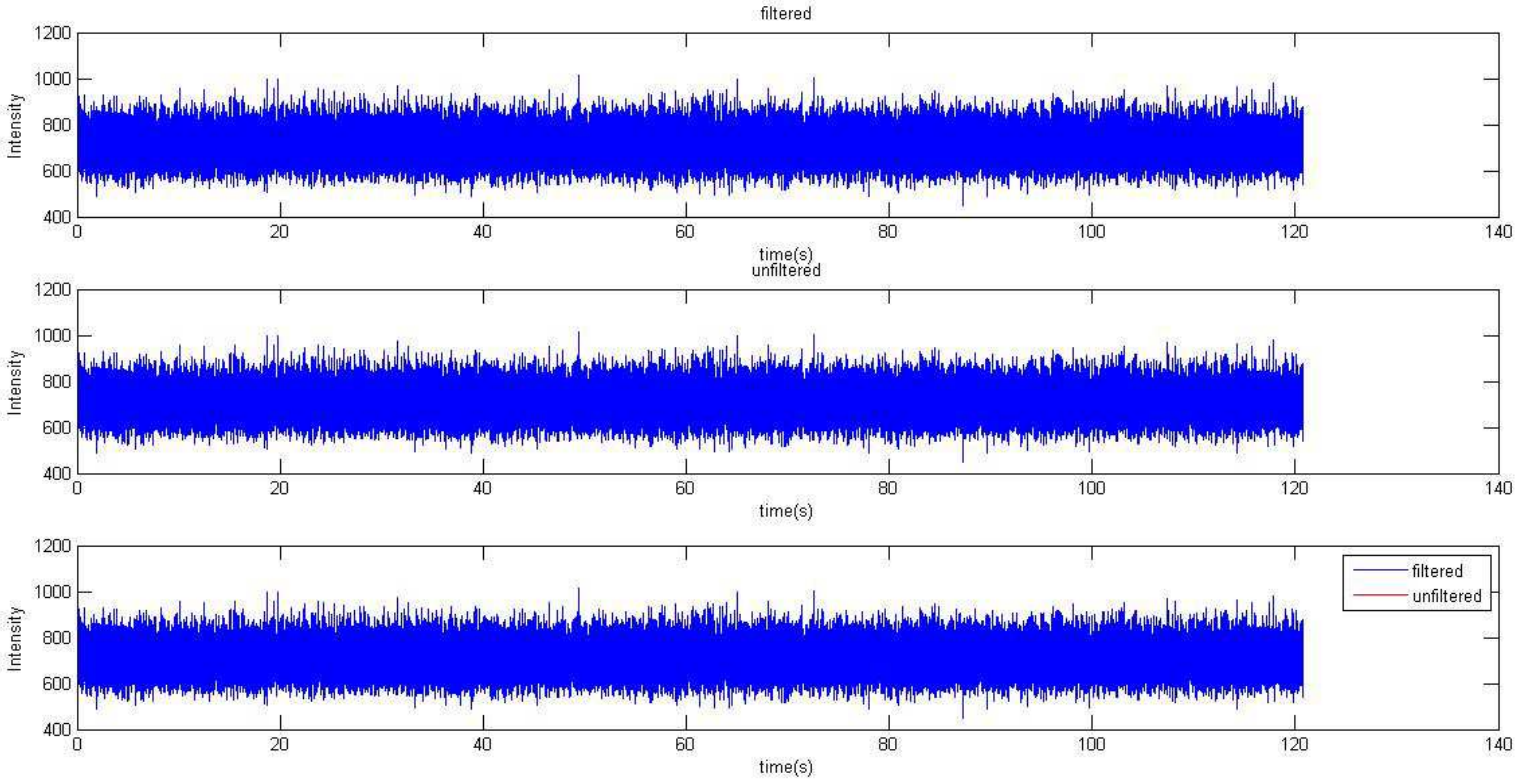
Noise input – filtering at 3 sigma , replacement with digital noise

Post-filtering reduction in mean noise value



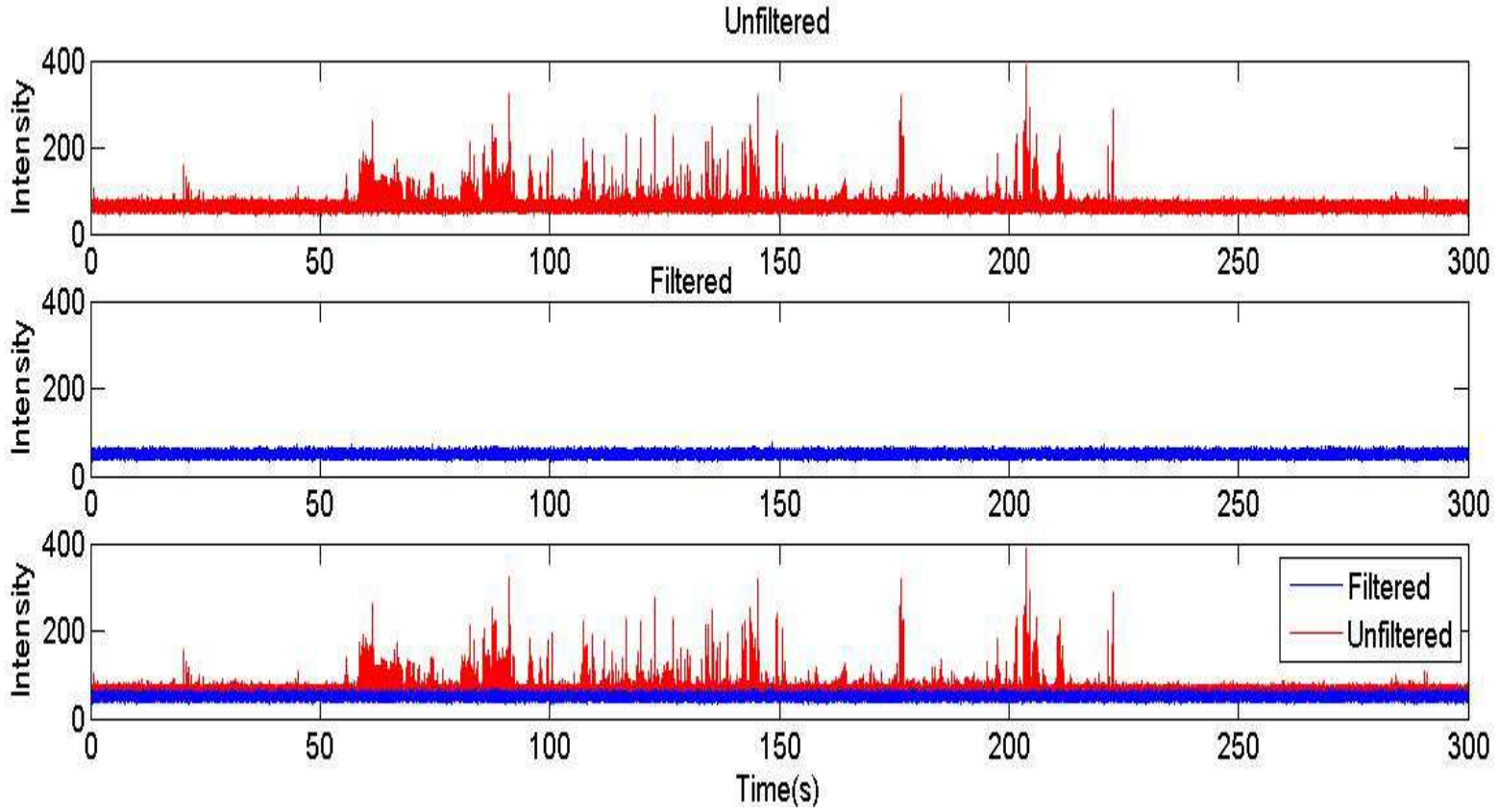
Noise input – filtering at 3 sigma , clipped at threshold

Post-filtering reduction in mean noise value



Noise input – filtering at 5 sigma , replacement with digital noise

Test Results from GWB (Antenna signals)



Time series of a spectral channel showing filtering at 3σ threshold computed in continuous mode – replacement with zero

Effects of RFI on Radio Telescope Receiver

- Presence of RFI
  - Signal fluctuations do not integrate down as $t^{-0.5}$ upon temporal averaging
  - Leads to reduced signal to noise ratio (SNR) and sensitivity
- Strong narrowband RFI lines
  - Produces harmonics
  - Pronounced effects due to spectral leakage
    - Increased side-lobe levels
    - Reduced dynamic range
- Limits detection and analyses of weak radio sources, temporal events and transients

Methods of RFI Mitigation

- Regulatory (Pro-active) Methods
  - Creating radio quiet zones (RQZ)
  - Controlling sources of RFI around the observatory
- Technical (Reactive) Methods
  - RF & Analog domain
  - Digital Subsystem
    - **Excision**
    - Cancellation
  - Offline data processing

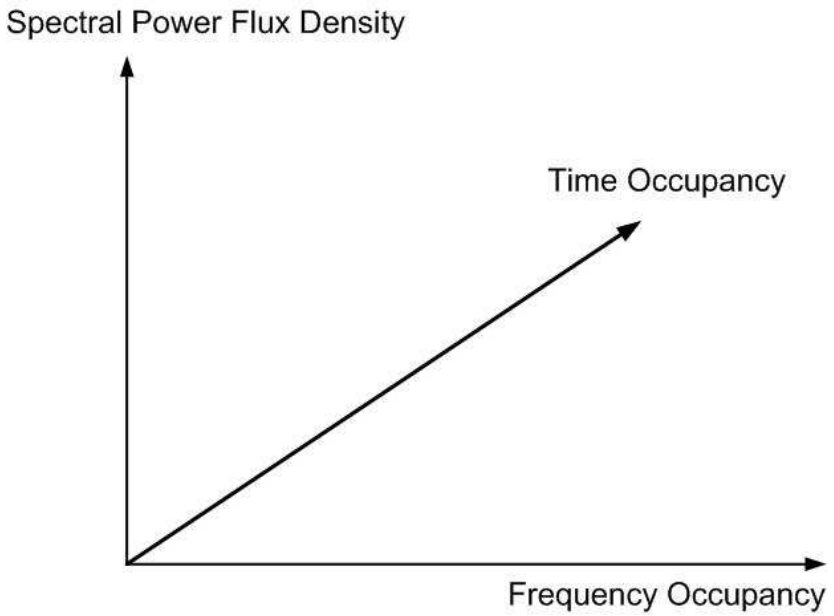


Image Courtesy: P. Dewdney