# Real-time RFI Mitigation for the GWB – Current Status & Plans: Part II

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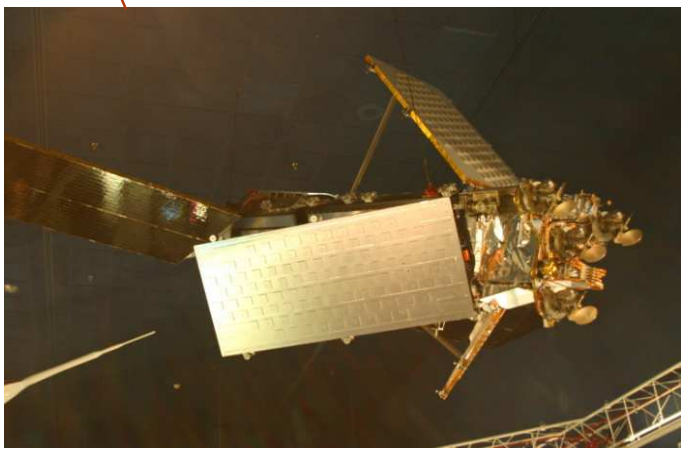
# Radio Frequency Interference

- Man-made electromagnetic radiation from electronic/electrical equipments
- RFI is typically 30 to 40 dB (i.e. 1000 to 10000 times) stronger than astronomical signal
- RFI has a non-random distribution
- RFI mitigation – very important problem (challenge) for contemporary radio telescopes

# Typical Sources of RFI

Narrowband RFI



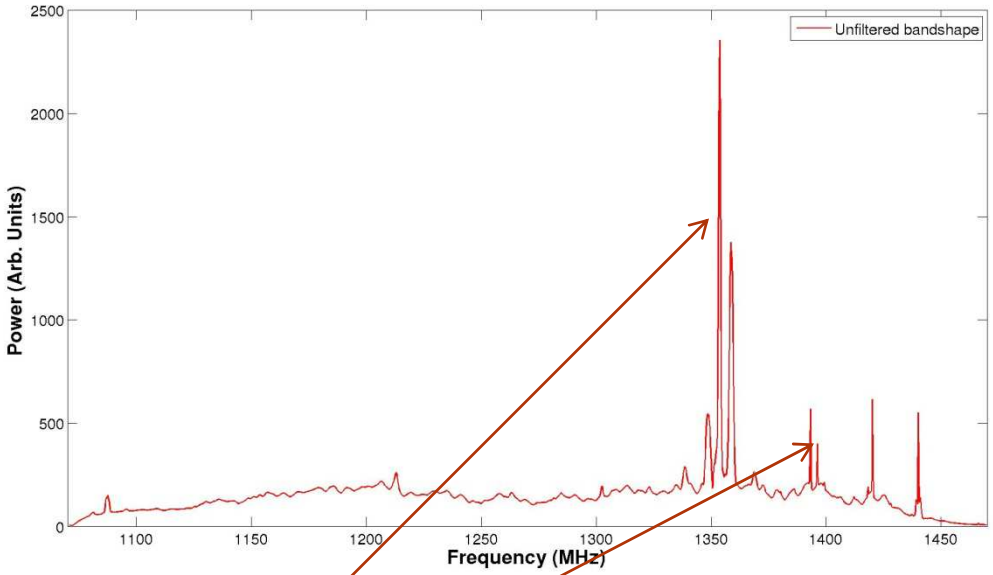
Sparking

Broadband RFI

Narrowband RFI

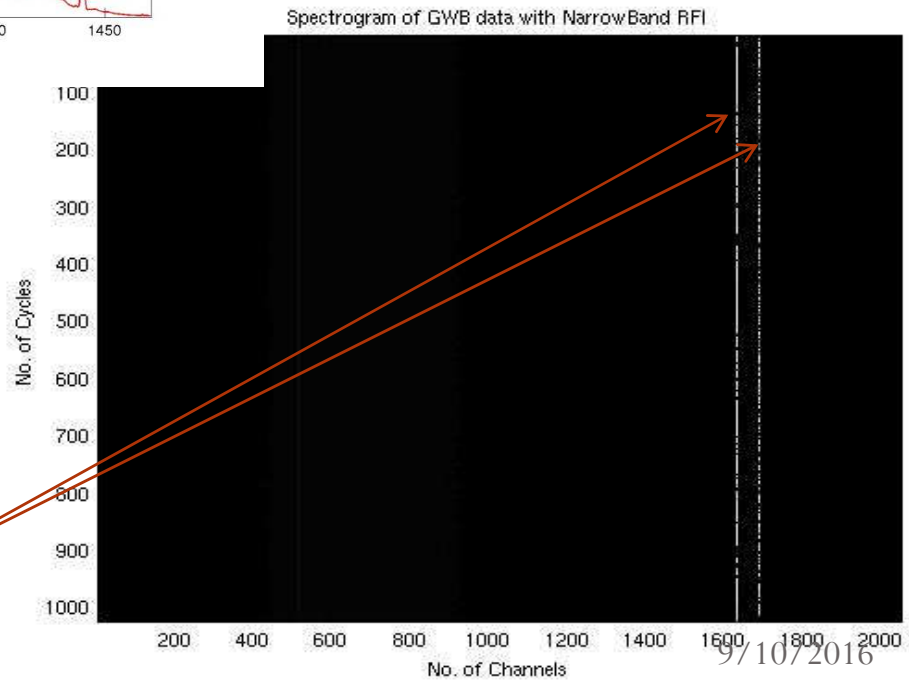
Image Courtesy: Wikipedia

# Narrowband RFI



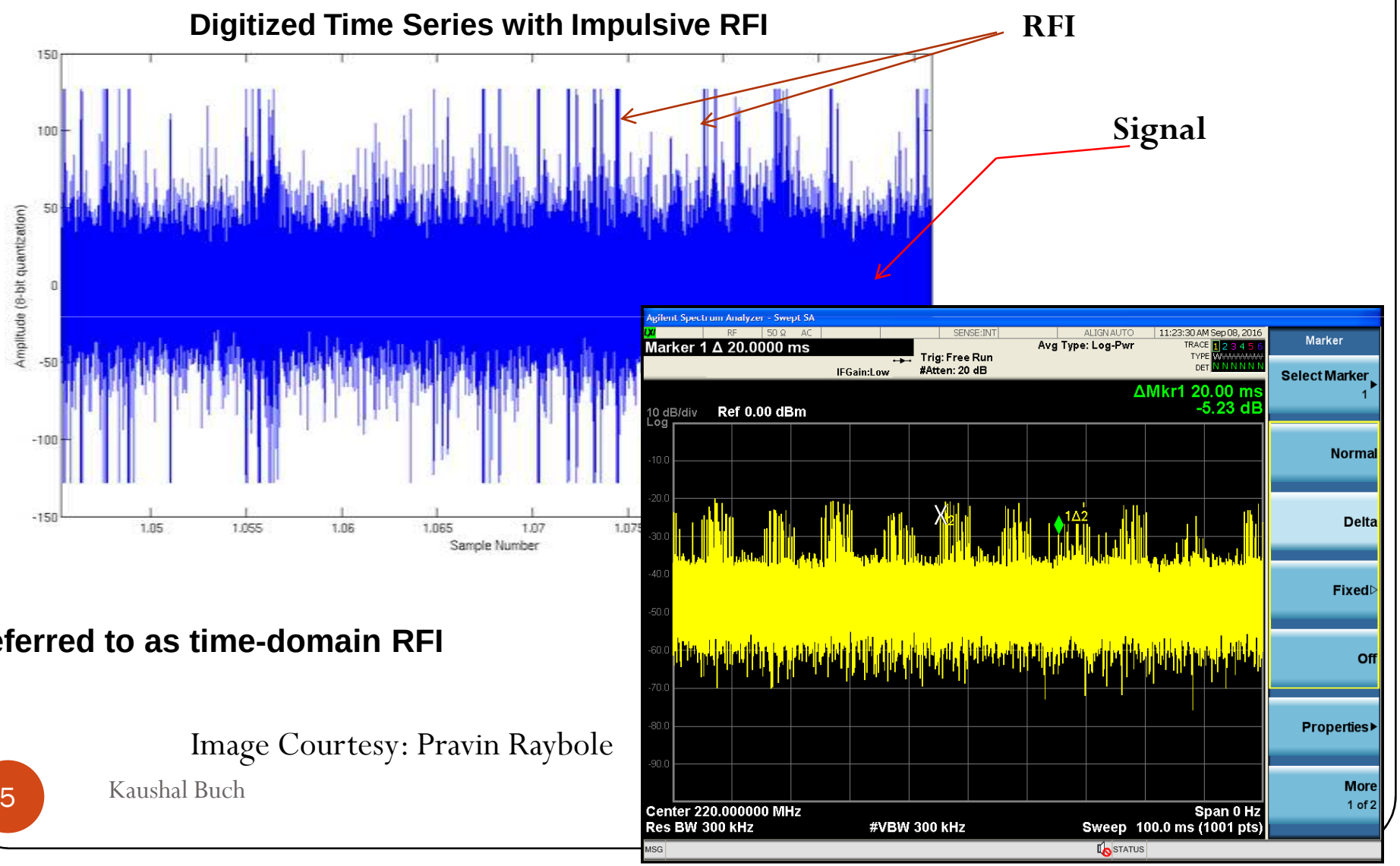

**RFI**

**Referred to as frequency-domain RFI**




**RFI**

# Broadband RFI




**Referred to as time-domain RFI**

Image Courtesy: Pravin Raybole

# Broadband RFI

- Primarily caused due to two major reasons - Sparking and Corona on high power transmission lines
  - Sparking occurs due to dielectric breakdown between two conductors leading to a gap discharge: can occur on LT and HT lines
  - Corona occurs by creation of voltage gradient across the lines: rarely observed, occurs on HT lines with voltage greater than 66 kV
- Other sources of broadband RFI include sparking due to automobiles and switching of inductive load

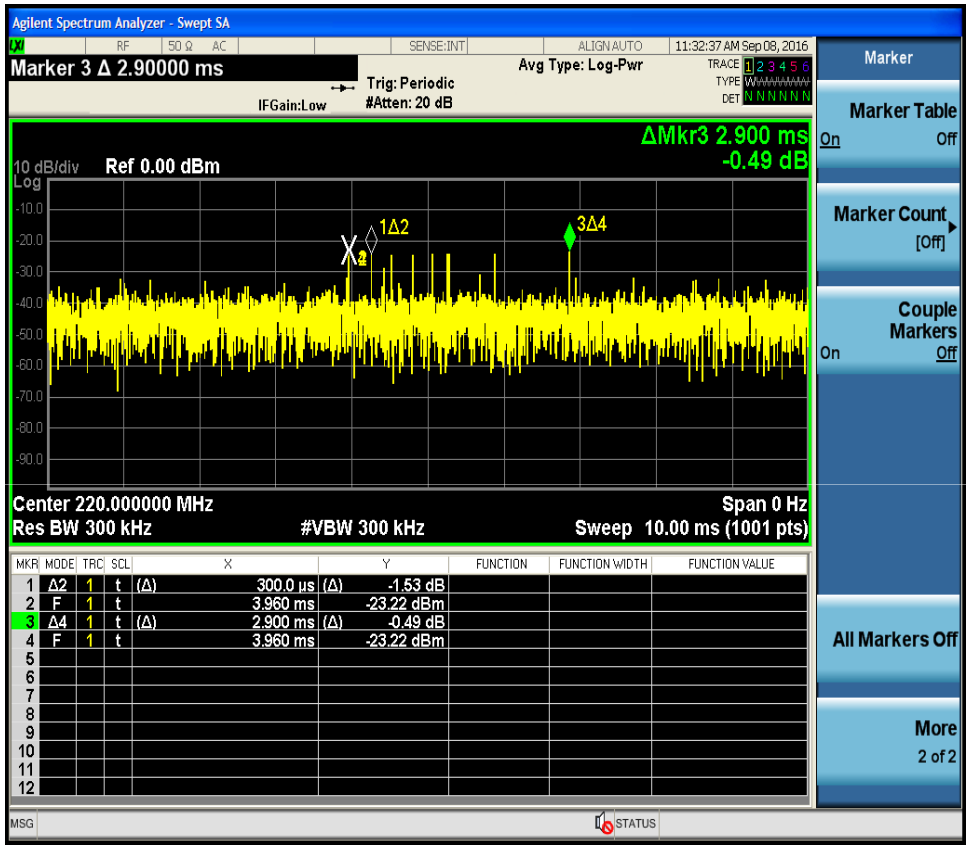
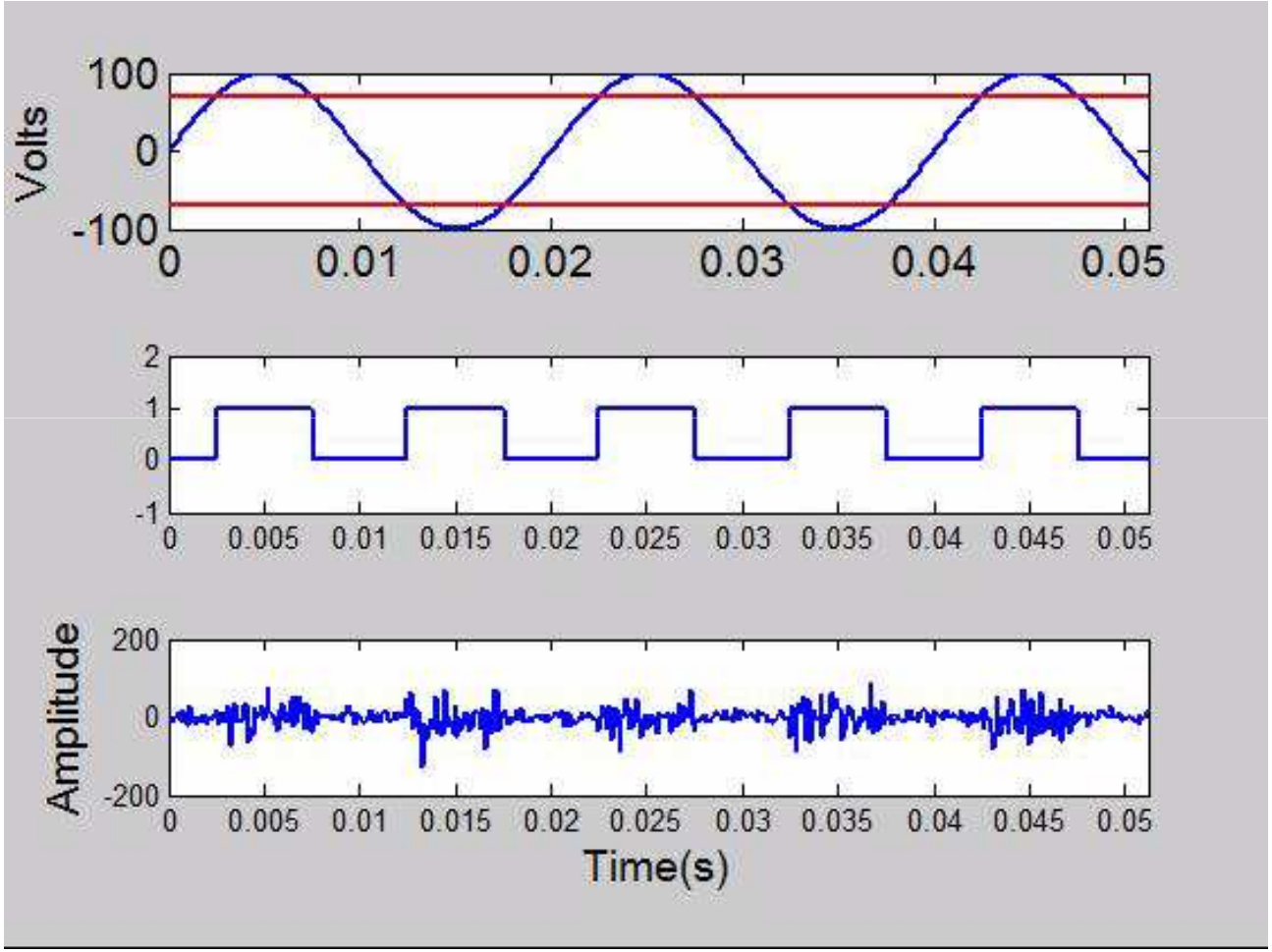



Image Courtesy: Pravin Raybole

**Broadband RFI mitigation is challenging as it cannot be carried out using linear frequency selective filters**

# Power-line Sparking : Simulation



# Additive Effect of RFI

- Generalized time-domain signal model (with RFI) for a radio telescope

$$x(t) = x_s(t) + x_n(t) + x_i(t)$$

- $x_s$ is the contribution due to astronomical source (desired signal), $x_n$ is the system noise (undesired signal) and $x_i$ is the radio frequency interference signal (undesired signal)

# 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

# Methods of RFI Mitigation

- Regulatory (Pro-active) Methods (Keep the receiver in linear operating region)
  - Creating radio quiet zones (RQZ)
  - Controlling sources of RFI around the observatory

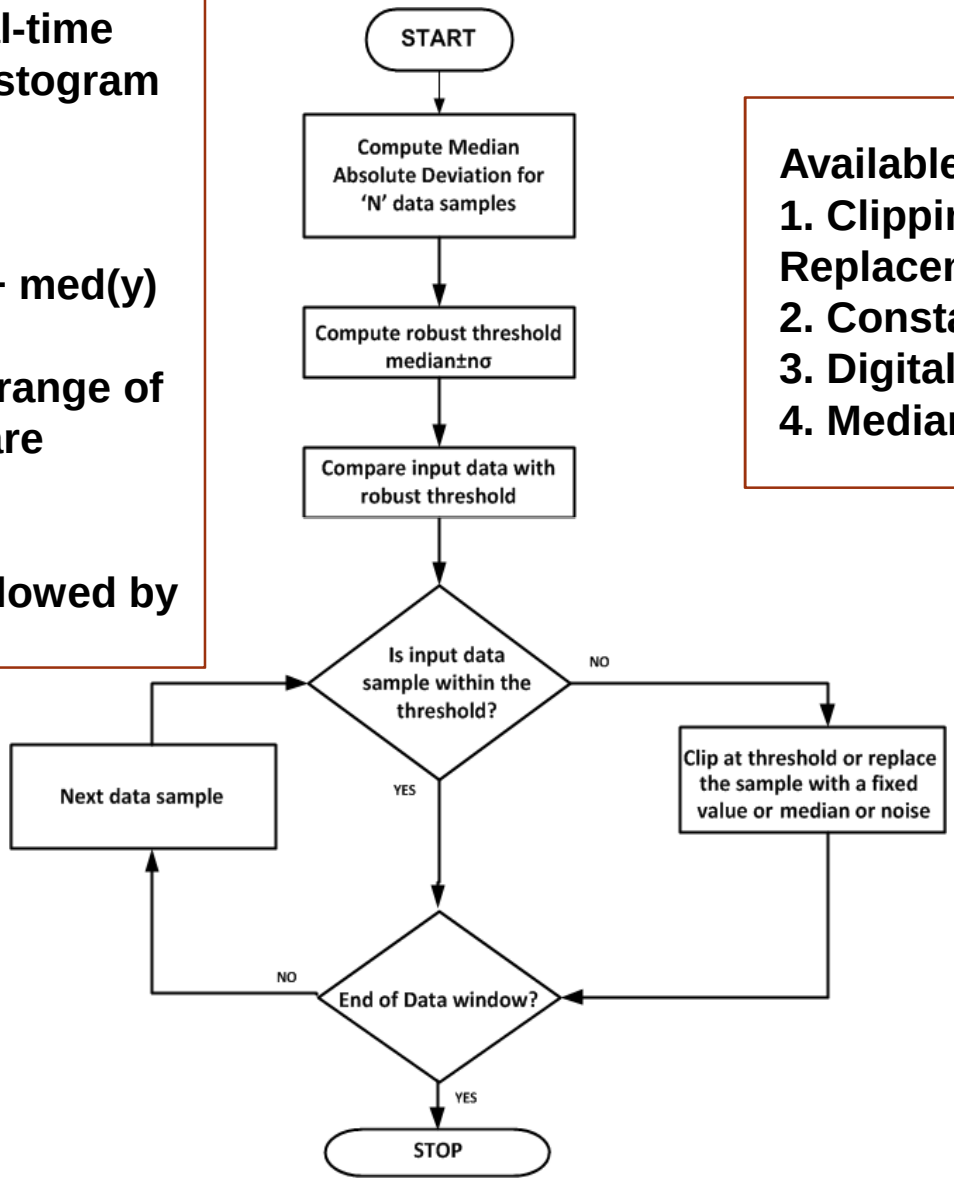
- Technical (Reactive) Methods
  - RF & Analog domain (Keep the receiver in linear operating region)
  - Digital Subsystem (Mitigate whatever RFI flows through the system)
    - Excision
    - Cancellation
  - Offline data processing

# RFI Excision

- RFI in astronomical data – outliers make Gaussian distribution heavy-tailed
- Excision assumes that RFI is much stronger than the astronomical signal
- Detection and excision by blanking or clipping the RFI affected samples
    - Can be implemented in temporal and spectral domains (either pre or post correlation)
- **RFI Excision requires - a. RFI Detection and b. RFI filtering**

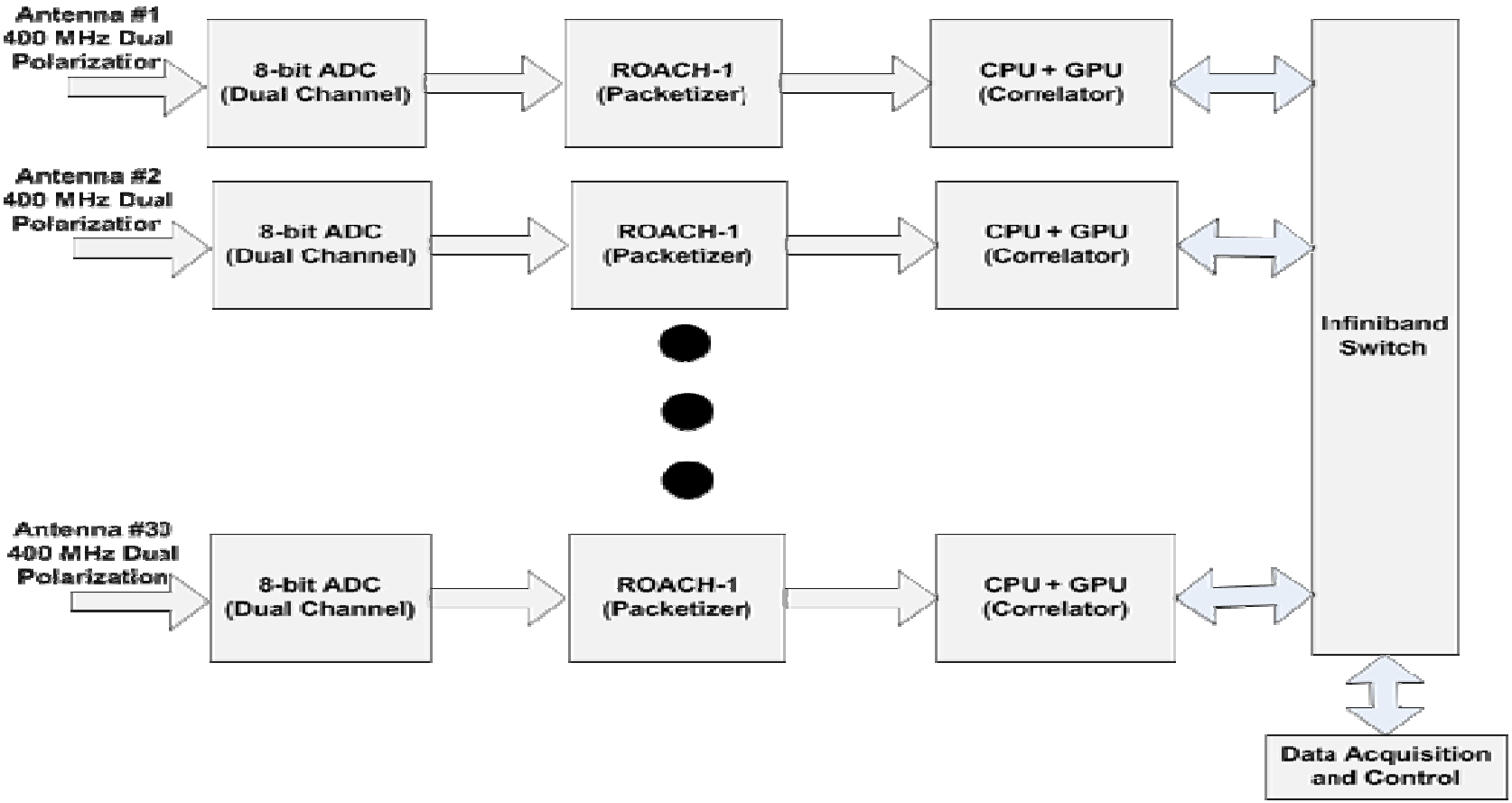
# MAD based RFI Detection and Filtering

- **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*$\sigma_{MAD}$ ] are treated as RFI**
- **RFI Detection is followed by filtering**



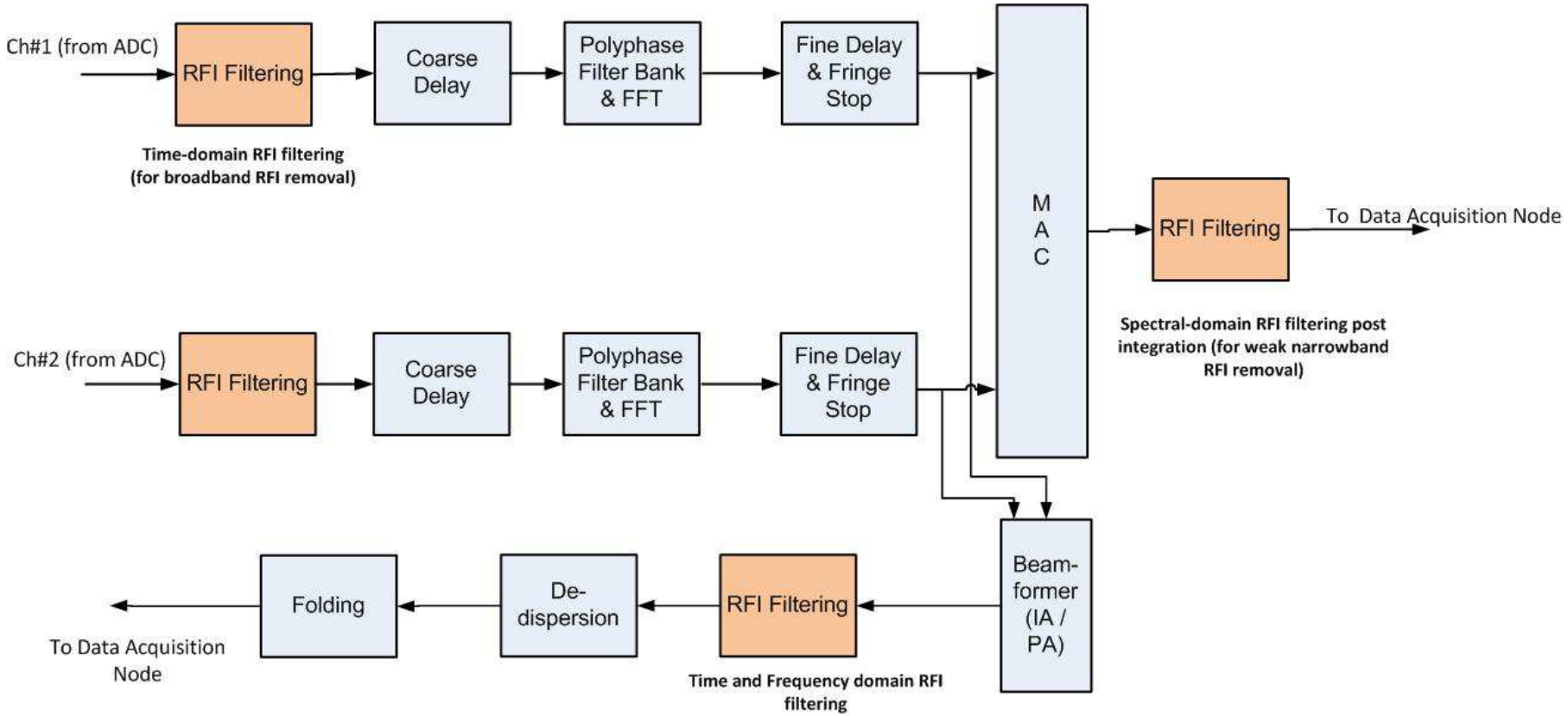

**Available filtering options:**
1. **Clipping**
**Replacement with**
2. **Constant value**
3. **Digital noise**
4. **Median**

# GMRT Wideband Digital Backend



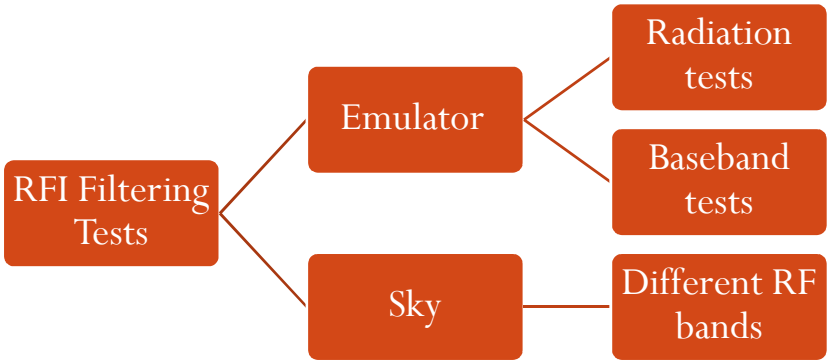

**Real-time broadband RFI Mitigation is implemented on ROACH-1 FPGA board**

# RFI Mitigation for GWB

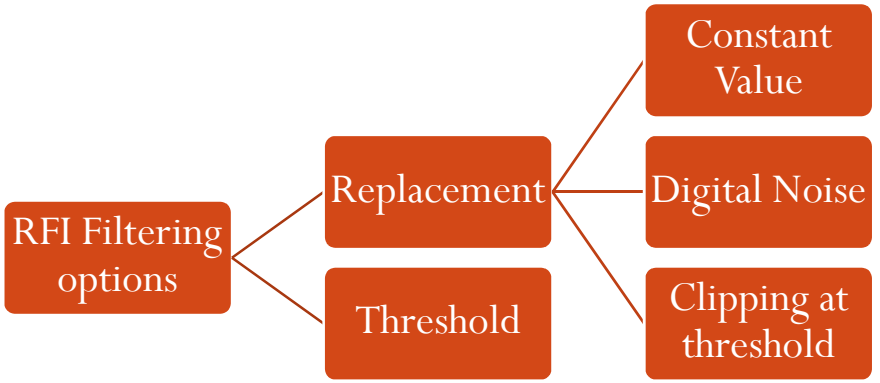



- **Requires implementation at multiple locations in the processing chain to remove diverse types of RFI**
- **RFI Mitigation is proposed to be carried out in pre-correlation and post-correlation domains in the digital subsystem of the GWB**

# Test Strategy

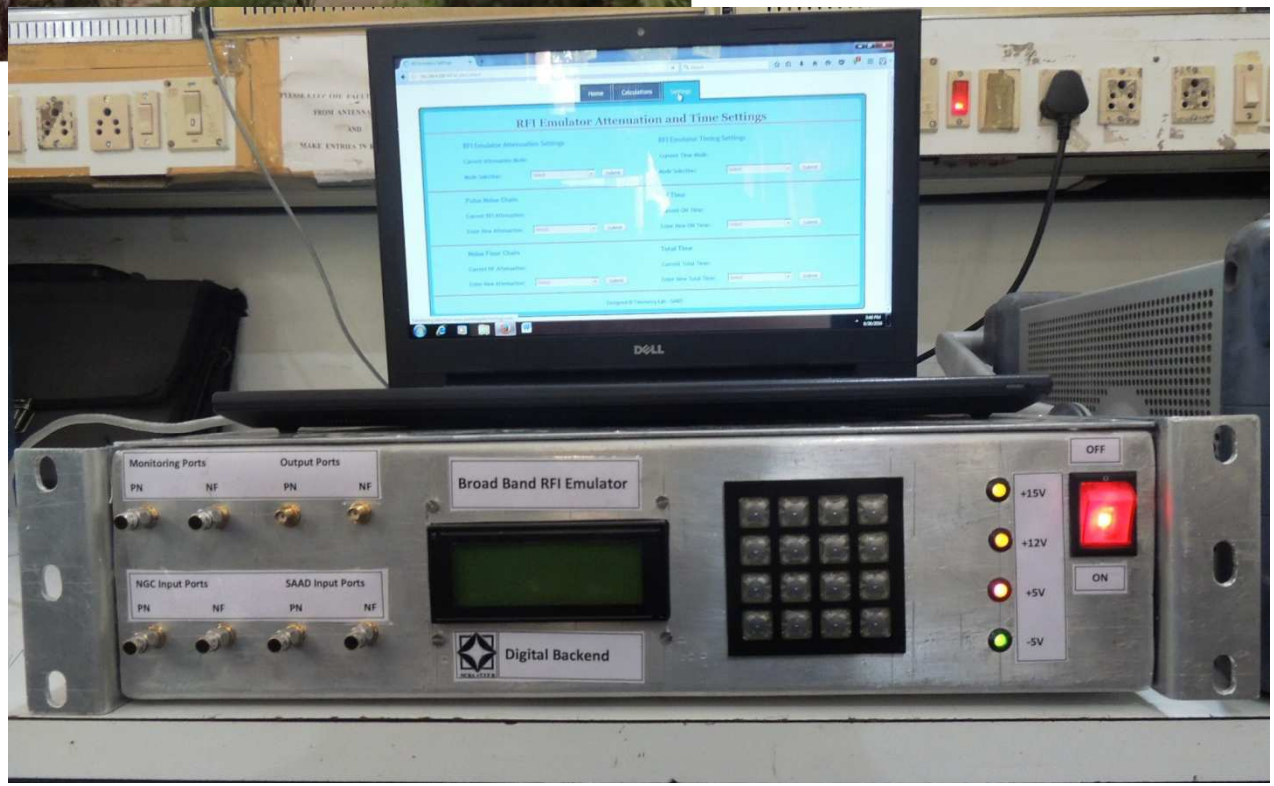



**Regular tests with GWB-3**



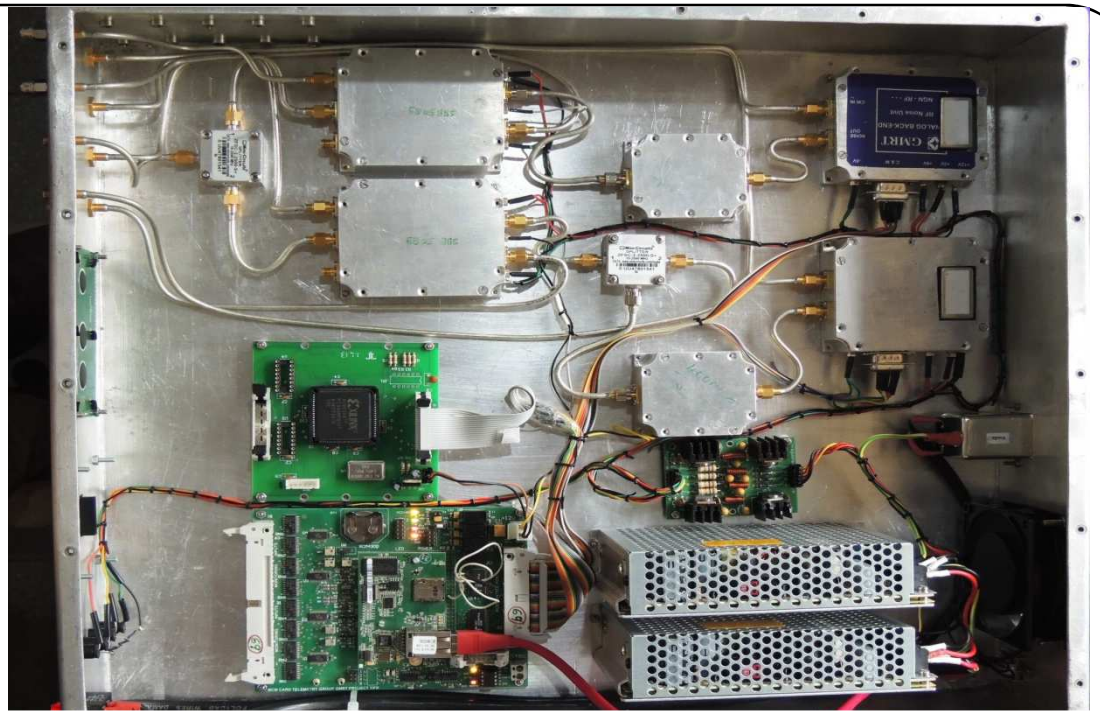

**Long-term tests with GWB-3**

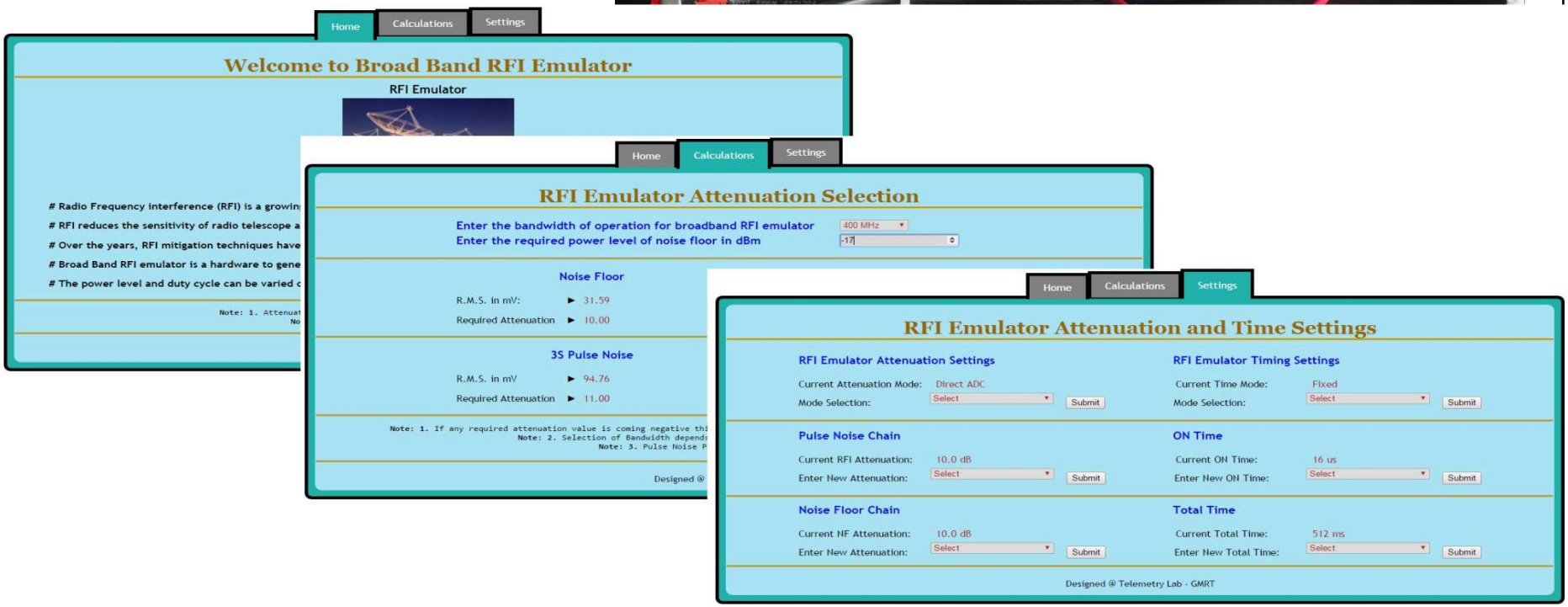
## Radiation Test using RFI Emulator unit




## Test using input to ADC

# RFI Emulator: Top view and Control Software



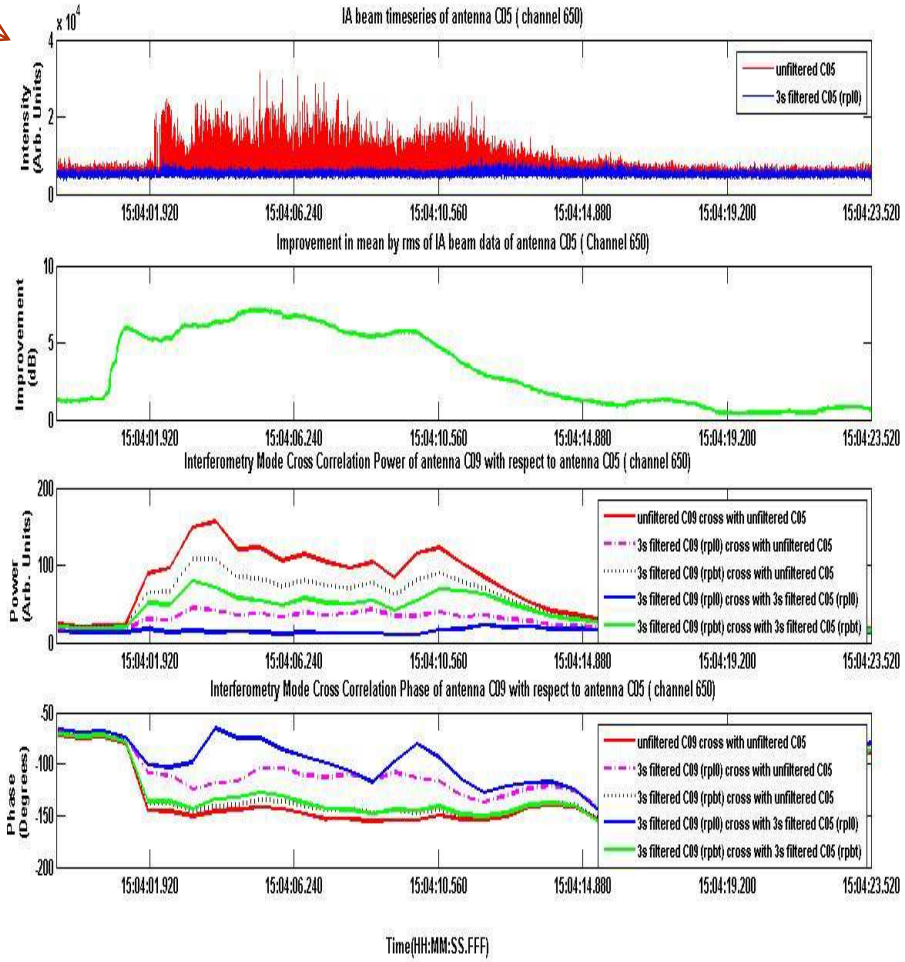


# Test Results

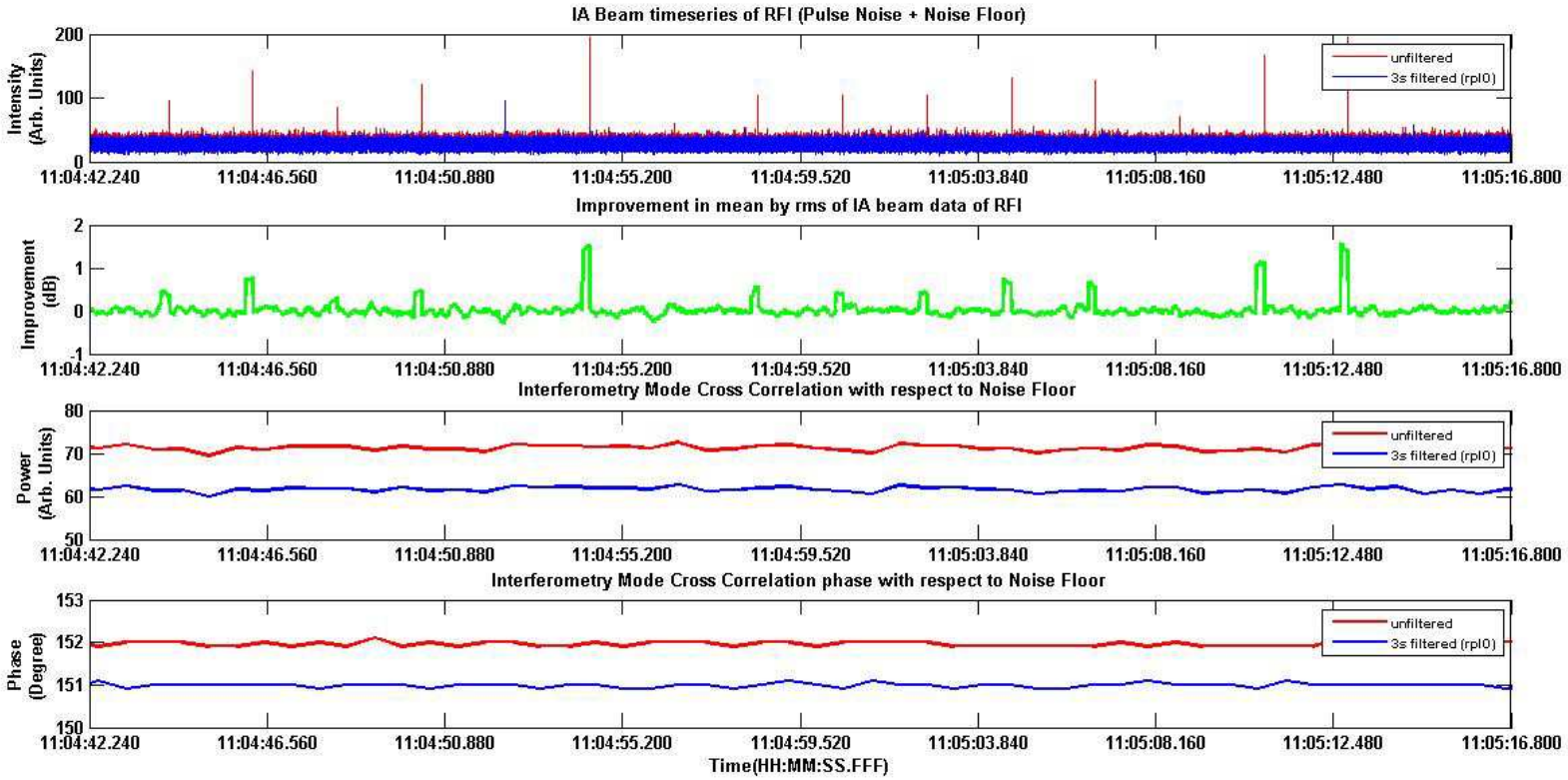
- **Single spectral channel plot over time (IA mode) from the GWB at 1.3 ms time resolution for filtered and unfiltered outputs**
- **Improvement (dB)**

  **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**

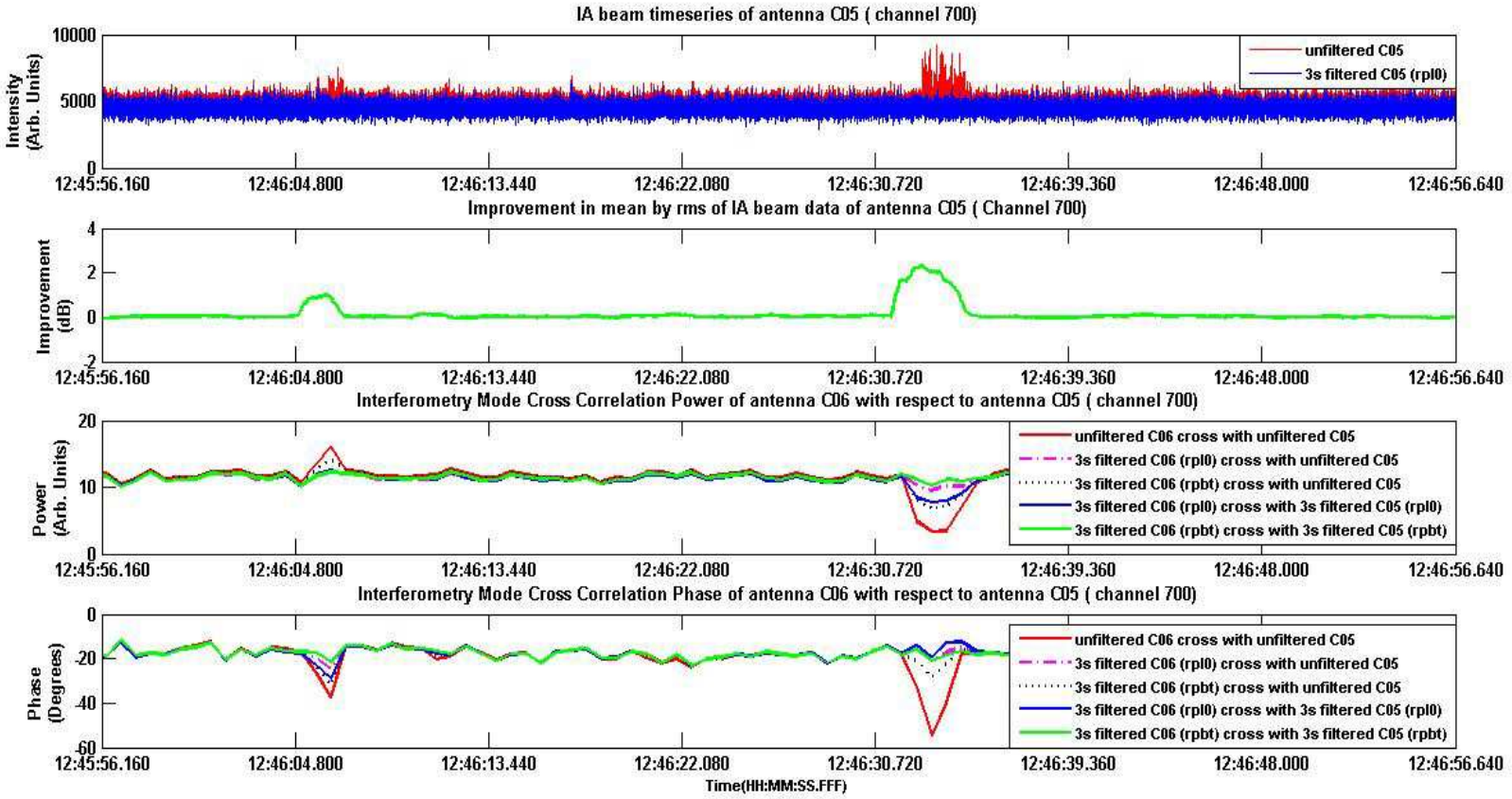


# Test on Emulator Output



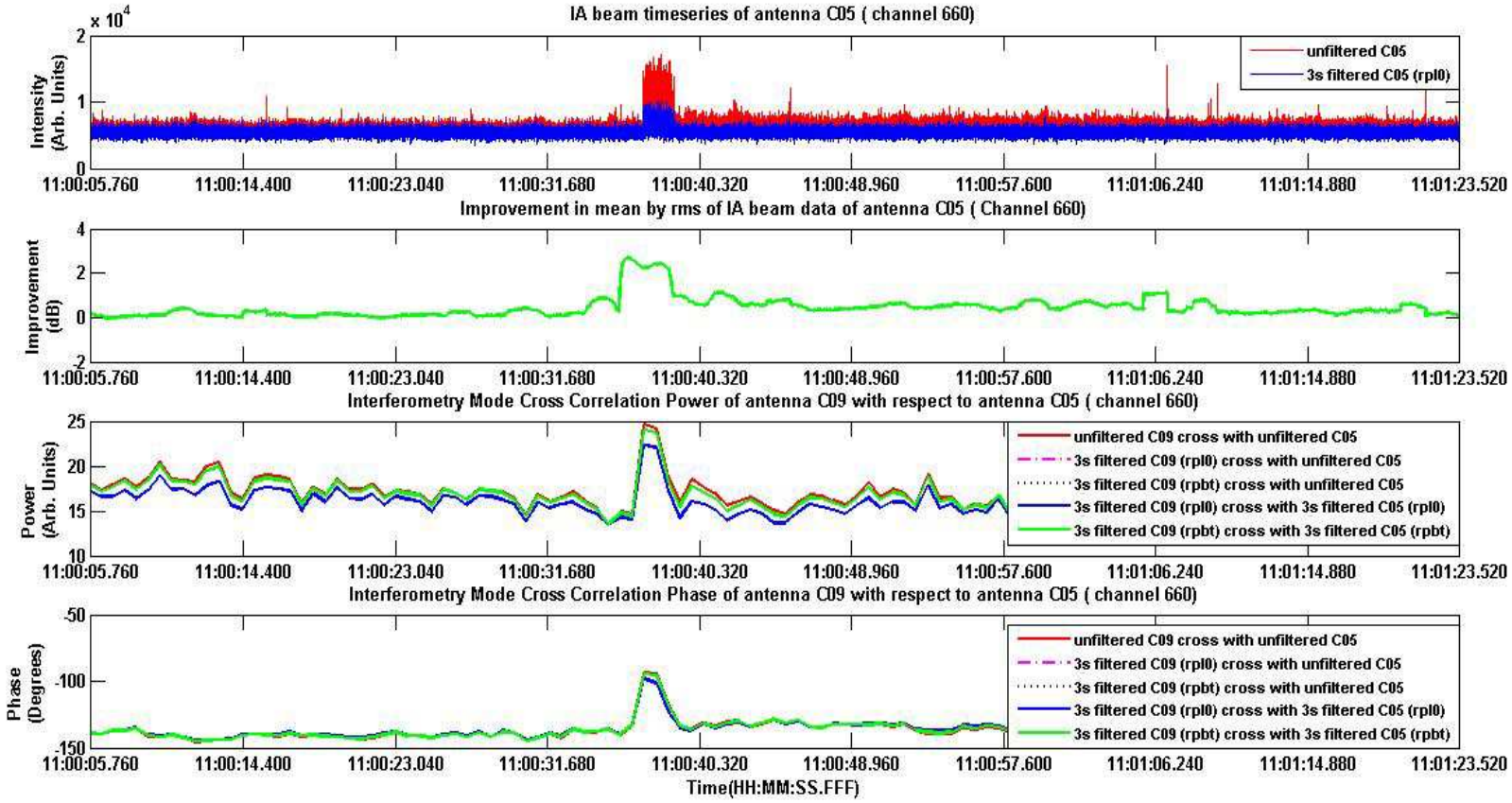

**Time series of emulated RFI showing filtering at 3σ threshold – replacement by zeros**

# Test Results (Antenna signals) (March 2016)



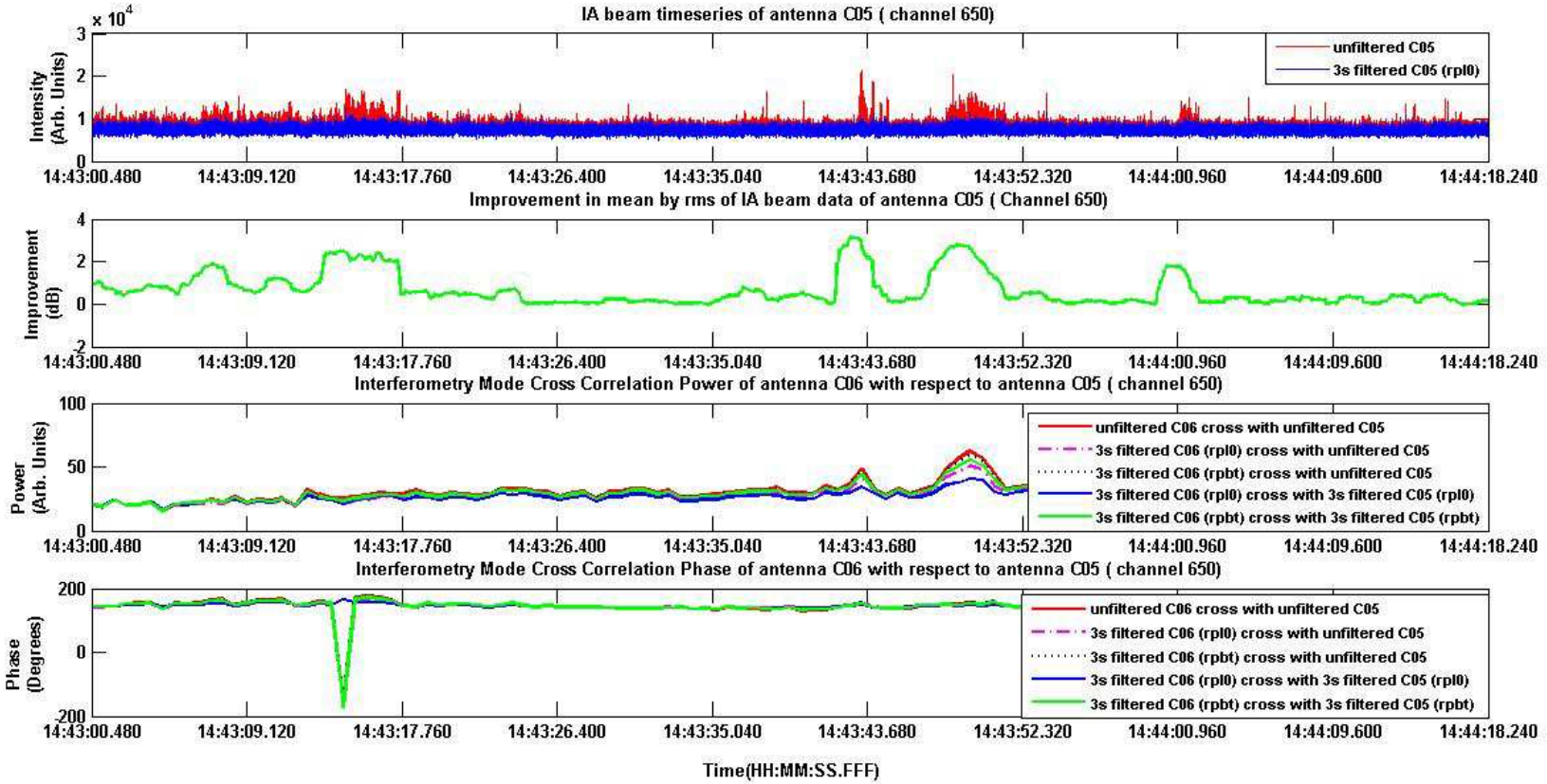

**Beam and correlator data of a spectral channel showing filtering at 3σ threshold – replacement with zero and threshold**

# Test Results (June 2016)



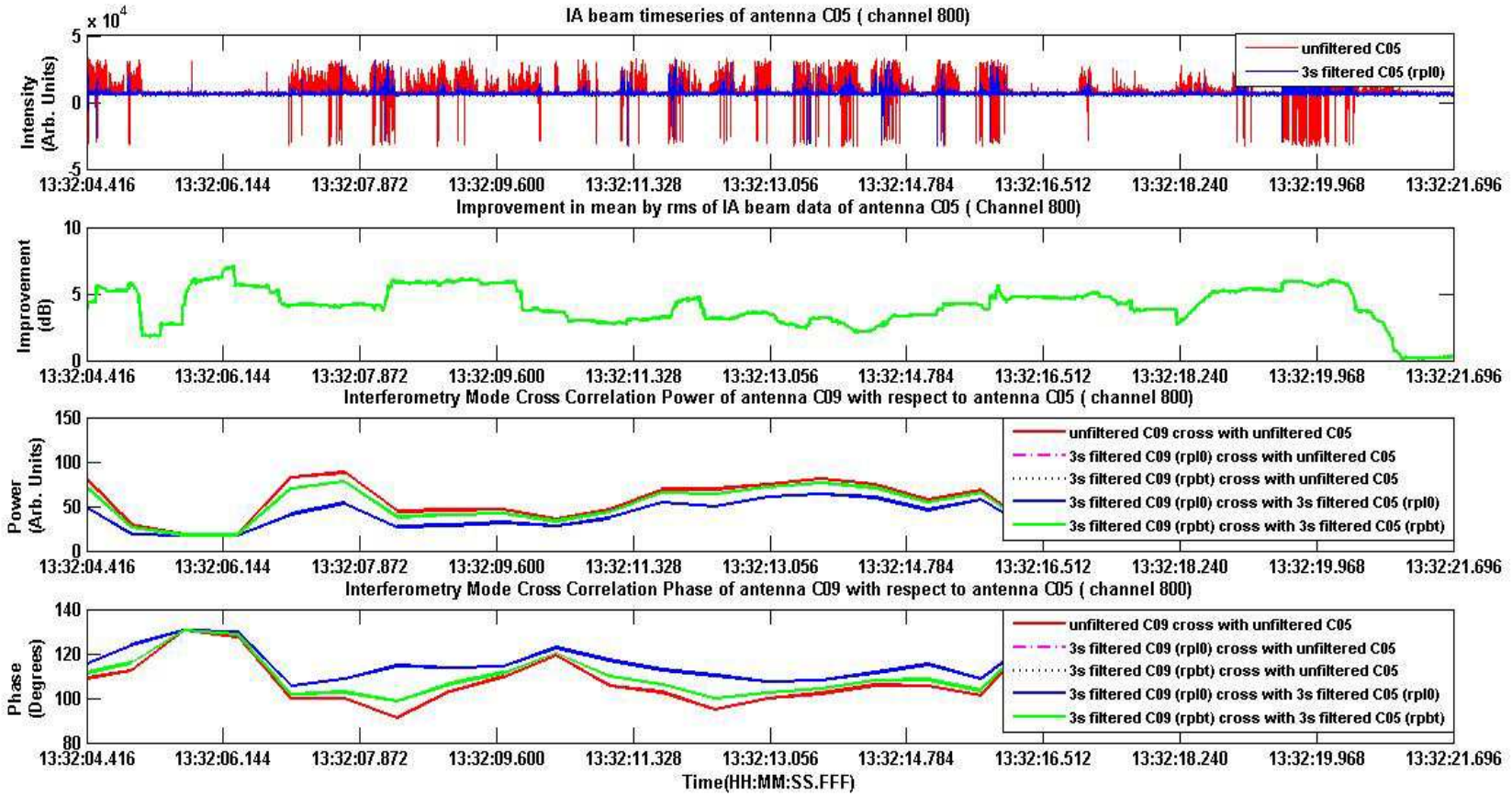

**Beam and correlator data of a spectral channel showing filtering at 3σ threshold – replacement with zero and threshold**

# Test Results (End of June 2016)



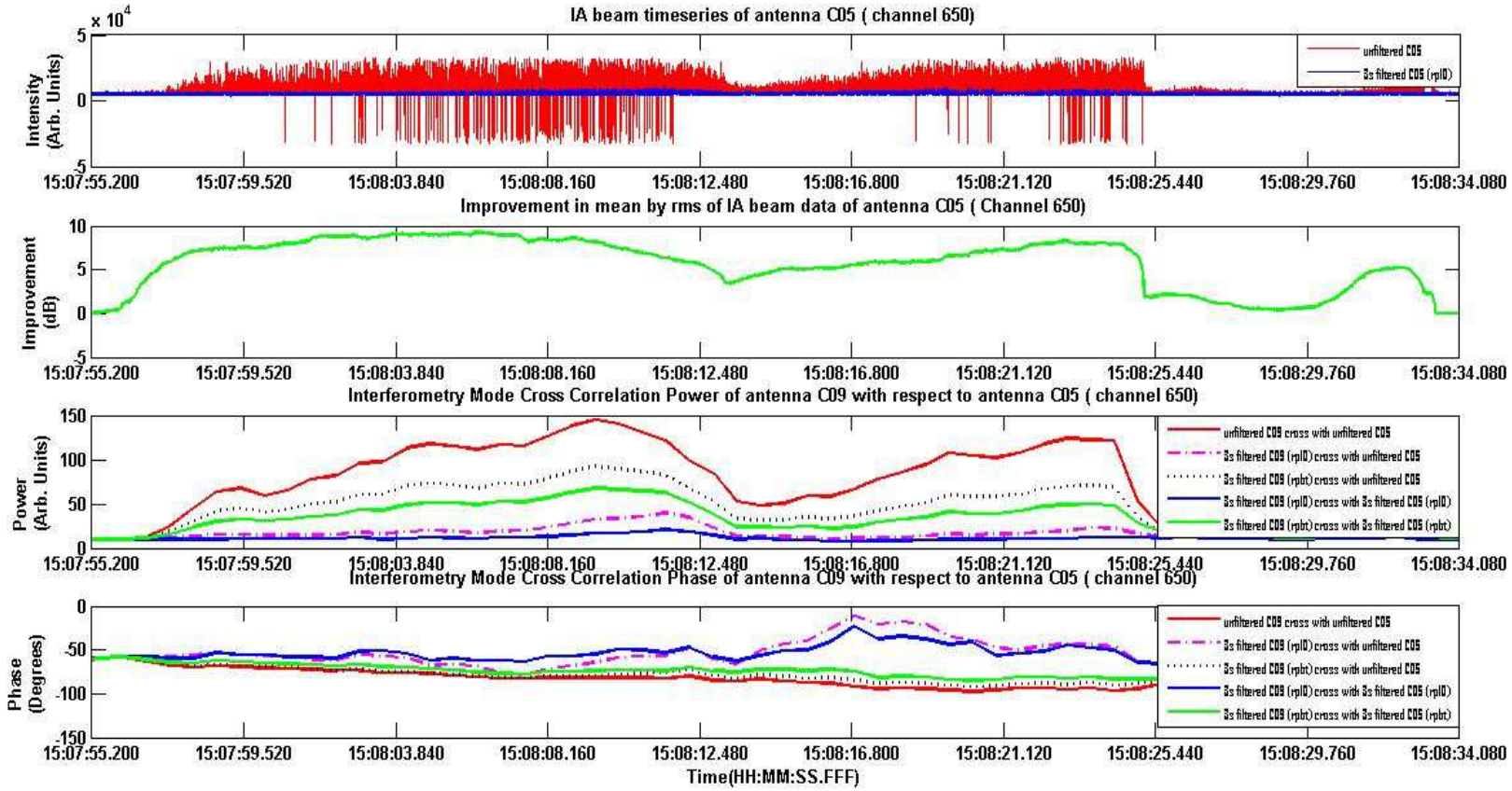

**Beam and correlator data of a spectral channel showing filtering at 3σ threshold – replacement with zero and threshold**

# Test Results (July2016)



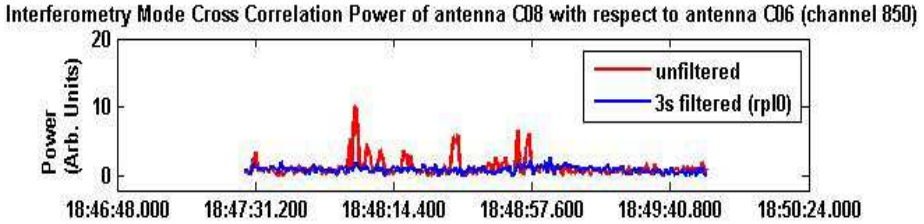

**Beam and correlator data of a spectral channel showing filtering at 3σ threshold – replacement with zero and threshold**

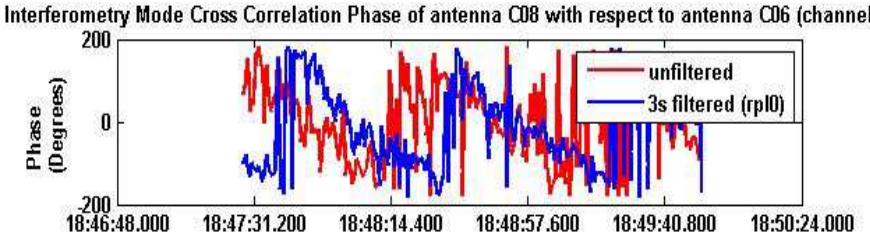
# Test Results (August 2016)

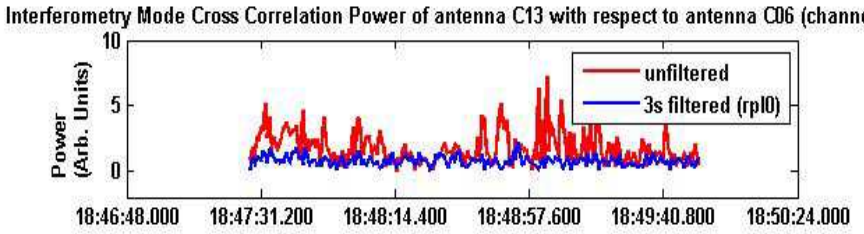


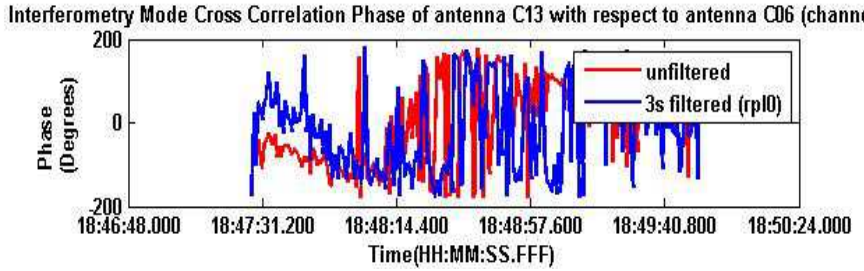

**Beam and correlator data of a spectral channel showing filtering at 3σ threshold – replacement with zero and threshold**

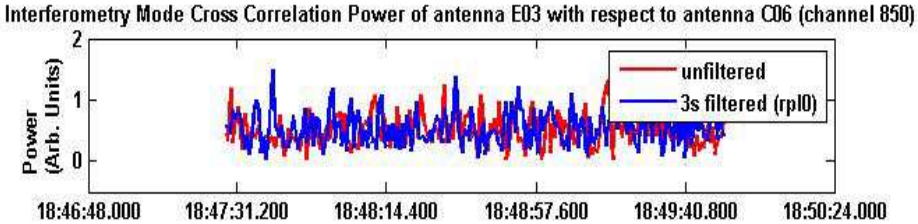
# Off-source tests (250-500 MHz)

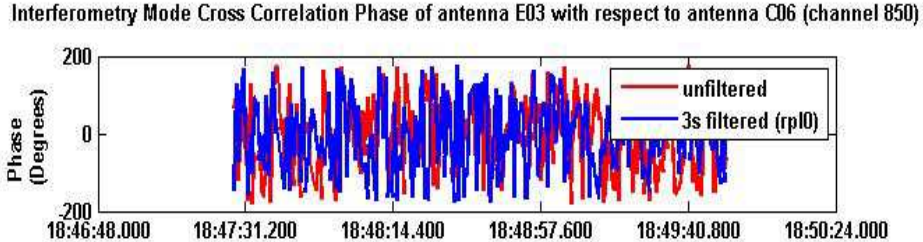


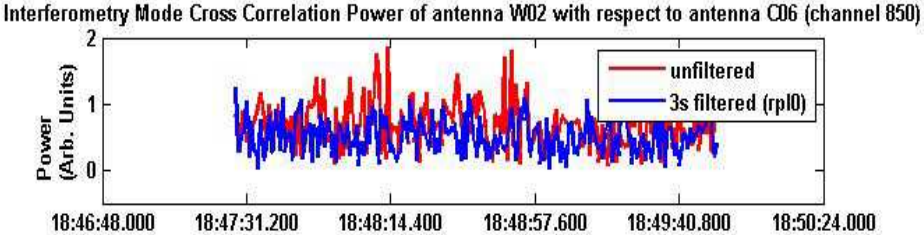



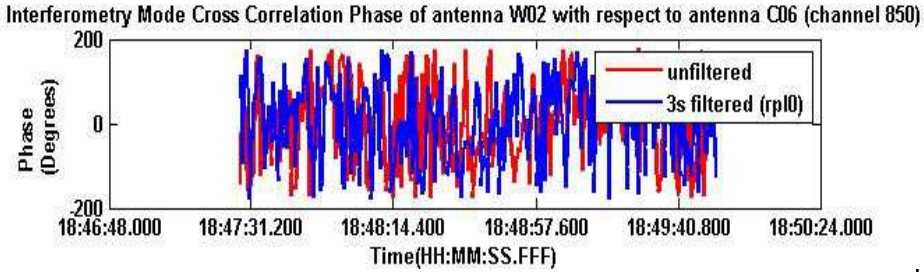



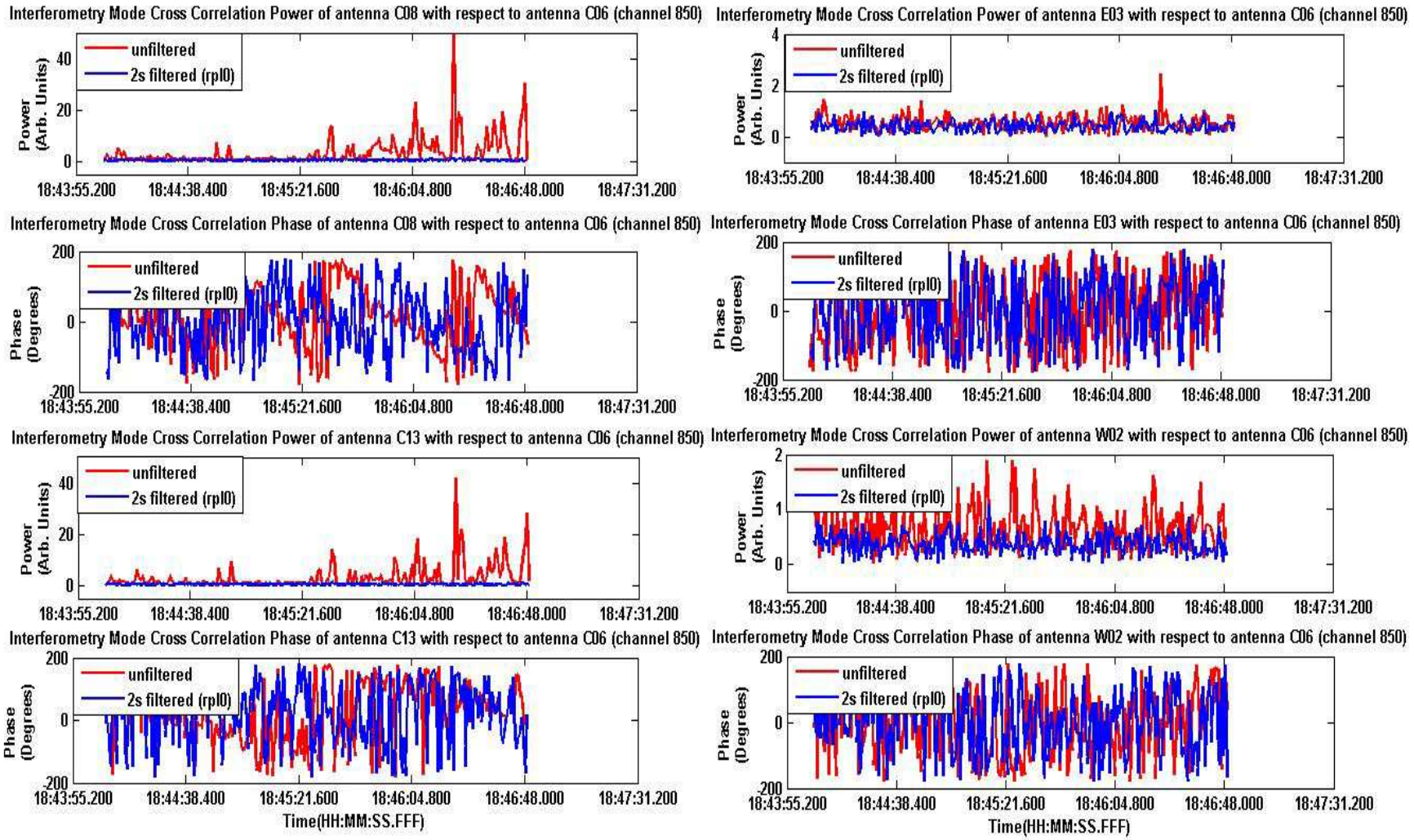



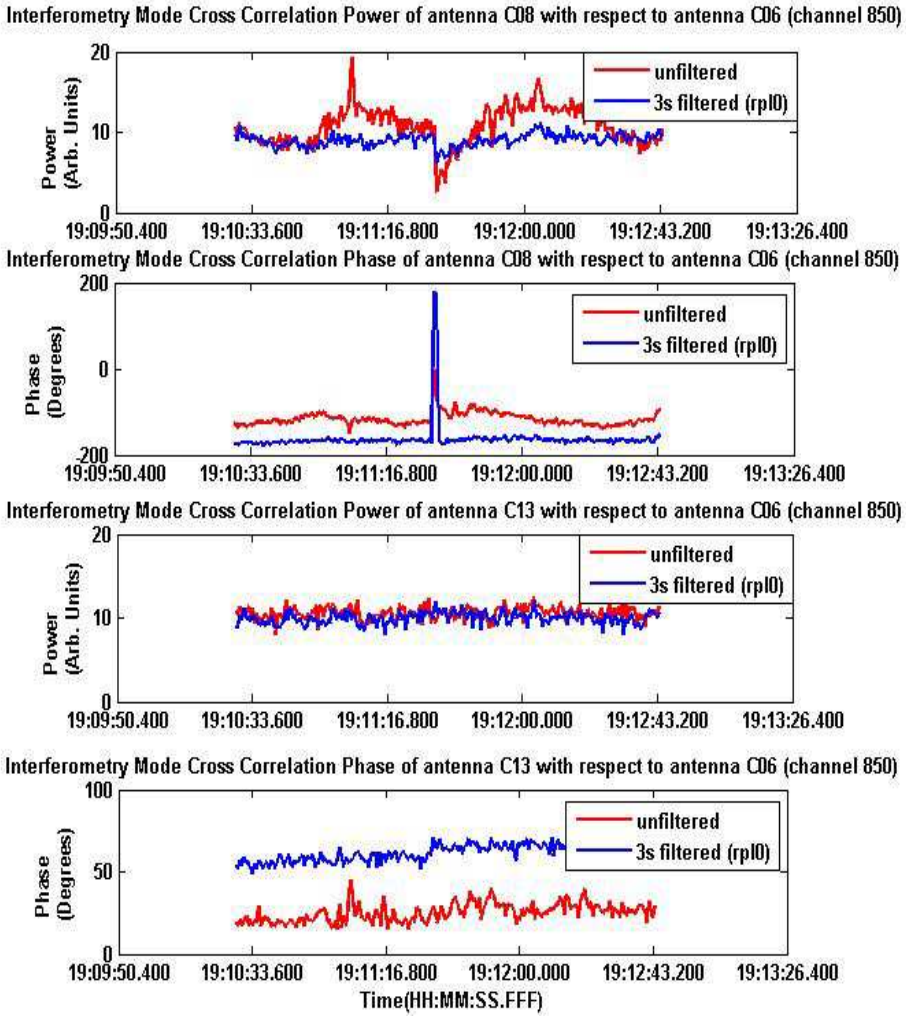

**3 sigma filtering (replaced by zero)**

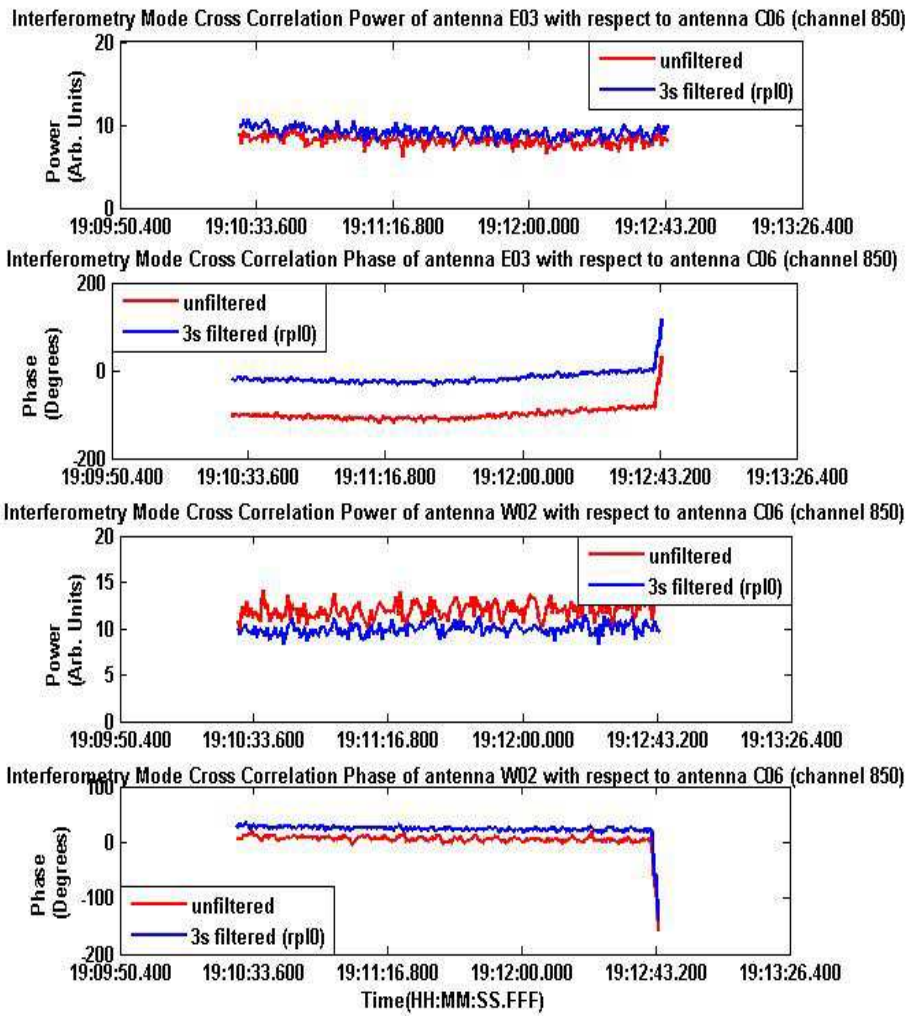
# Off-source tests (250-500 MHz)




**2 sigma filtering (replaced by zero)**

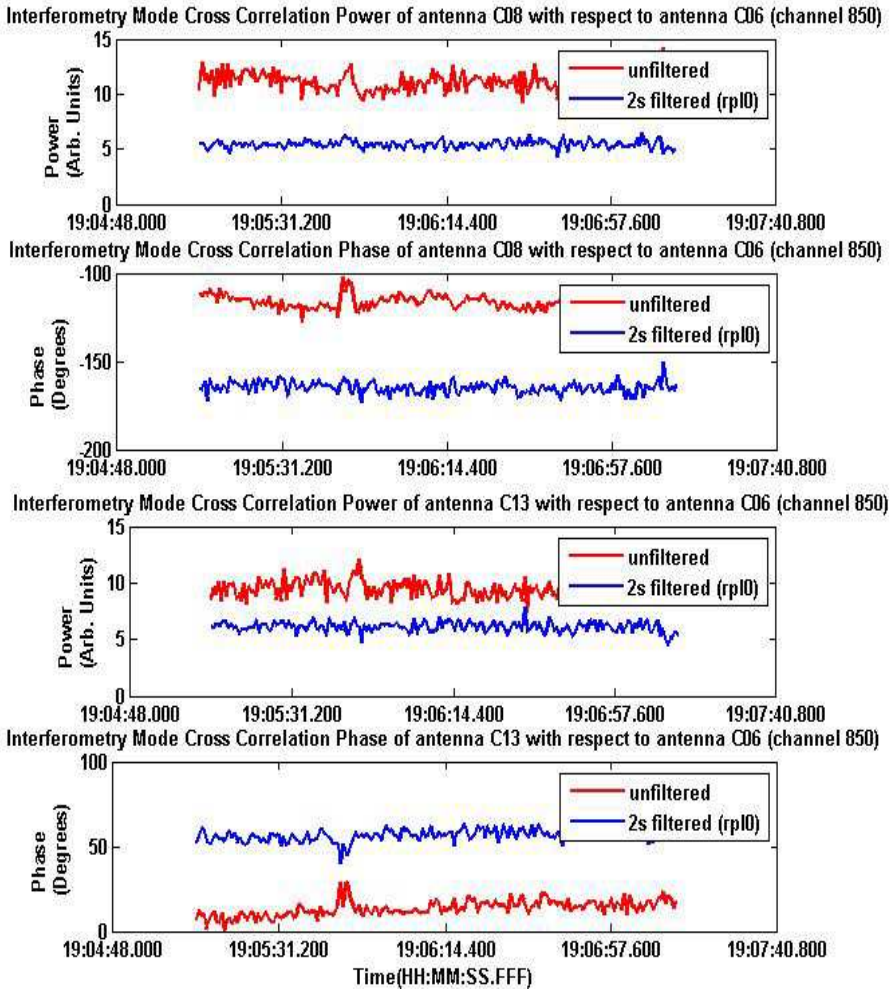
# On-source tests (250-500 MHz)

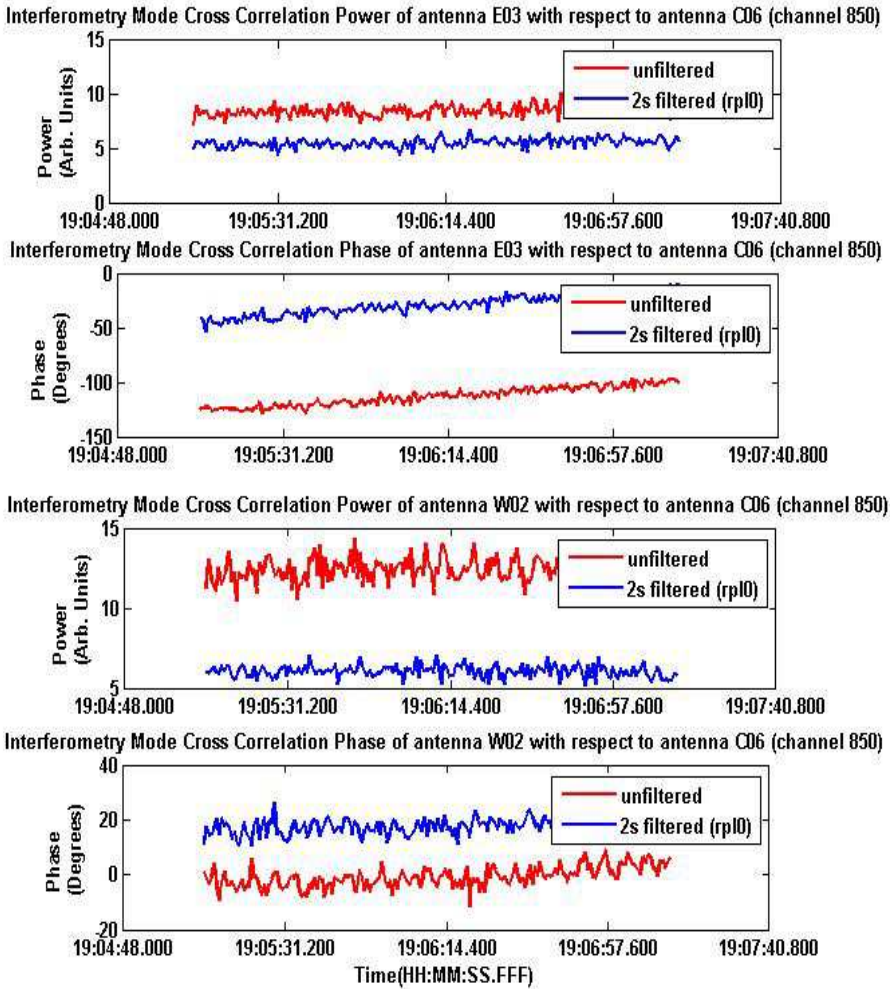



**3 sigma filtering (replaced by zero)**

# On-source tests (250-500 MHz)




**2 sigma filtering (replaced by zero)**

# Results from test observations with GWB-3

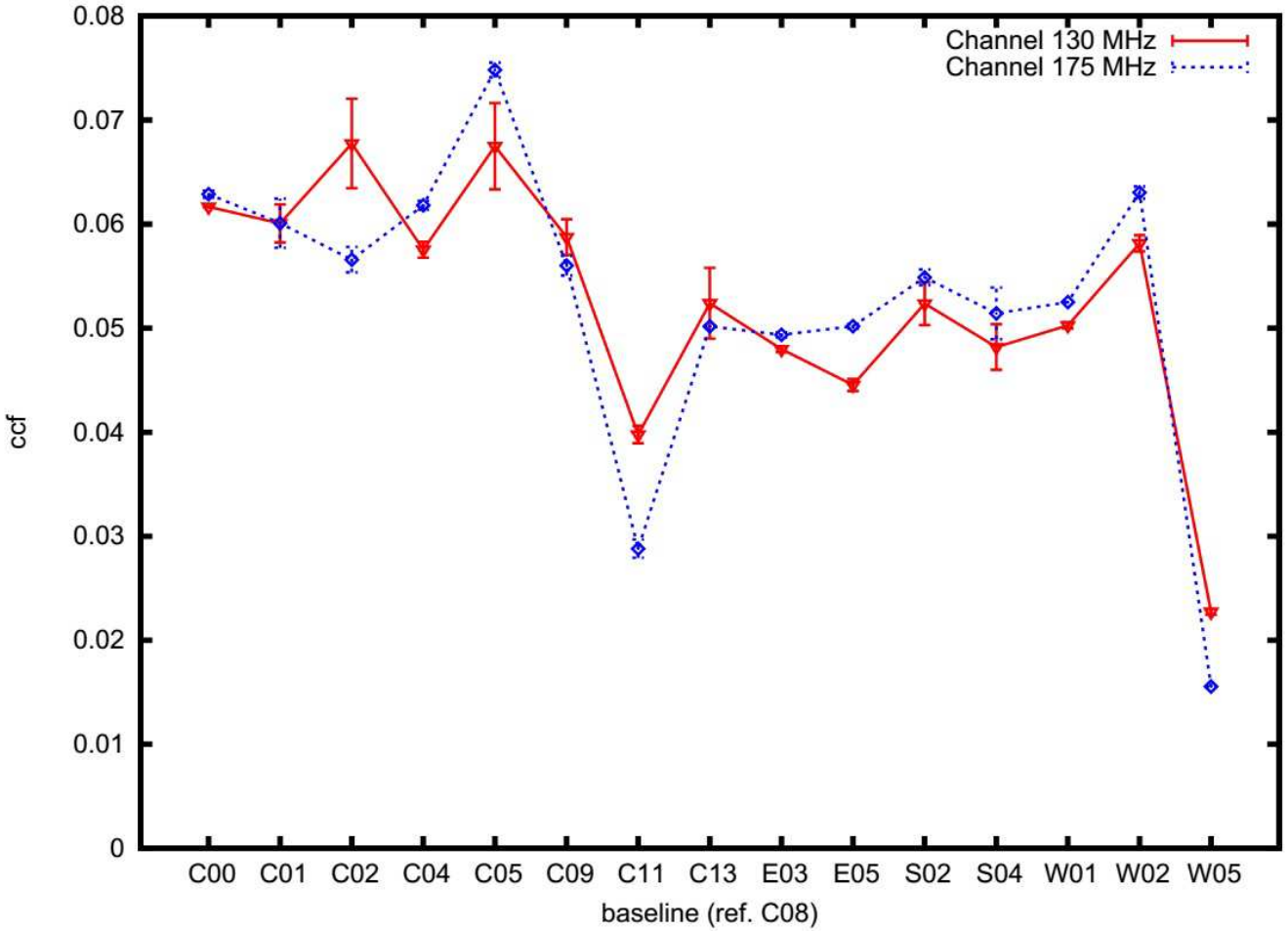
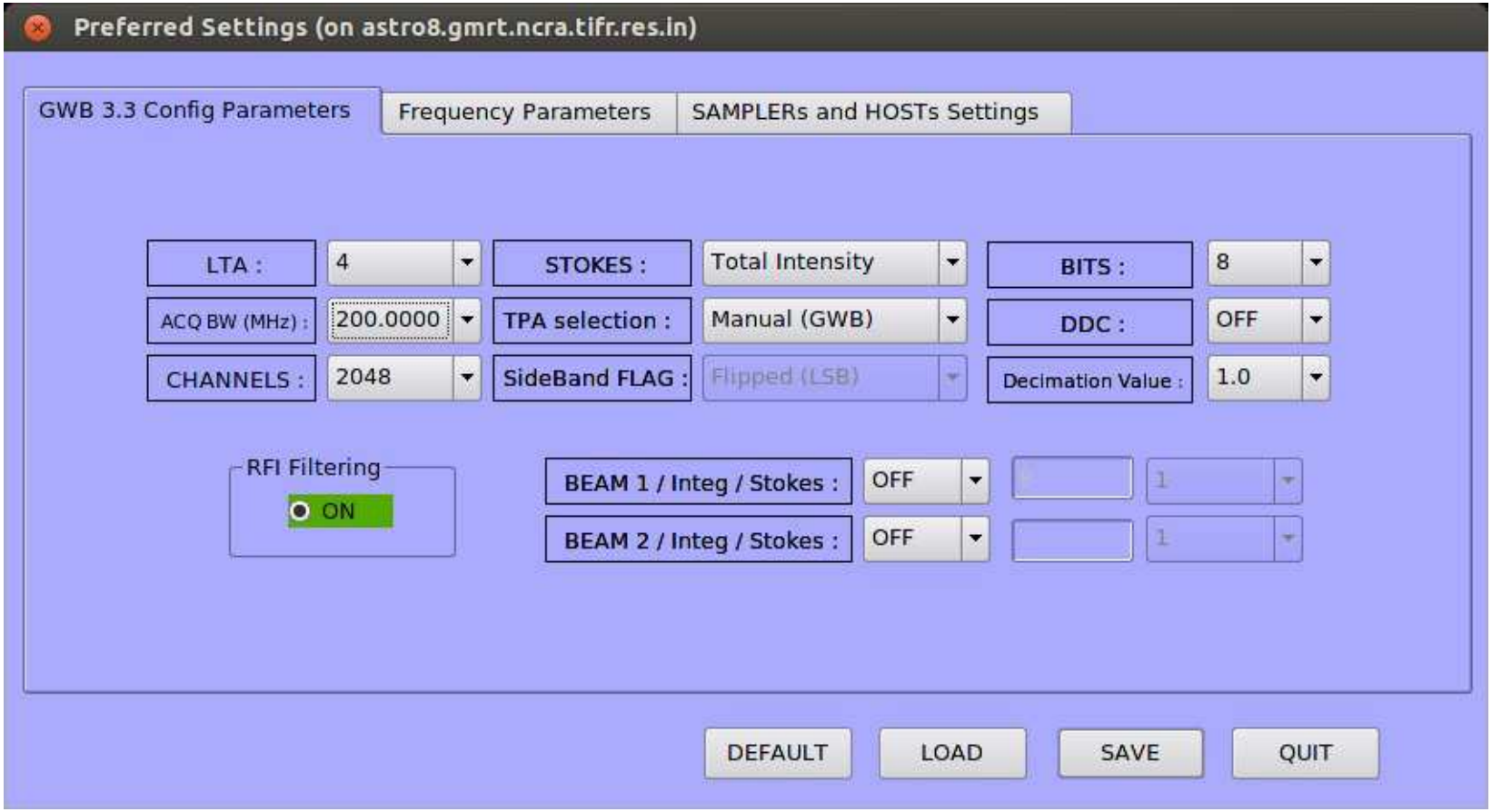




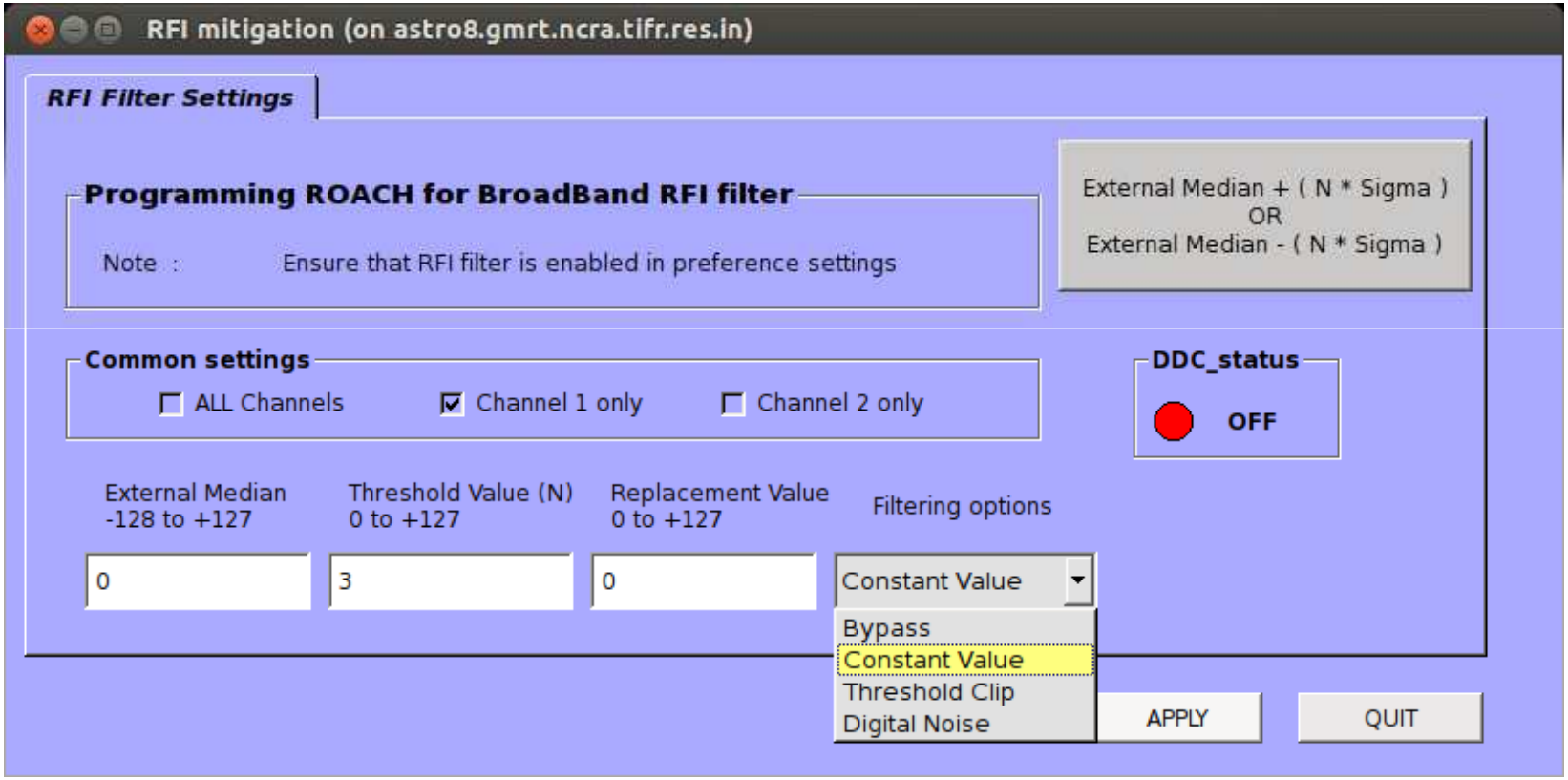



Image Courtesy: Dharam Vir Lal

# GWB Main GUI


Preferred Settings (on astro8.gmrt.ncra.tifr.res.in)
GWB 3.3 Config Parameters
Frequency Parameters
SAMPLERs and HOSTs Settings
LTA :
4
STOKES :
Total Intensity
BITS :
8
ACQ BW (MHz) :
200.0000
TPA selection :
Manual (GWB)
DDC :
OFF
CHANNELS :
2048
SideBand FLAG :
Flipped (LSB)
Decimation Value :
1.0
RFI Filtering
ON
BEAM 1 / Integ / Stokes :
OFF
BEAM 2 / Integ / Stokes :
OFF
DEFAULT
LOAD
SAVE
QUIT

# GWB-3 GUI for RFI Filtering




**Detailed SOP available with the GMRT control room, can be used with GWB3.3**

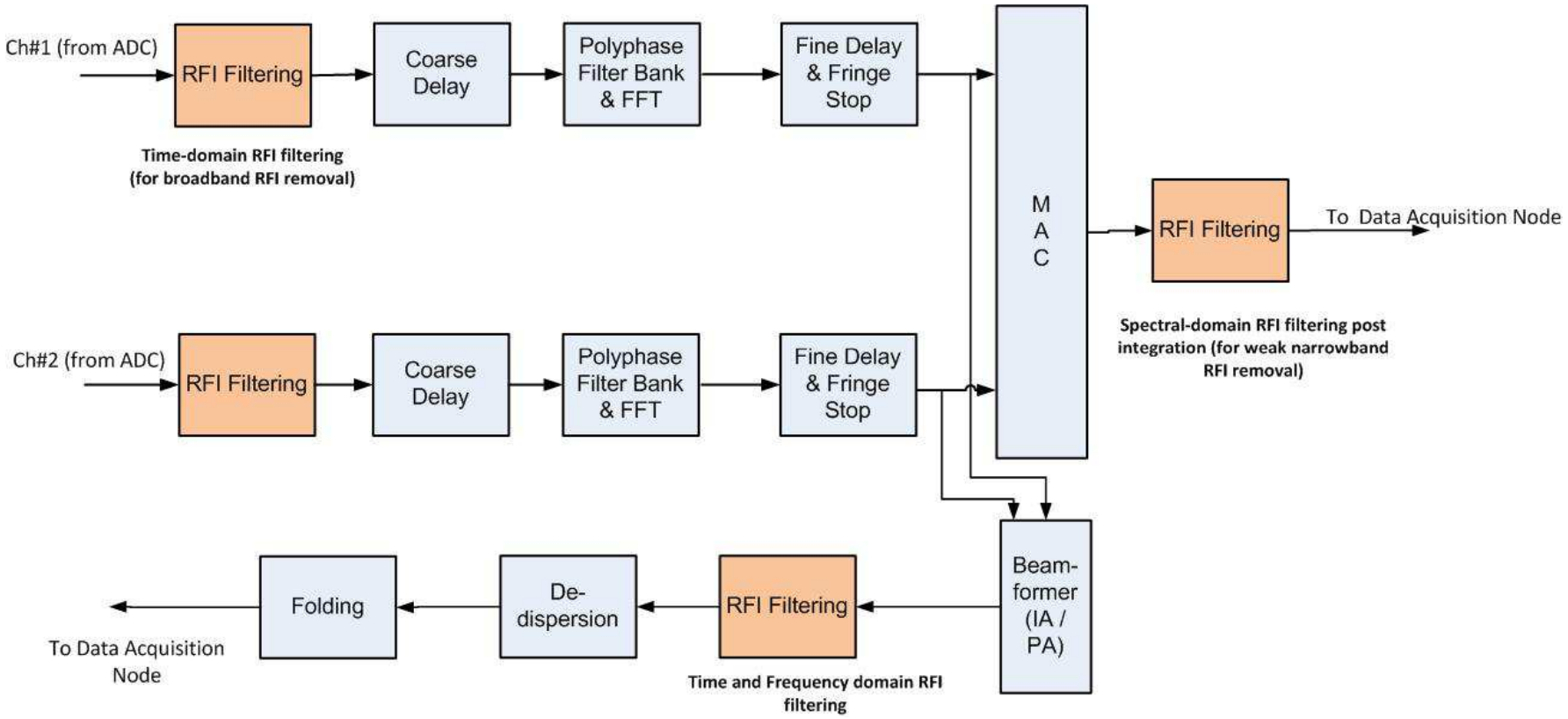
# RFI Filtering: Features in GWB-3

- Possible to set fractional filtering threshold (in steps of 0.1)
- Various filtering options available (constant values, threshold, digital noise)
- Filtering possible in Ch-1 or Ch-2 or both
- 'Bypass' option is also available
- Filtering for 200 or 400 MHz mode as well as narrowband modes of GWB-3
- Number of samples flagged per antenna for a given scan
  - % RFI can be calculated as this feature provides total number of samples and the number of flagged samples

# Book-keeping of flagged samples

- The amount of samples flagged / filtered should be reflected in some form to the user – this is necessary as the data is being altered
- Since the flagging would 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.)
- The final number of data points filtered can be reflected in terms of weights for each visibility output.
- How to handle this when multiple types of RFI are being filtered simultaneously ?

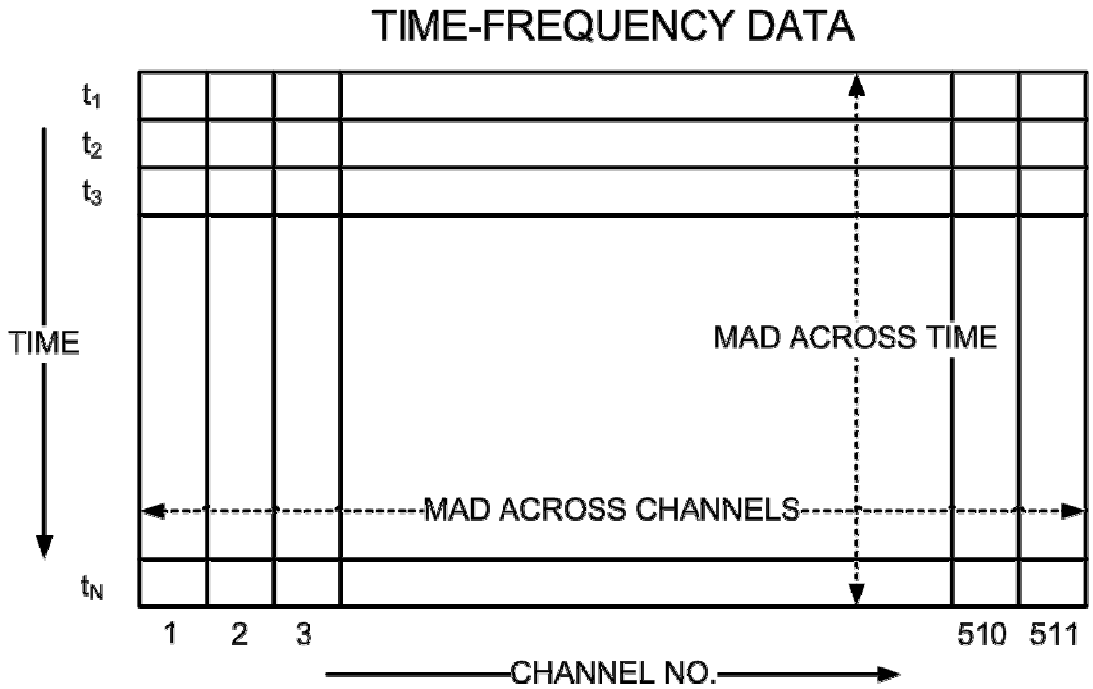
# Spectral Domain RFI Filtering




**Real-time Narrowband RFI Mitigation is carried out after the MAC block**

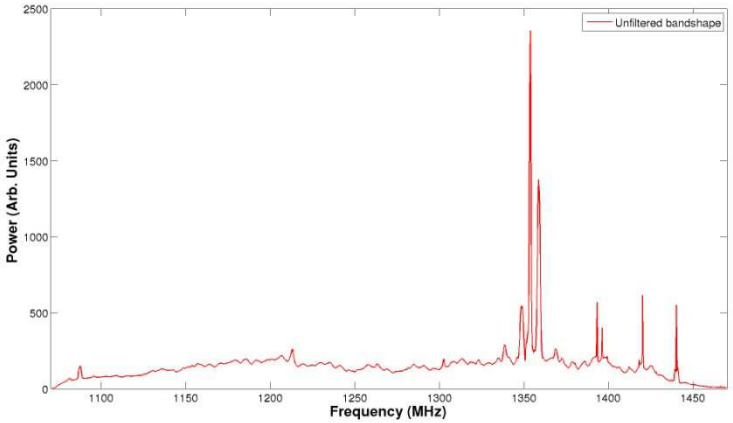
# Two Approaches to Spectral RFI filtering

- 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.

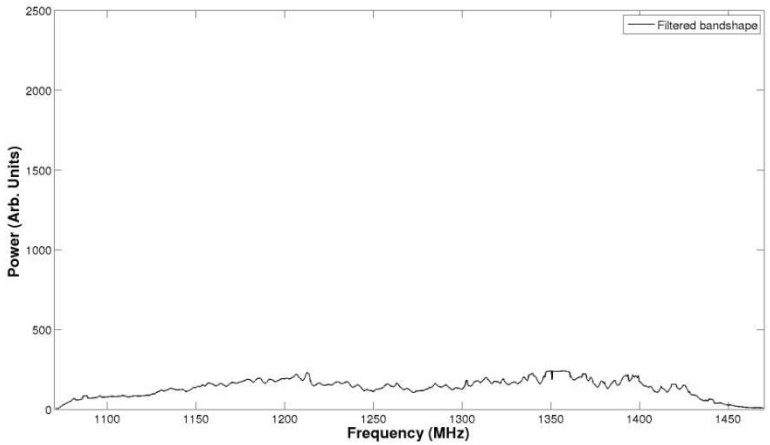


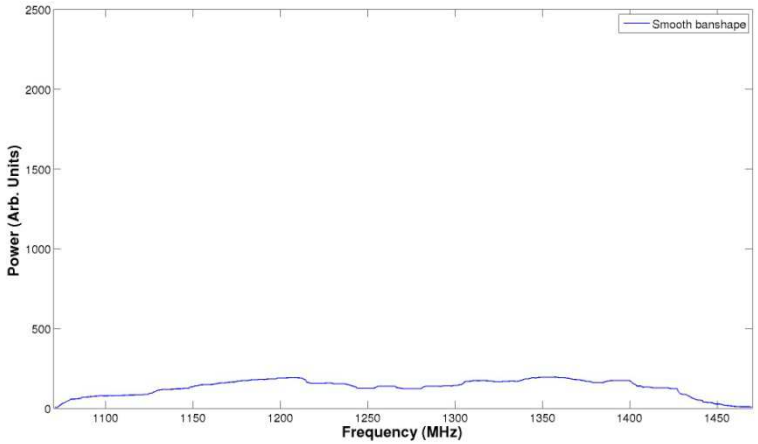
# Narrowband RFI Filtering (MFAC)

**Unfiltered spectrum**

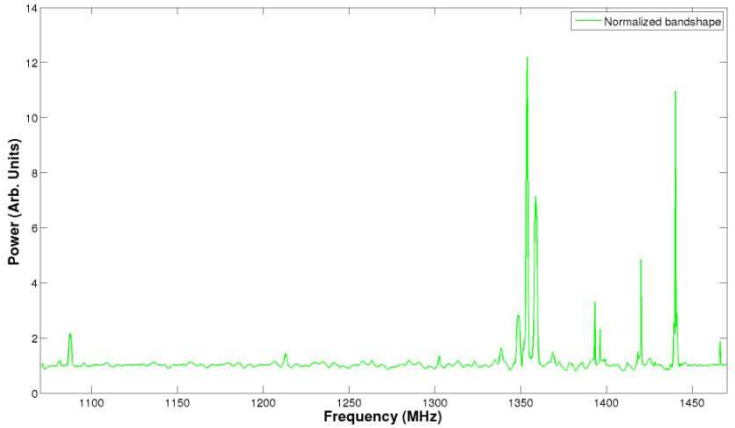



**Filtered spectrum**



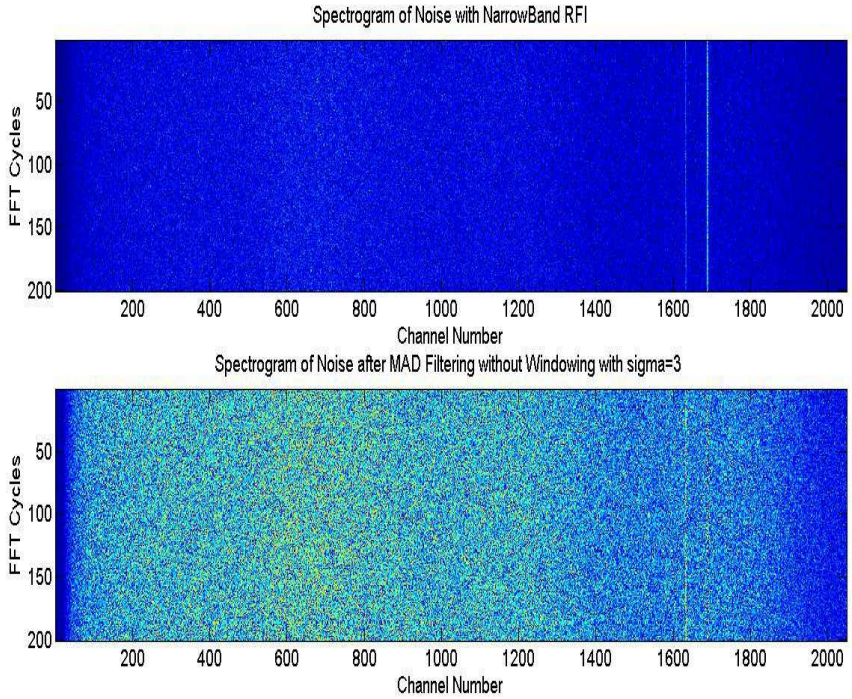




**Smooth spectrum**

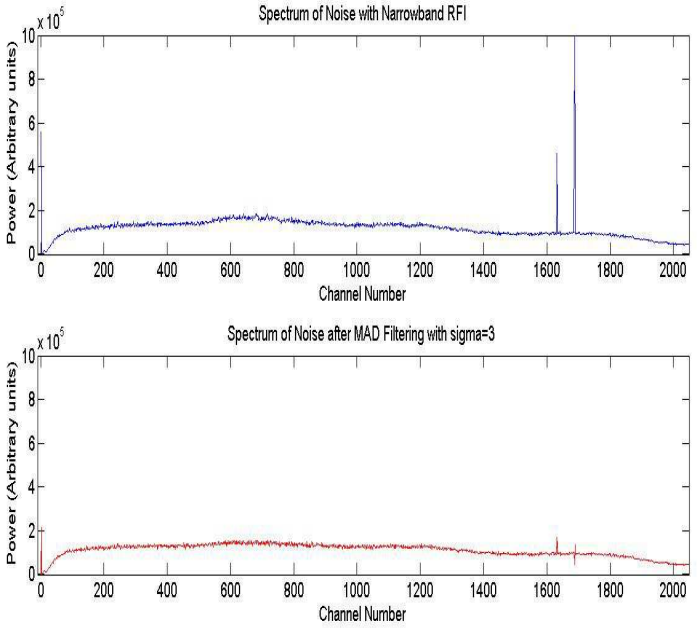



**Normalized spectrum**

# Spectral RFI – across channel filtering

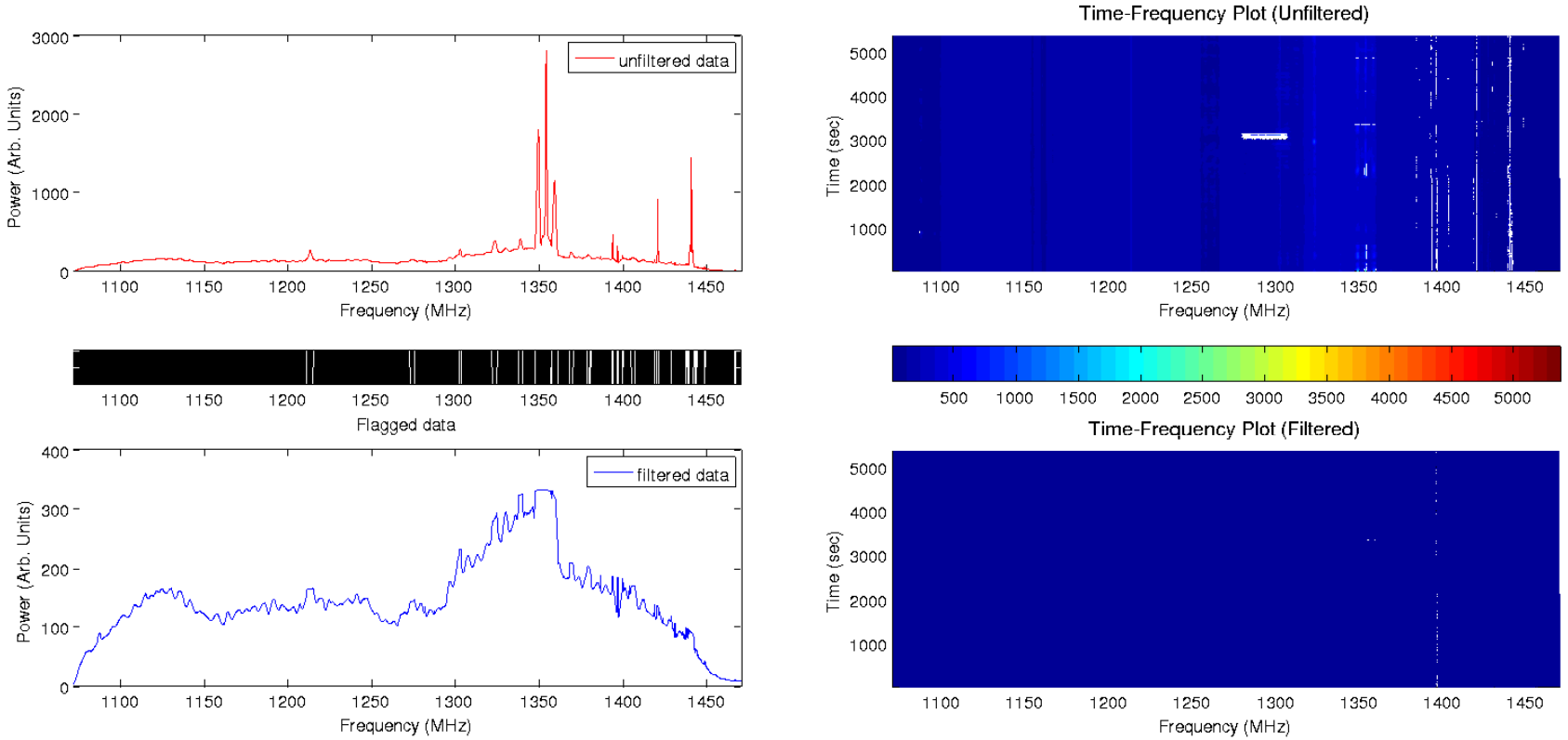



**Two distinct interference lines (from broadcast TV transmission removed using across the channel filtering**




**GWB Spectrum Output – Pre & Post RFI filtering**
**RF: 500 – 700 MHz, BW: 200 MHz**

# Narrowband filtering on GWB data




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

# Summary

- Broadband RFI mitigation using MAD-based filtering in real-time 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 to understand the effect of filtering on power spectrum and cross-correlation are being carried out
- RFI Emulator has been designed for carrying out controlled tests for testing and fine-tuning RFI filtering designs.
- Narrowband RFI mitigation using MFAC has been demonstrated on recorded lta files.

# Future Plans

- Record of detected / filtered samples (flag) –to be implemented in the GWB
- Fine-tune the parameters for optimal broadband filtering
- Study of RFI filtering on the overall improvement for continuum, spectral-line and pulsar observations
- Implement real-time narrowband RFI filtering on CPU on self outputs
- Development of cancellation techniques for reducing the overall loss of astronomical data

# Acknowledgements

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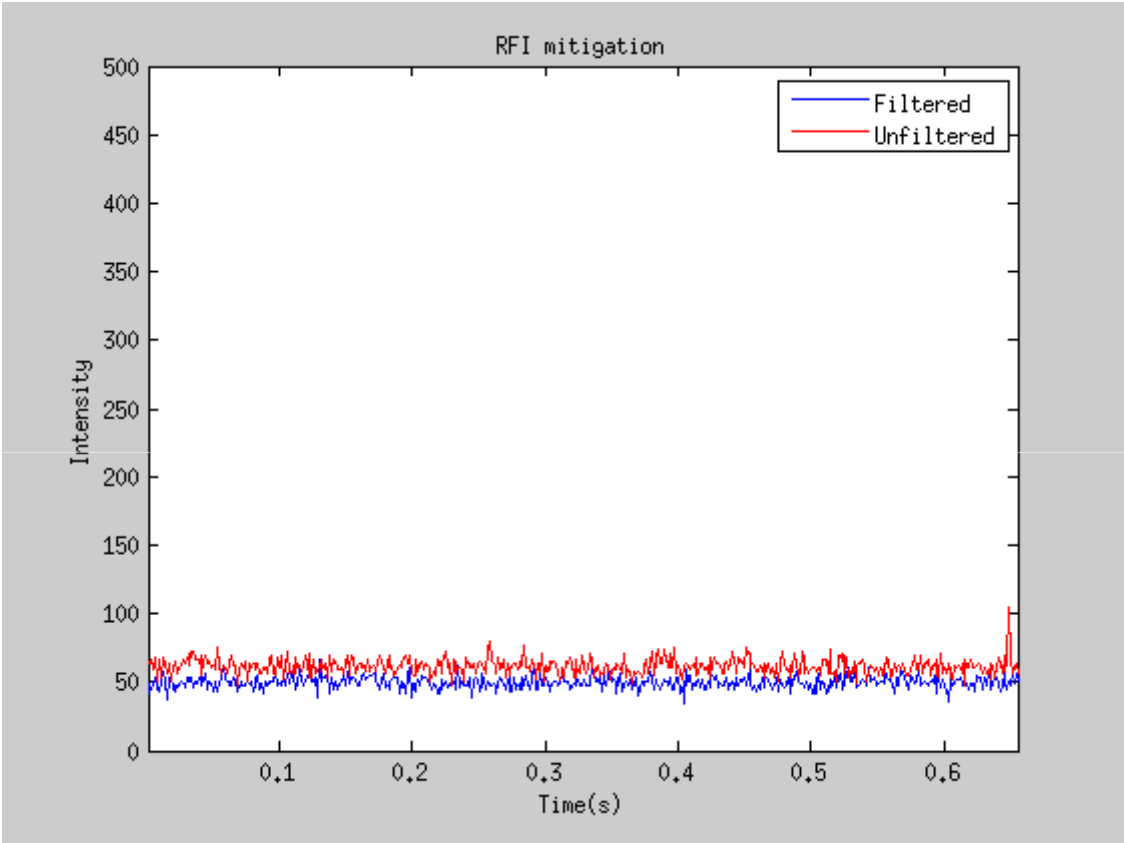
GMRT Control Room

STP students
Kshitij Aggarwal
Tushar Sawadekar
Shriram Nerkar
Nishit Baburaj


Thank You!

# Short Video Clip – GWB output




**GWB in IA mode – Intensity Plot of Channel 500 (RF ~ 651 MHz)**

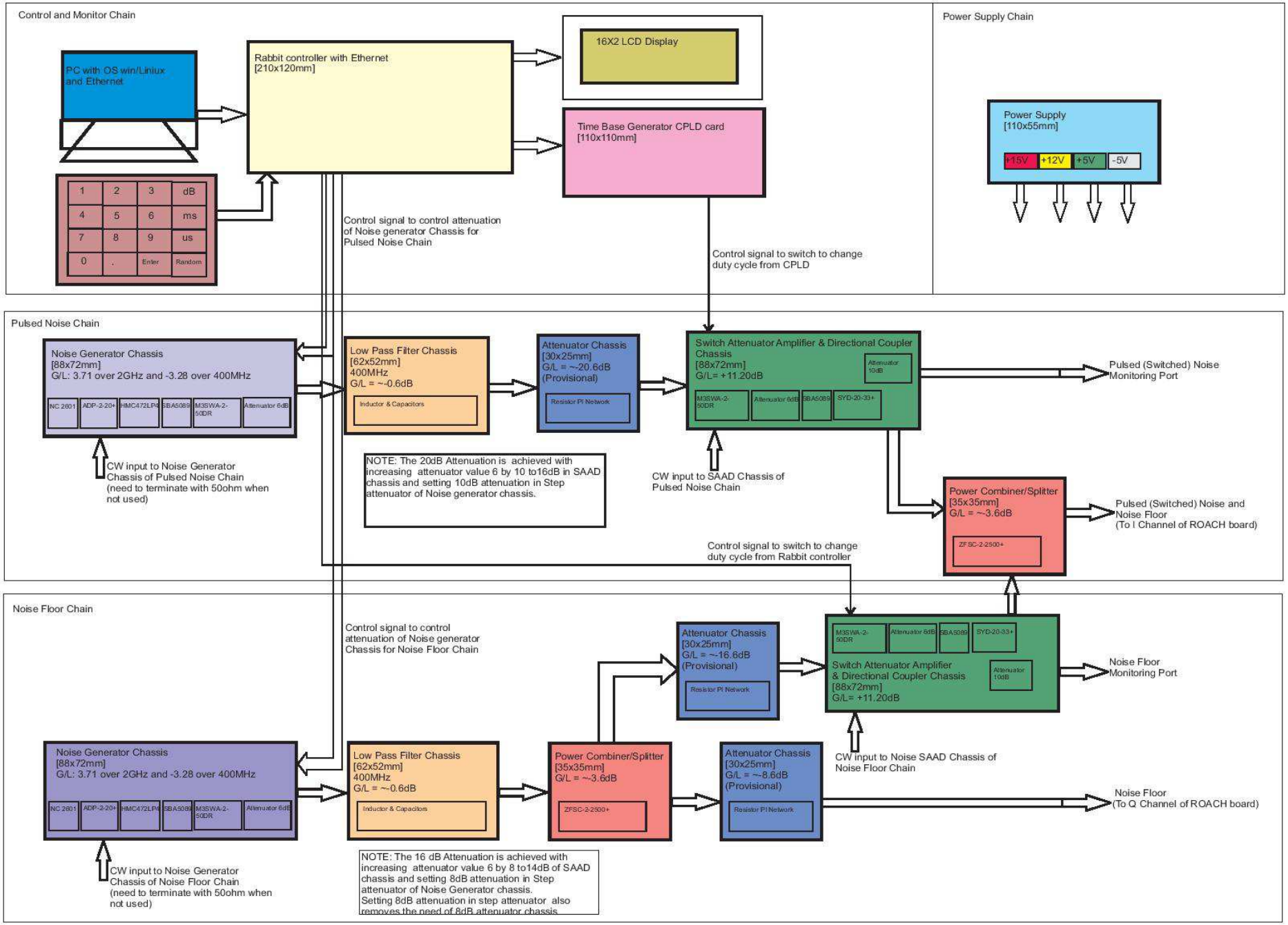
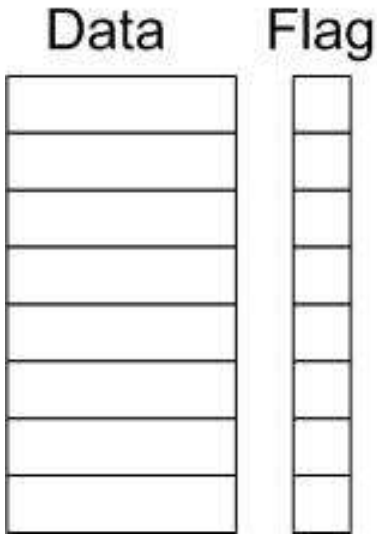


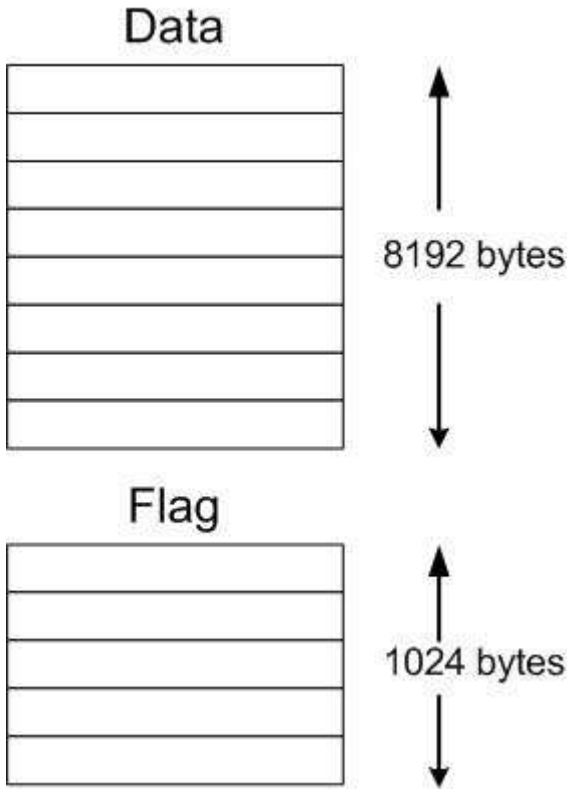

Fig. : Block Diagram for RFI Emulator

# Book-keeping of detected / filtered data

Proposed scheme



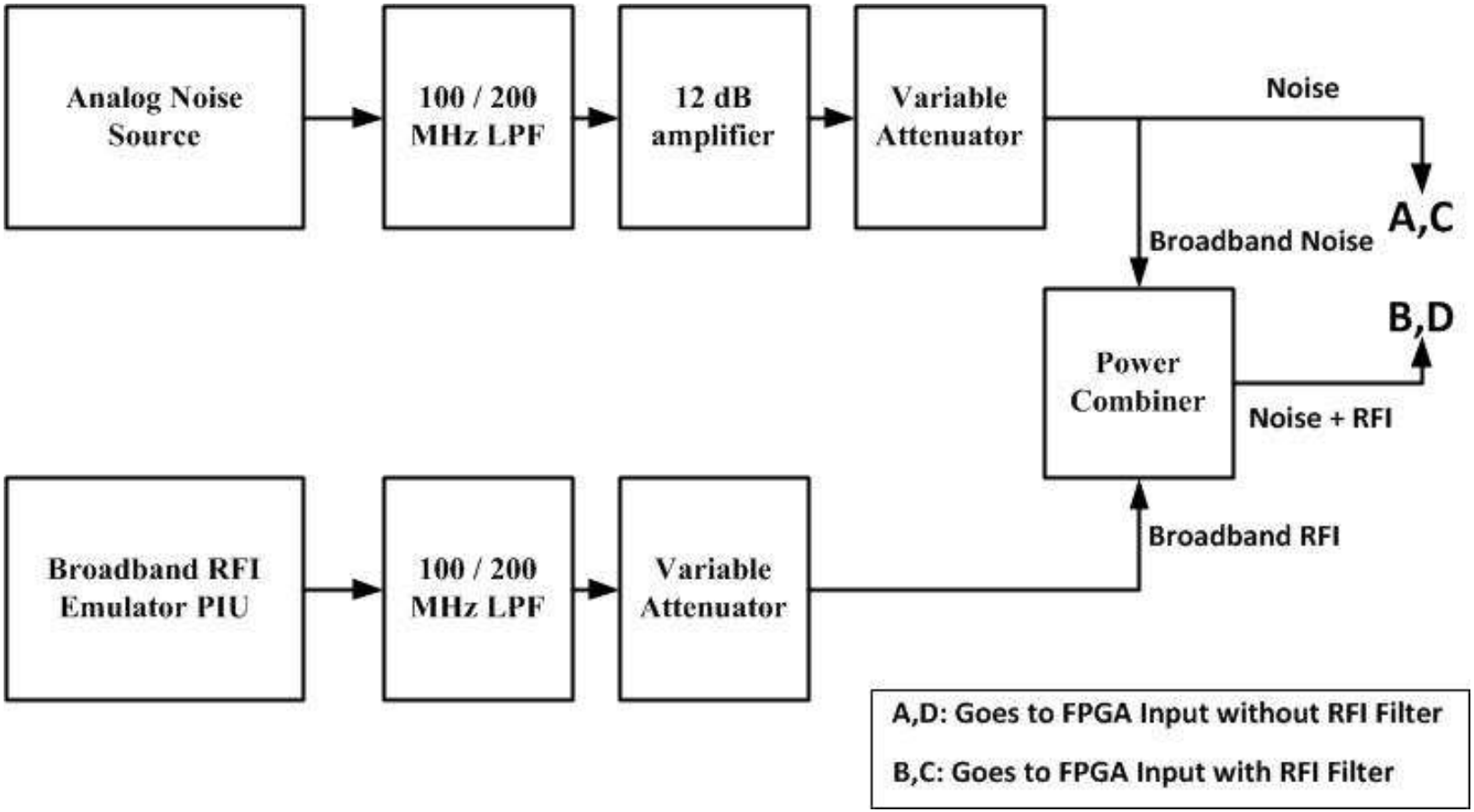

10 GbE packet format



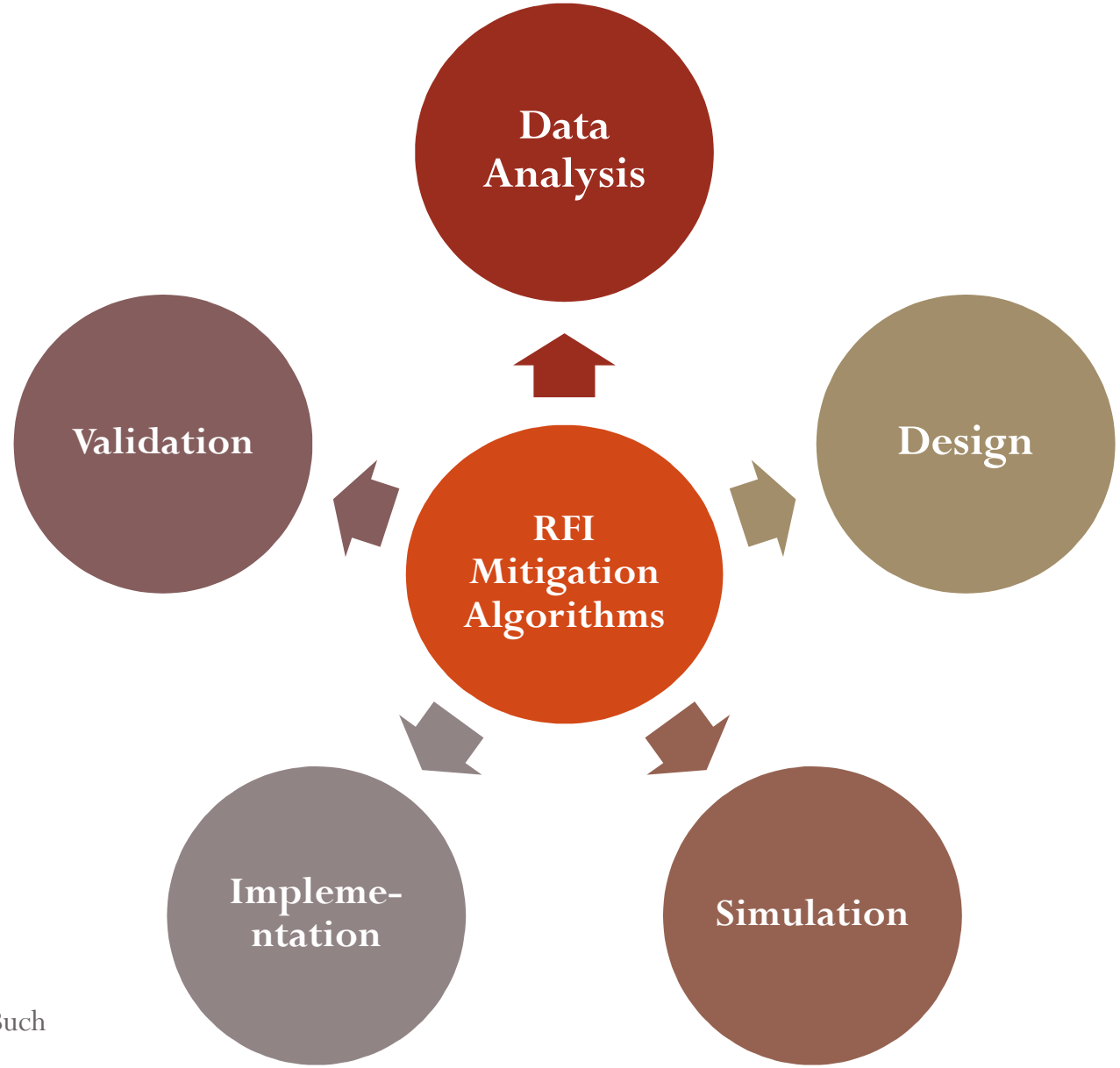

- One-bit flag for each sample (8 bits)
- 12.5 % overhead in transporting the data (and processing it in the later stages of the signal processing chain)

**Limited by jumbo packet size (9000 bytes) and available data transfer rate**

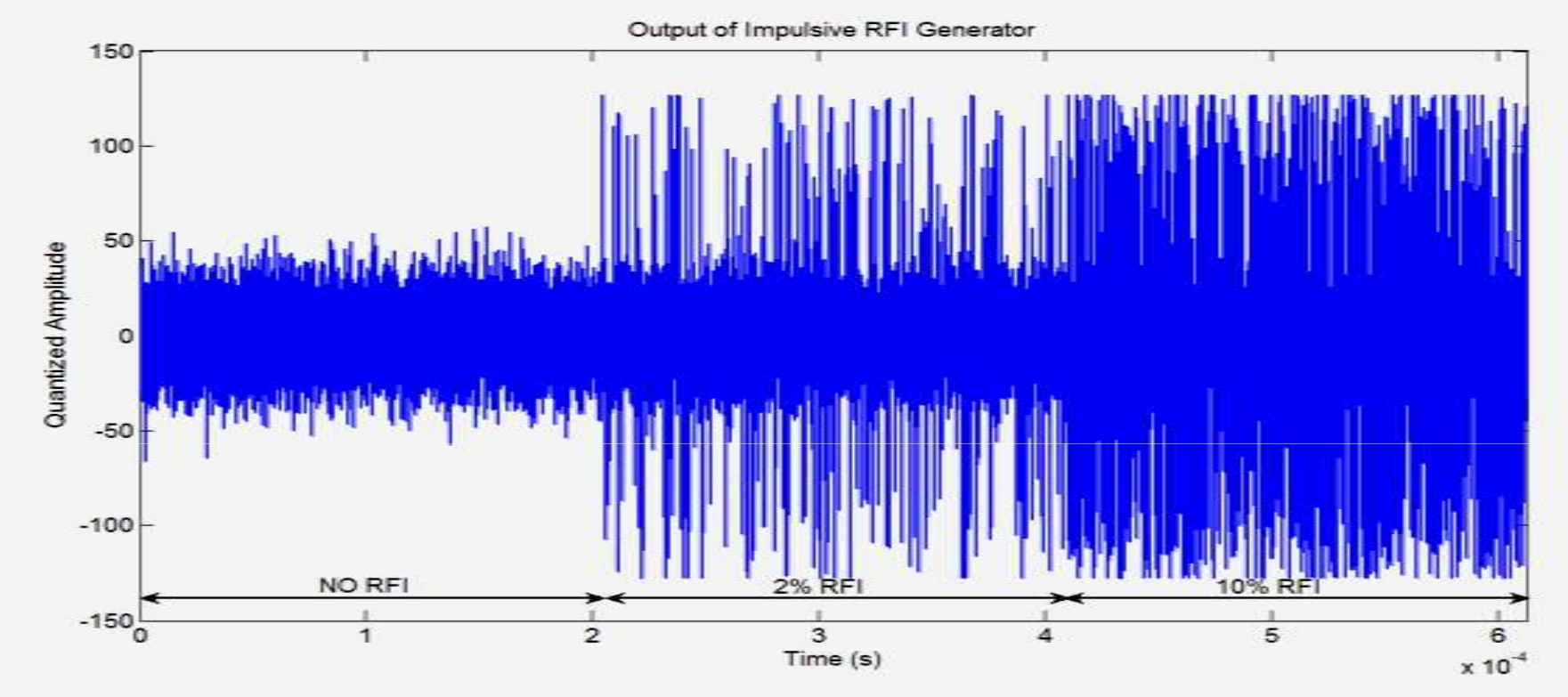
# Plans for further testing



# Development Cycle

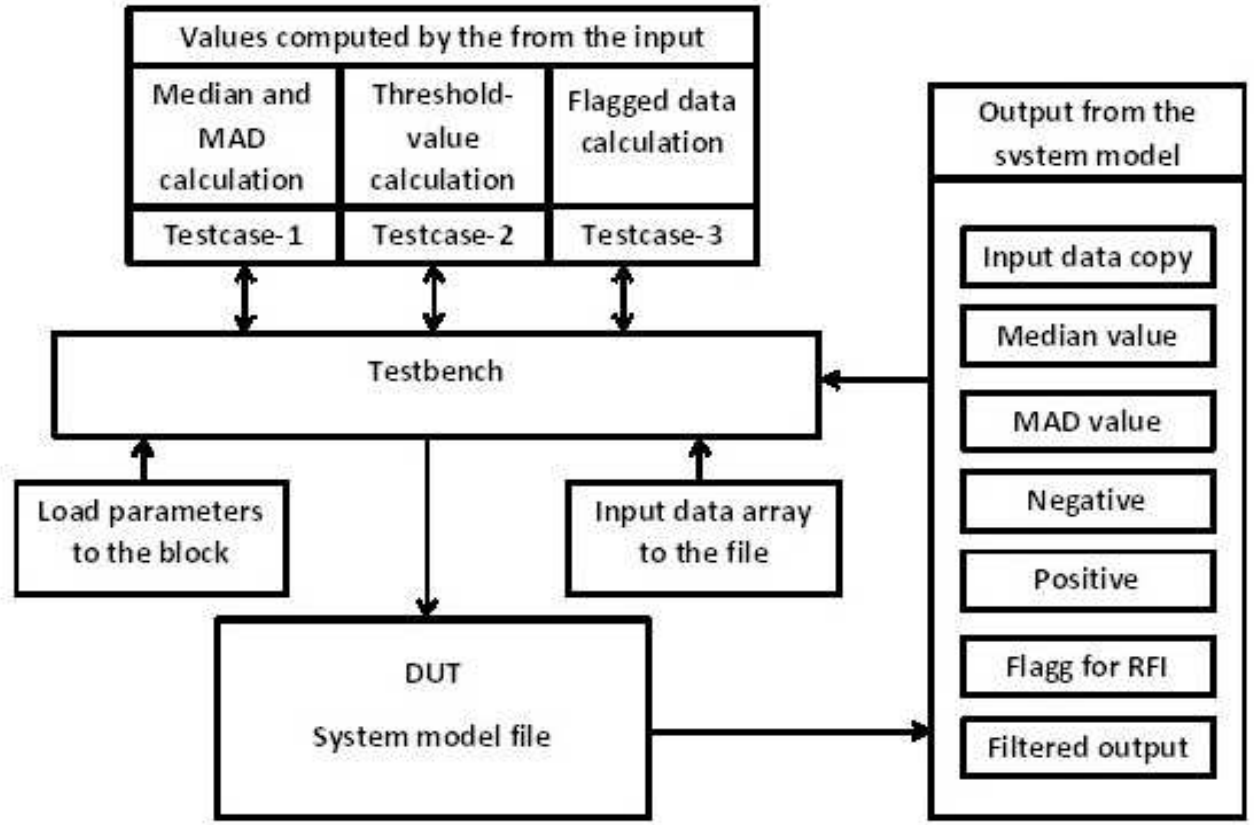


# Functional Verification

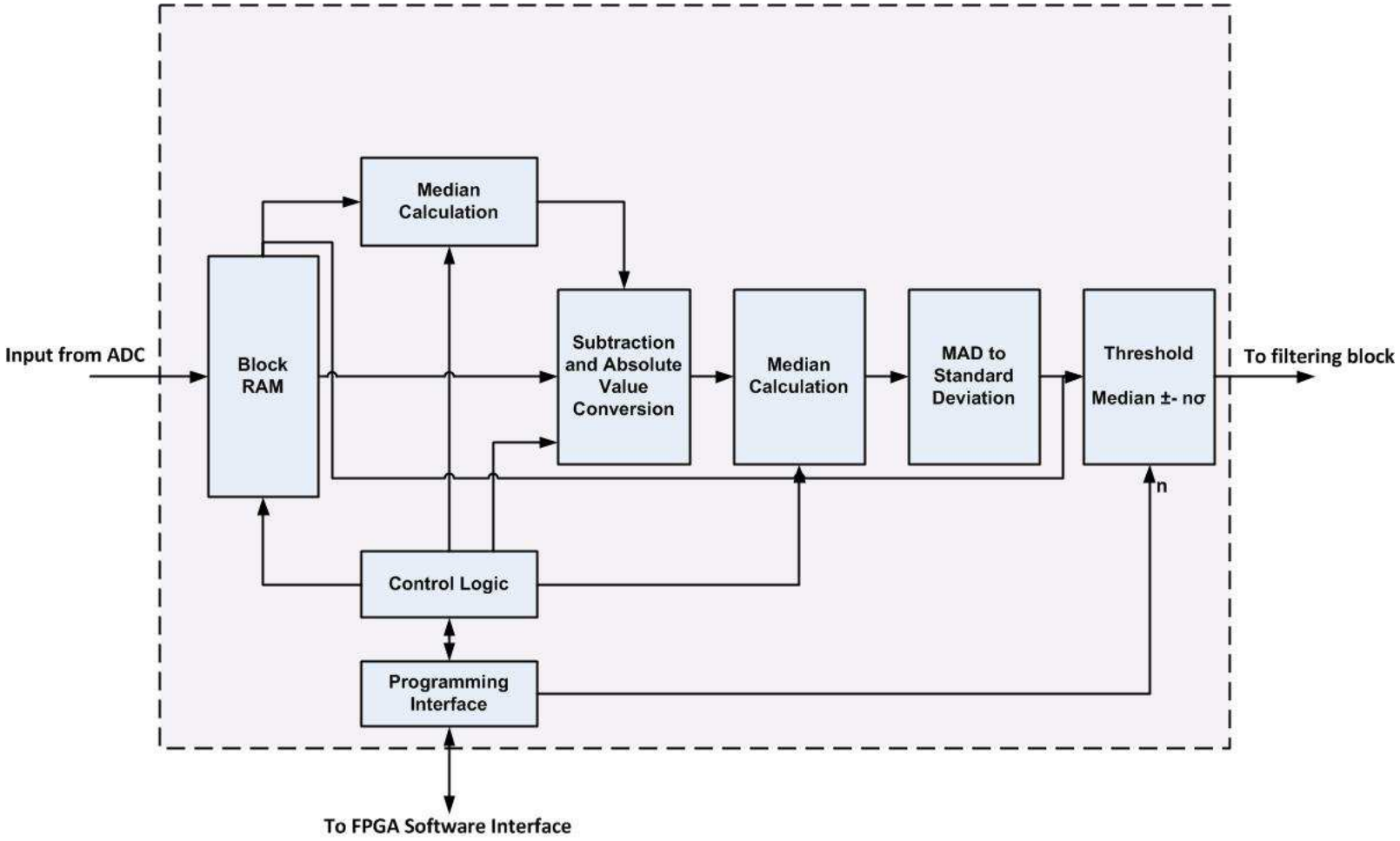



- RFI with different types of RFI was emulated using Matlab. This is required for validation of RFI mitigation algorithms.
- Example shows impulsive RFI of varying degree used as a test-bench for quantifying the efficacy of the RFI algorithm.

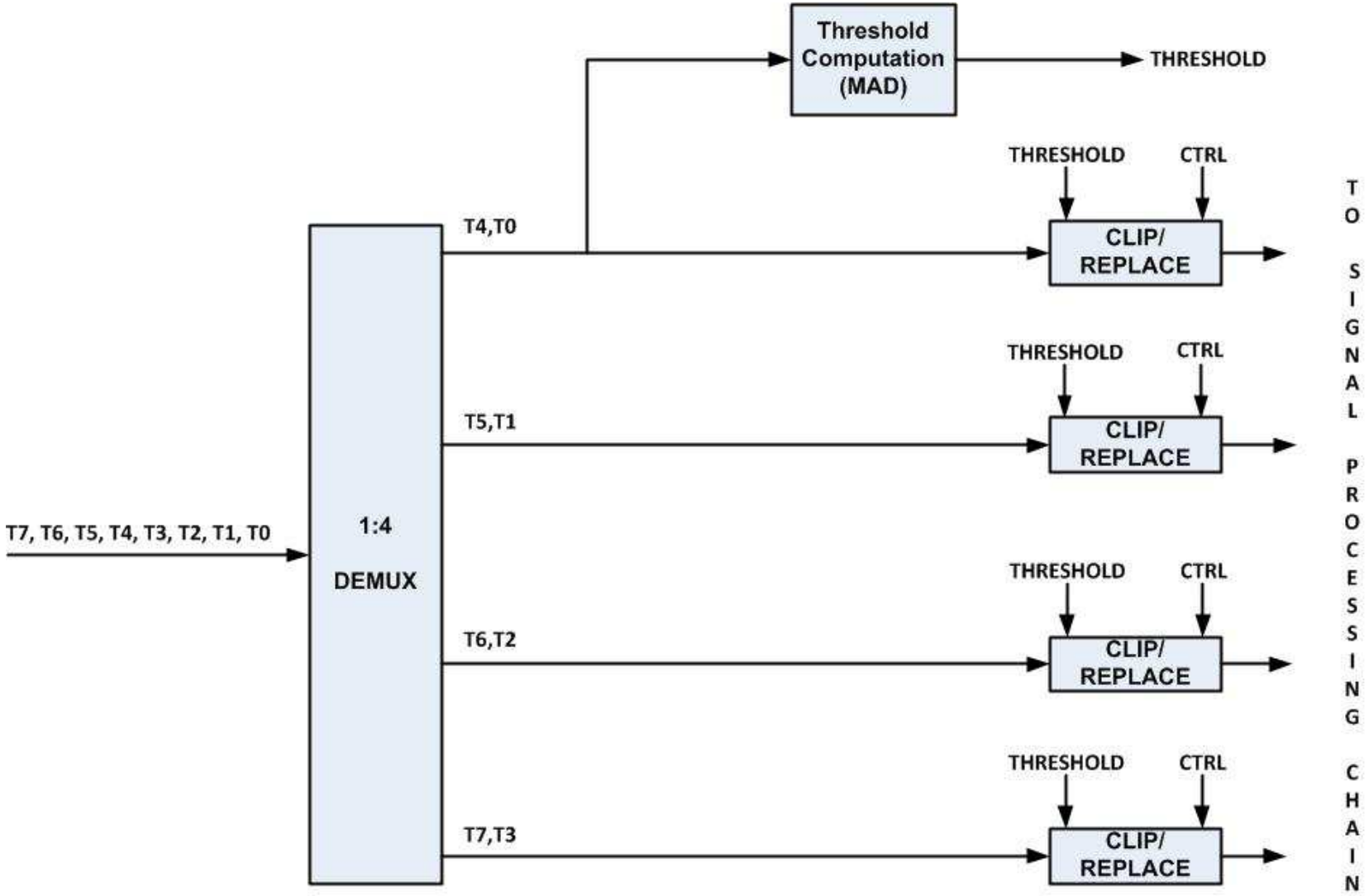
# Automated Verification Environment in Matlab-Simulink



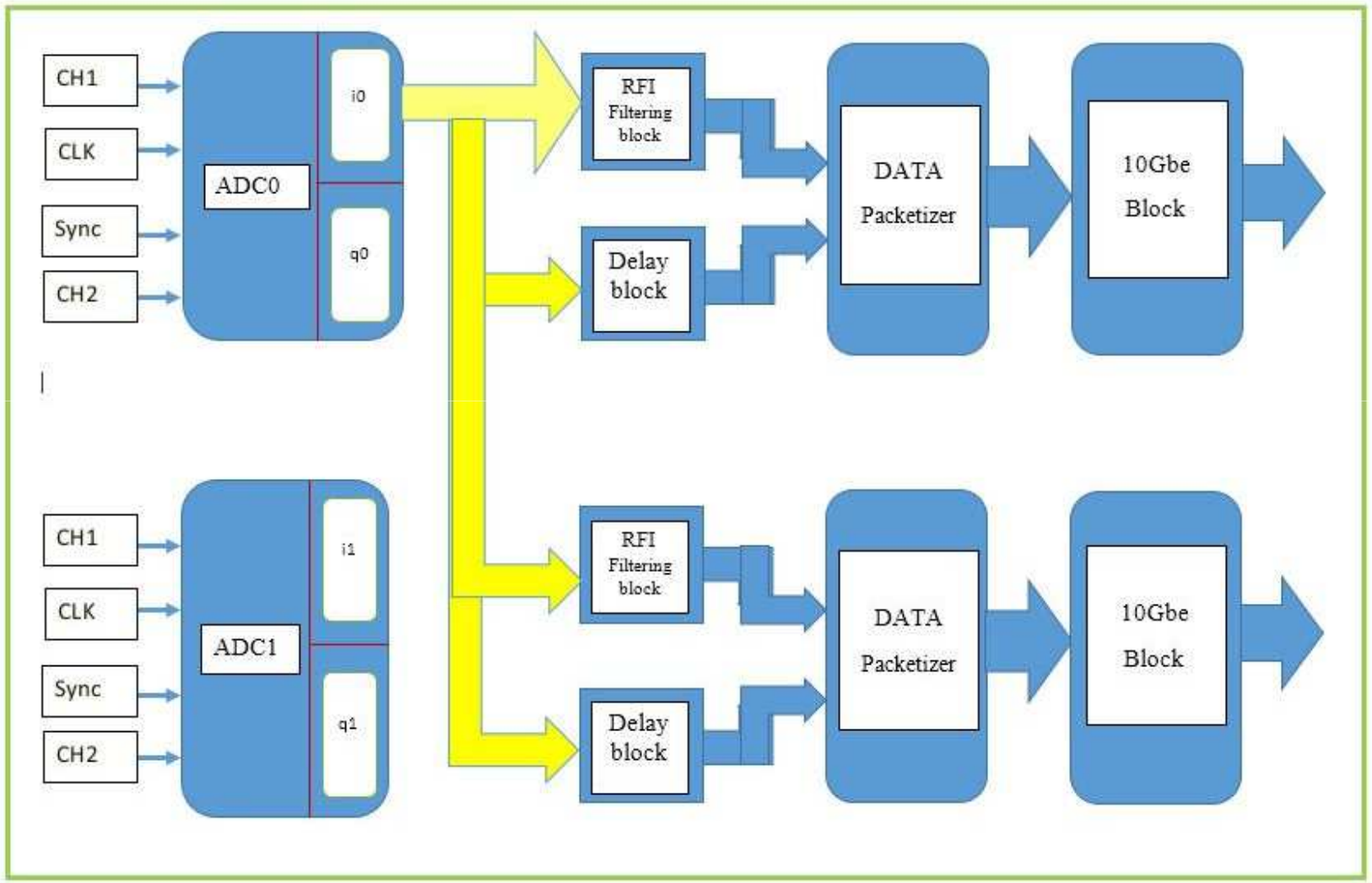
# Block Diagram – MAD Computation



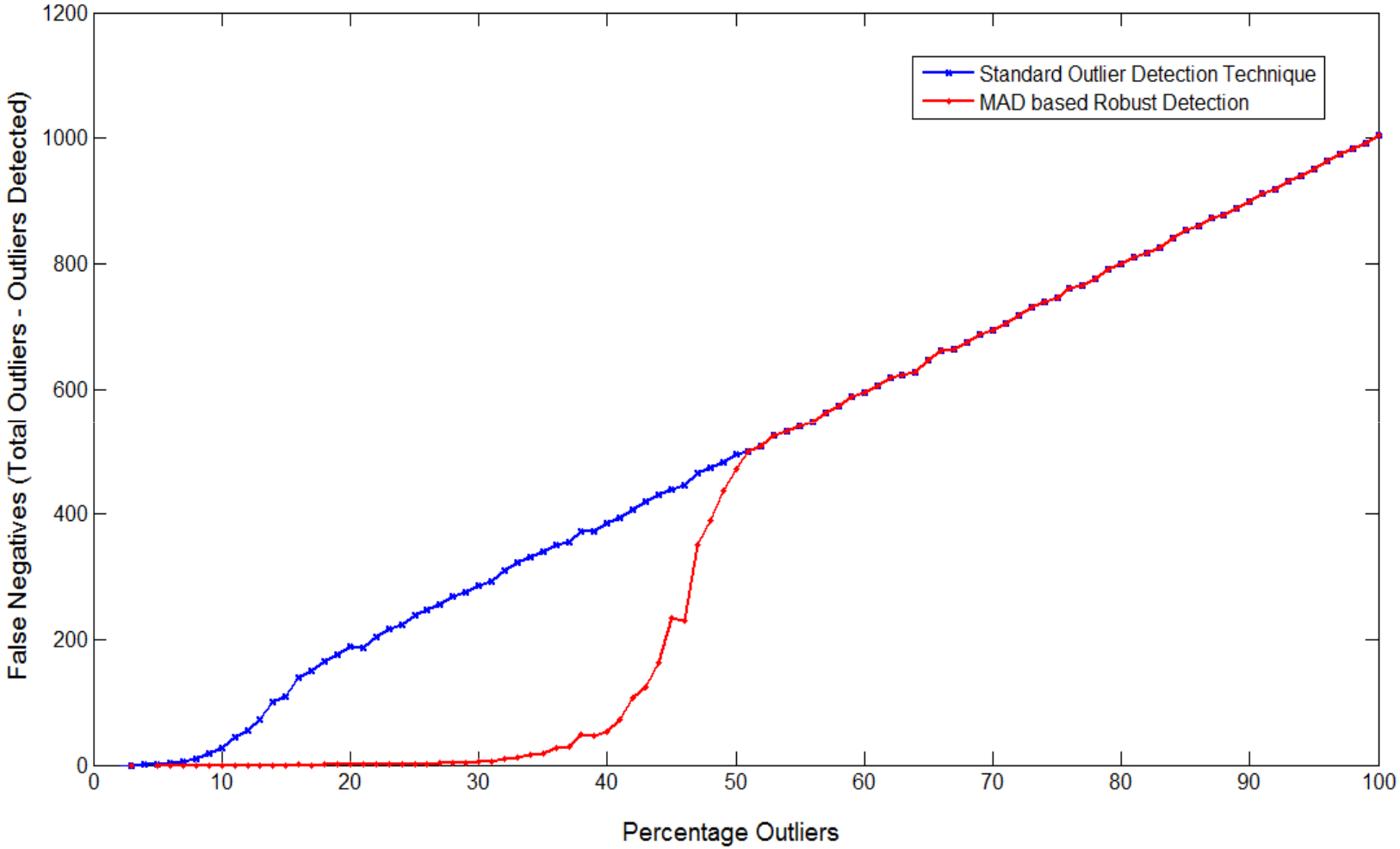
# Real-time RFI Filtering : Block Diagram



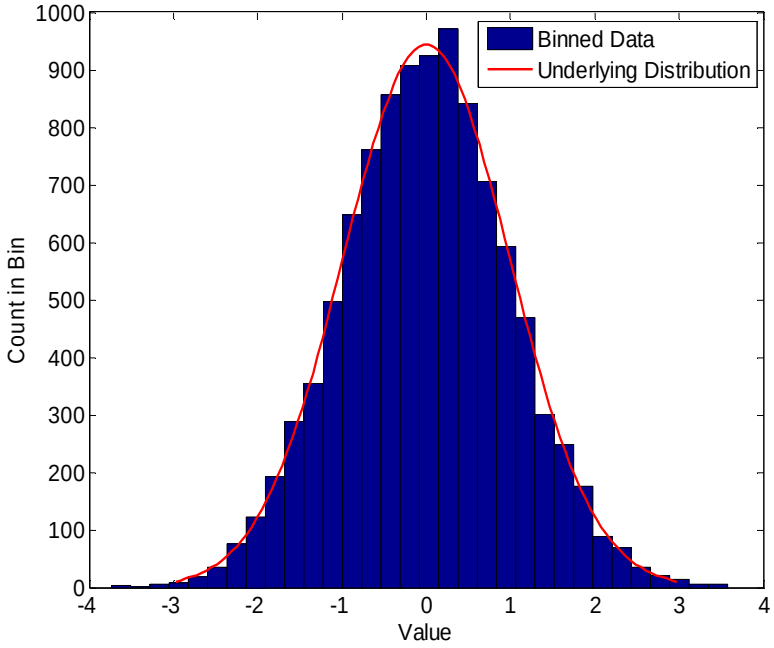
# Test Configuration

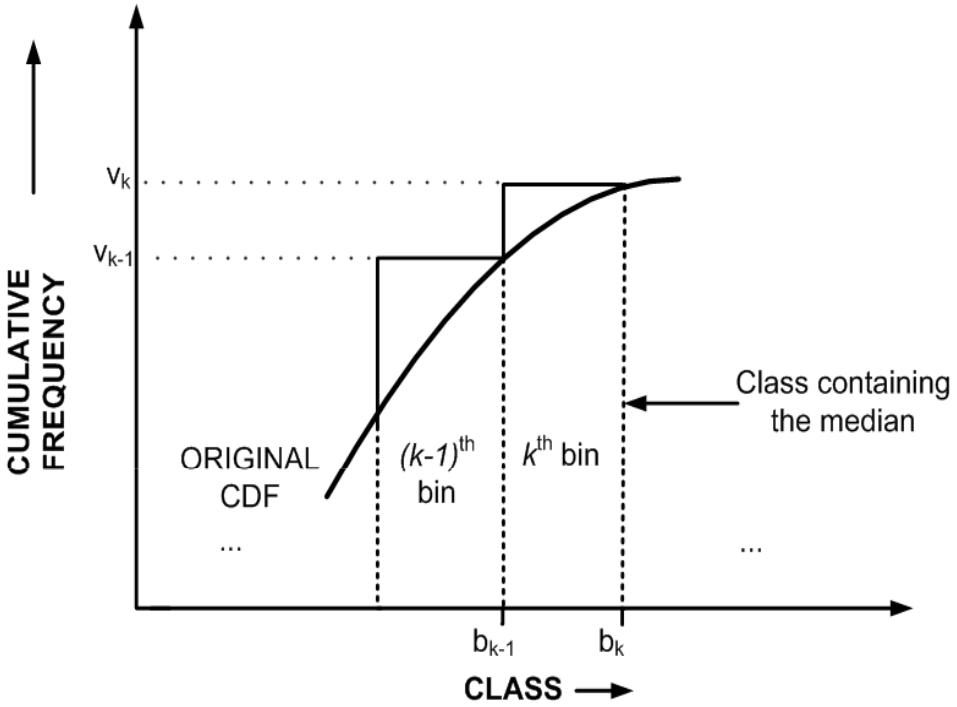


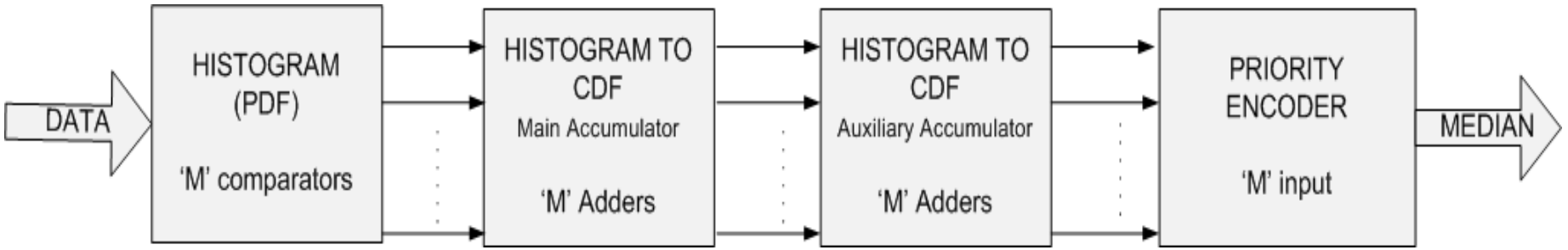
# Outlier Detection



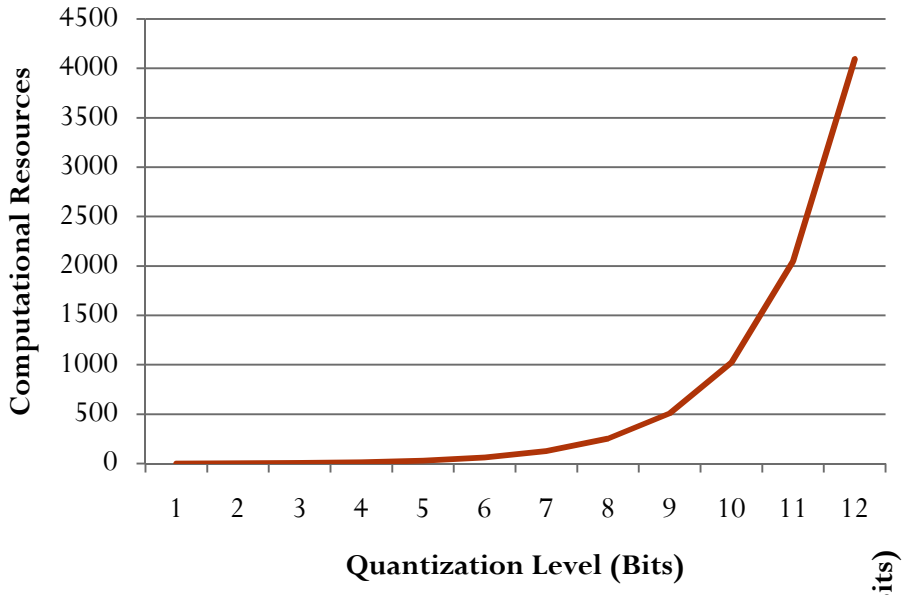
# Histogram approach



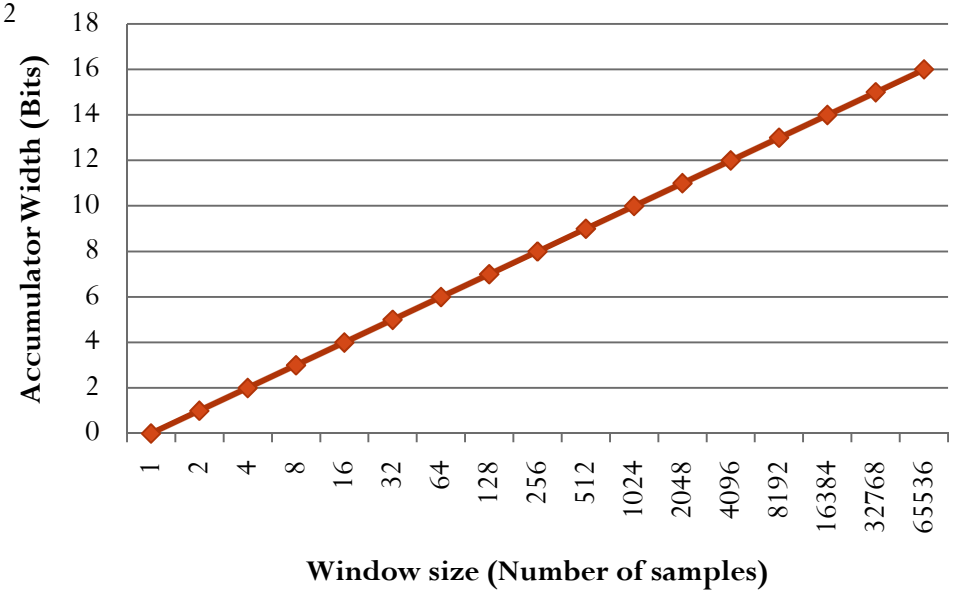



# Resource Utilization – Histogram Method

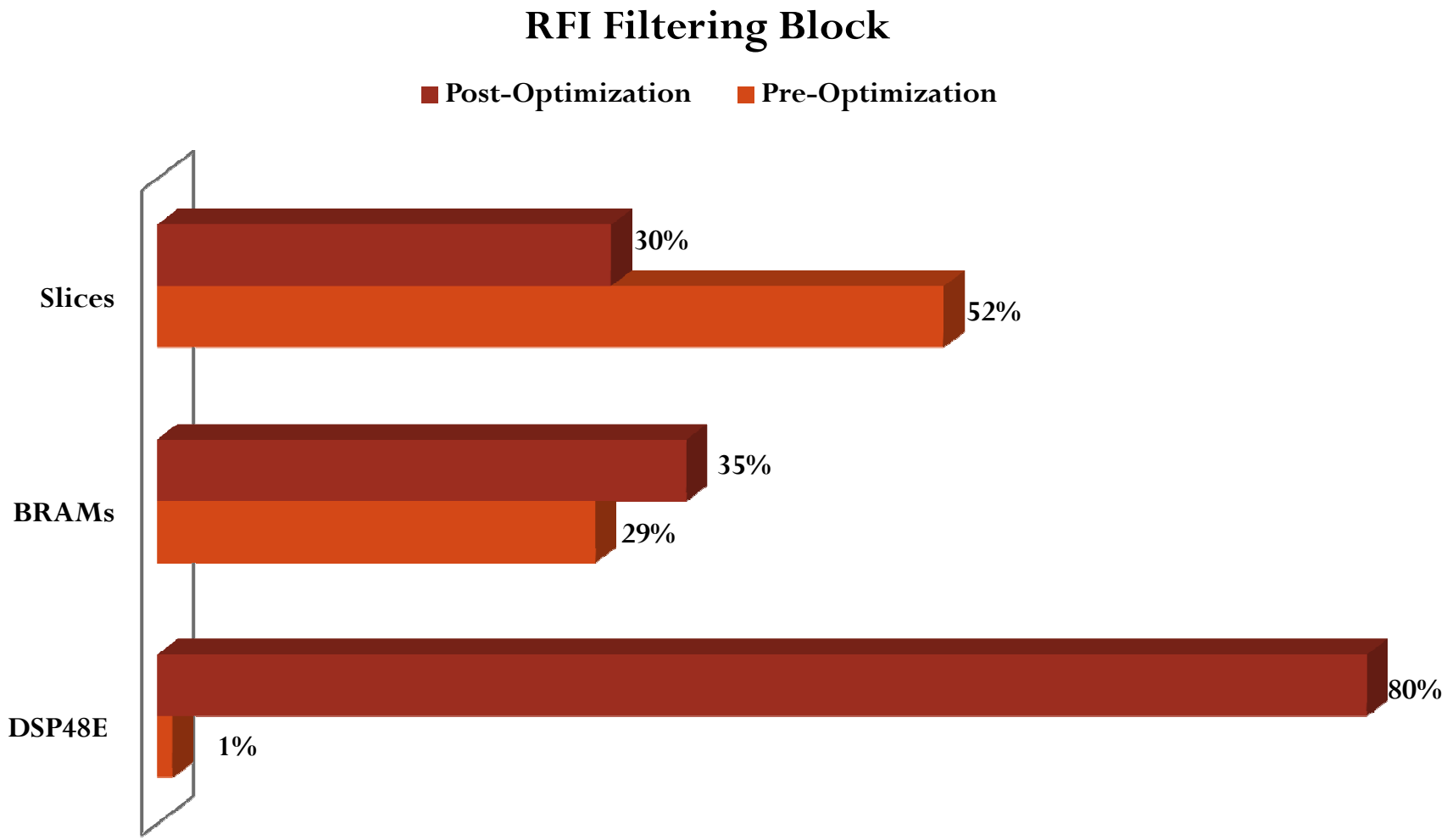



**Computational Resources scale as $2^N$ for 'N' quantization levels (bits)**

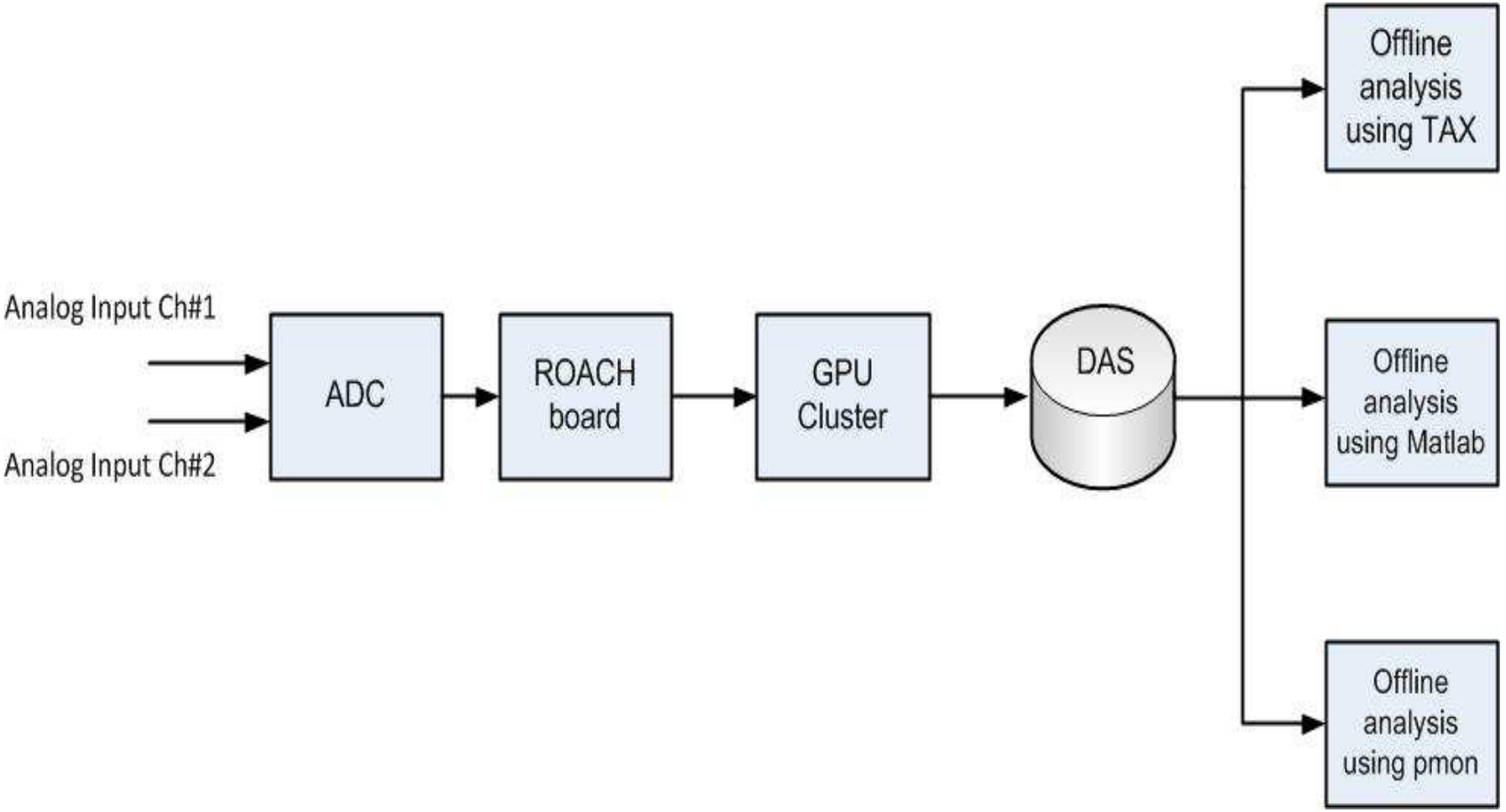
**Accumulator Width (bits) scale as $\log_2 W$ for 'W' window size (samples)**



# RFI Filtering Block – Resource Optimization

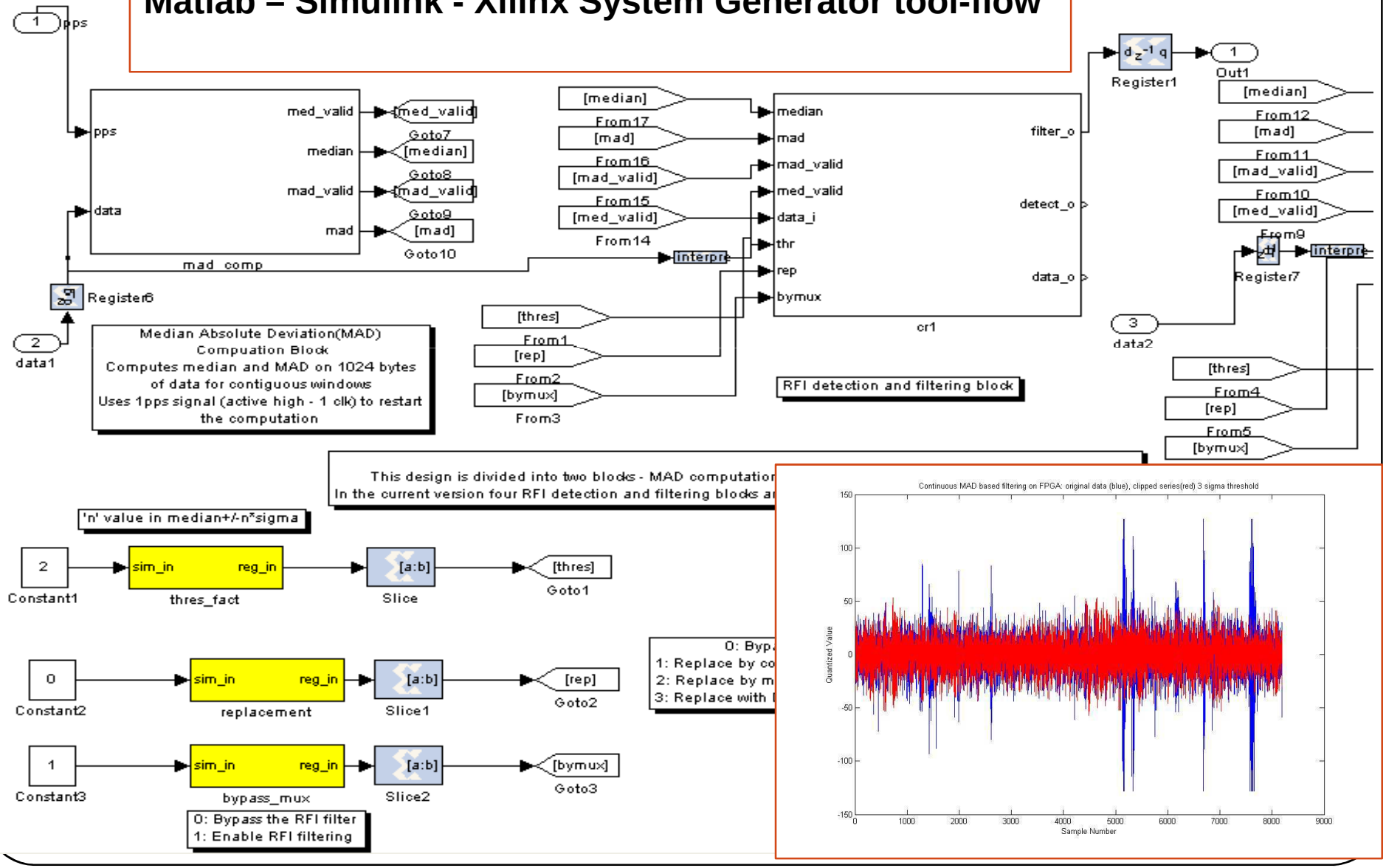


# GWB Testing – Block Diagram

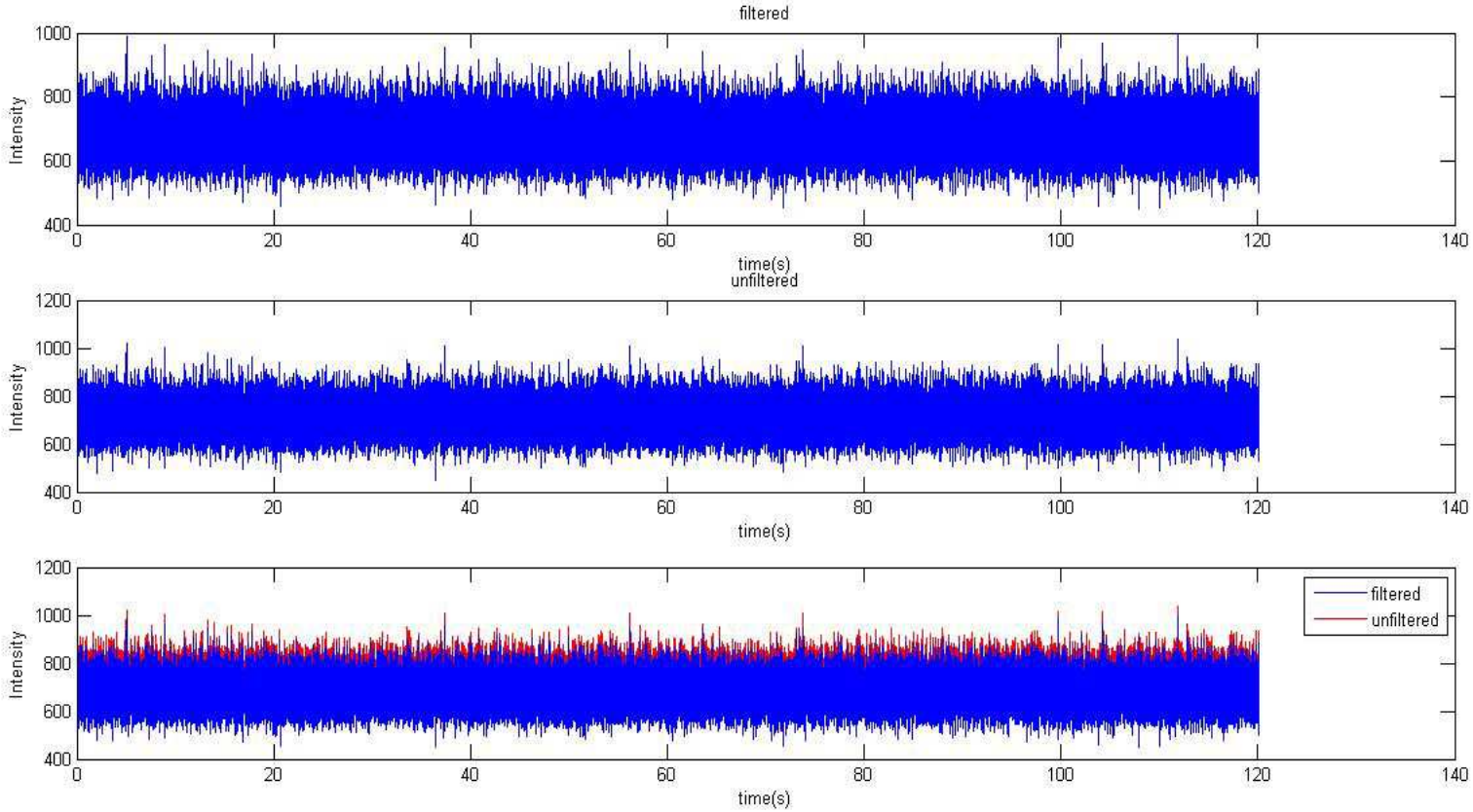


# FPGA Design

**Matlab – Simulink - Xilinx System Generator tool-flow**

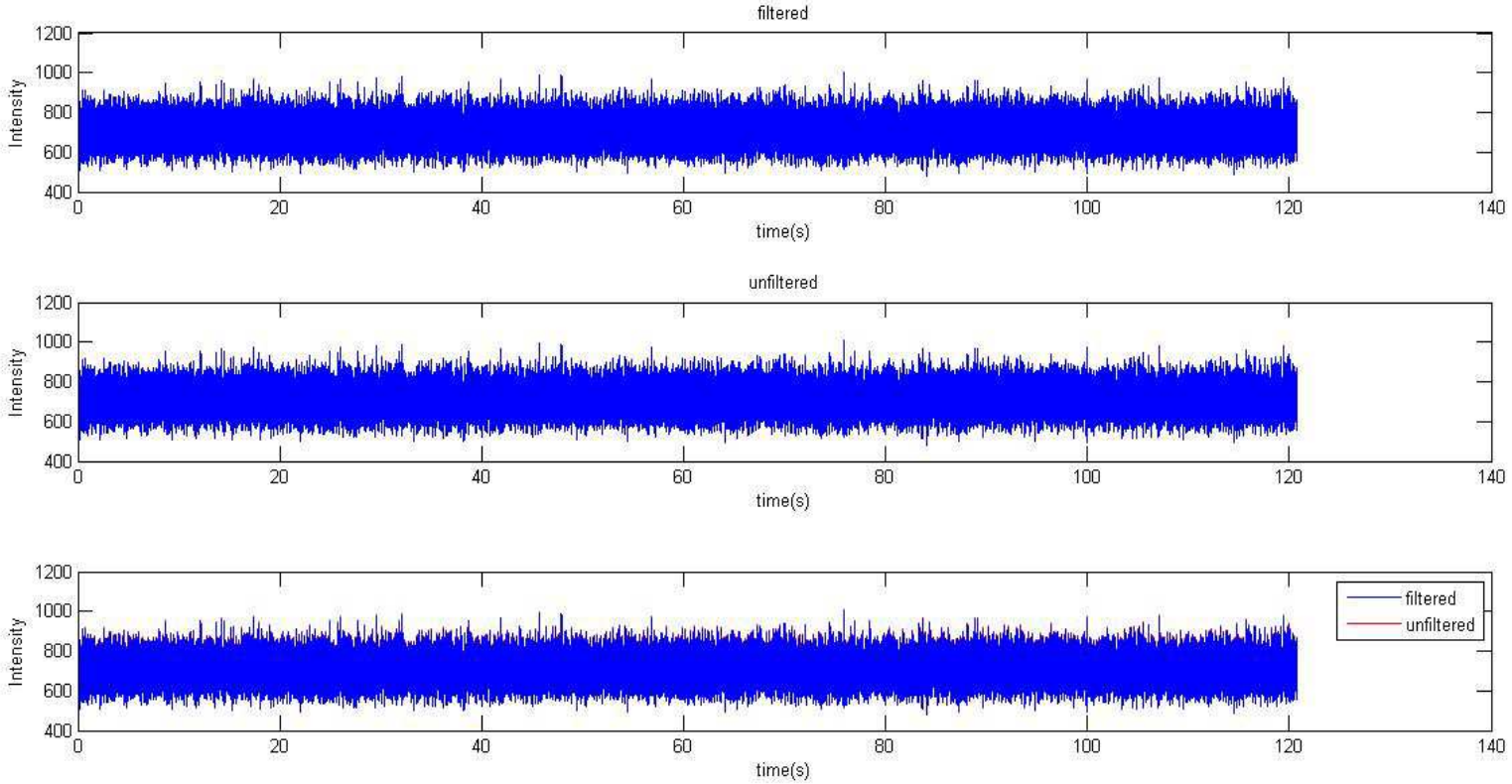


# Post-filtering reduction in mean noise value



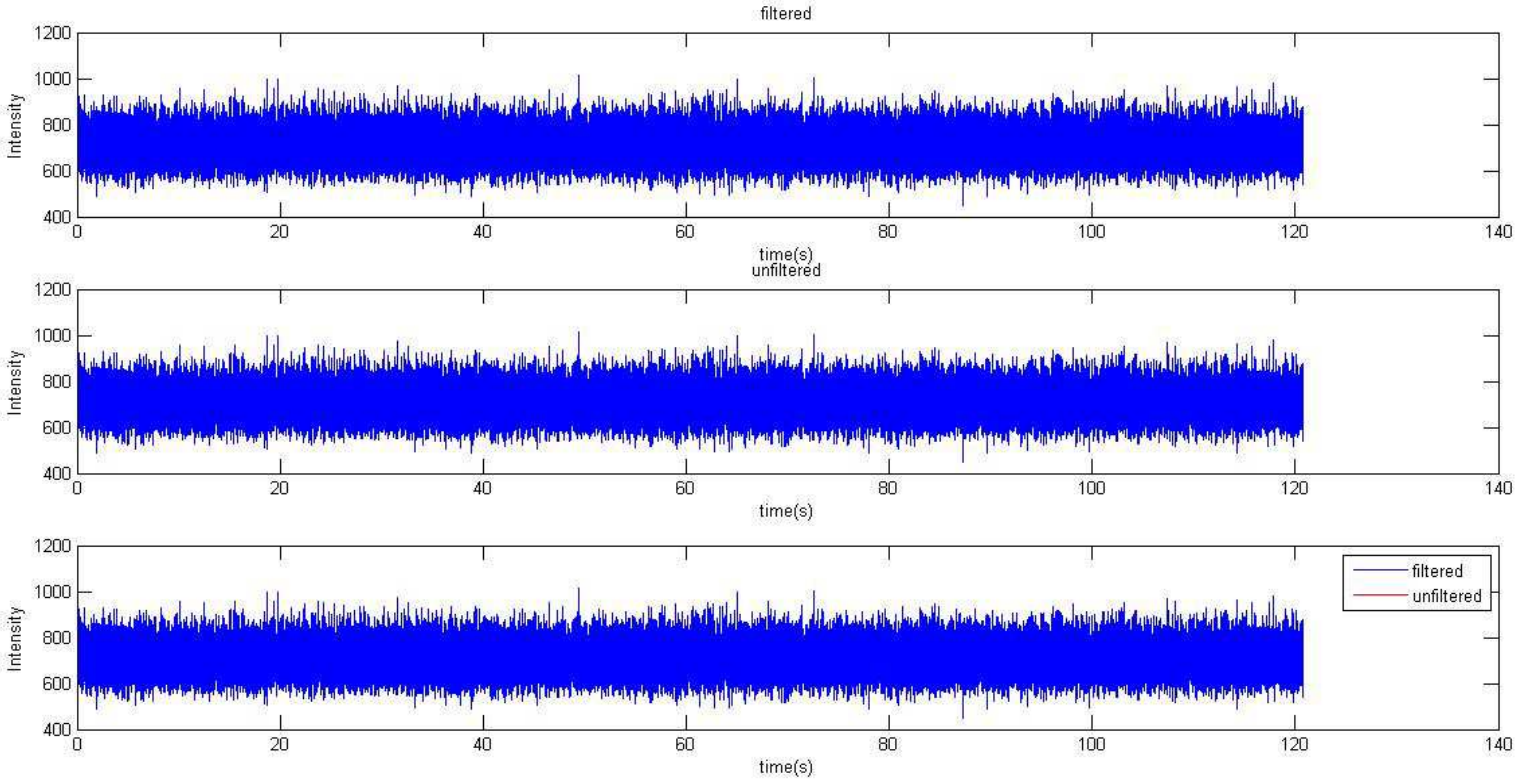

**Noise input – filtering at 3 sigma , replacement with digital noise**

# Post-filtering reduction in mean noise value



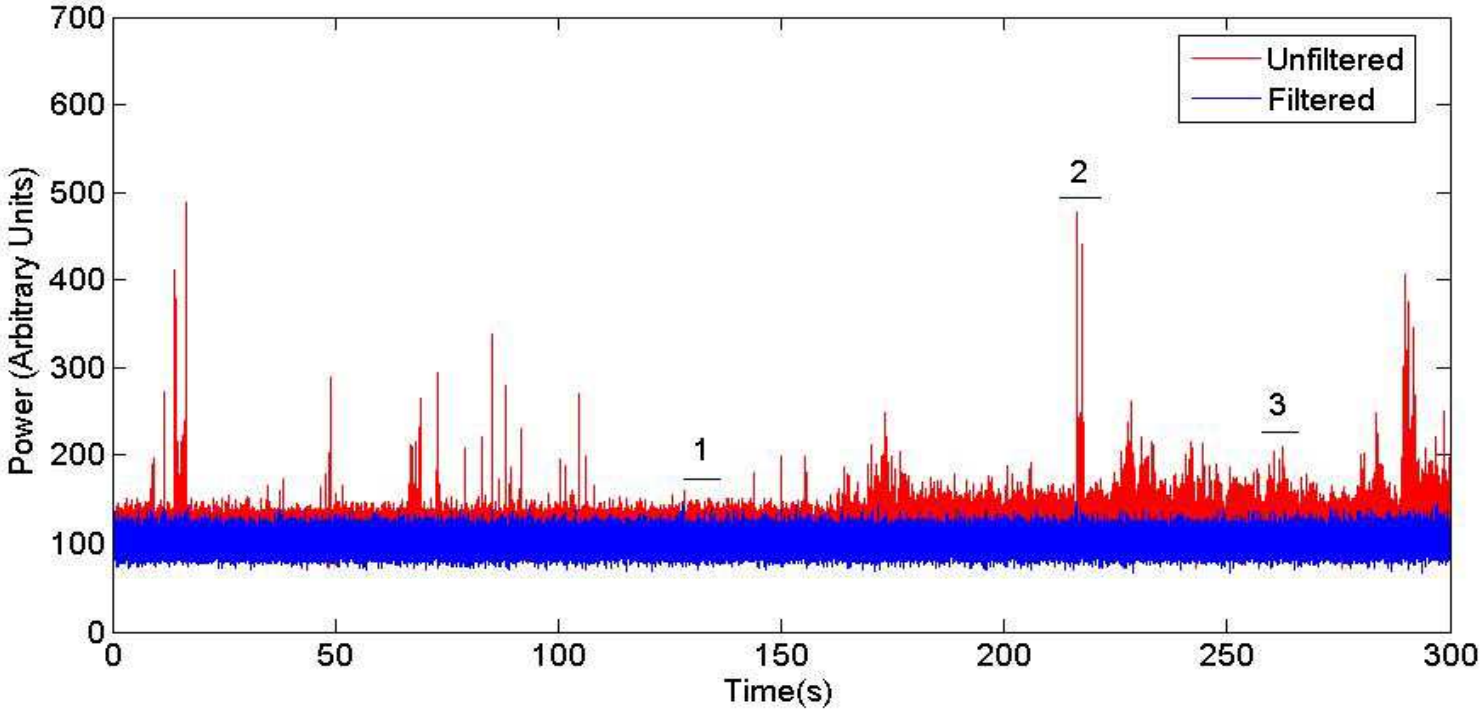

**Noise input – filtering at 3 sigma , clipped at threshold**

# Post-filtering reduction in mean noise value




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

# 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 |

# Modes of Operation

- **Continuous mode** – compute MAD on each window and apply the change on the same window
- **External Trigger mode*** – compute MAD on one window after getting trigger from an external source
- **External Update mode** – Use the value of MAD provided by external source – implements only the filtering part

* Interval between computations depends on receiver gain fluctuations