Radio Frequency Interference Excision from Interferometers

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Radio Frequency Interference

Low frequency observations are seriously limited by RFI

- **Constricts frequency space**
- **Effectively increases Tsys**
- **Vitiates calibration solutions ... real killer**

GMRT performance < 400 MHz is 5-15 times poorer than expected

Image dynamic ranges have rarely exceeded a few 1000s

Available software packages cannot handle low frequency RFI

- **Too many spectral channels**
- **Often difficult to identify the base (RFI-free) level**
- **Only flagging, at best**

RFI Excision – the hard way

A more efficient approach is to estimate the magnitude of the cosmic signal below the RFI – Excision / Mitigation

Some previous efforts which have been implemented

- Fridman & Baan at Westerbork
- Ue Li Pen's effort at GMRT

The first two use specialised hardware

- High speed data sampling
- Fourier transform
- Clip spikes
- Inverse transform

RFI Excision - the soft way

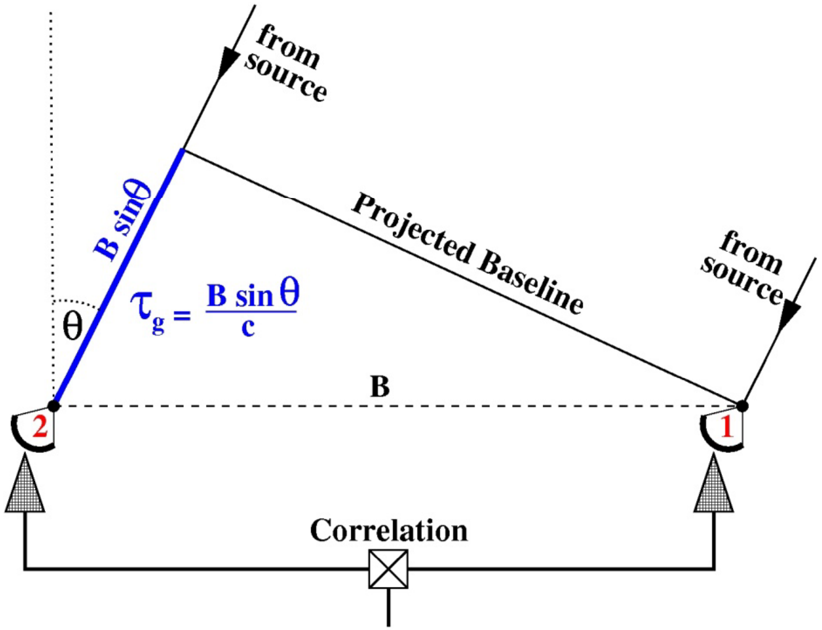
I will describe a purely software approach to excise RFI from interferometric data … using existing hardware

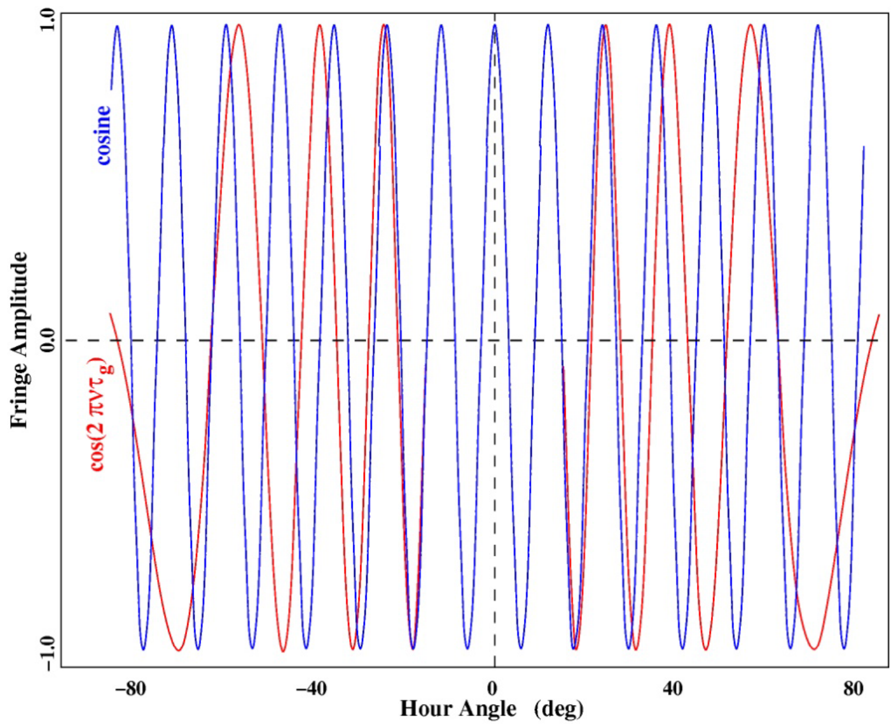
- Conceptually, a new approach to RFI excision
- The only purely software technique available
- Can be applied to any fringe-stopping interferometer
- Offline analysis
- Highly parallelisable

The RfiX Concept

In a radio interferometer the correlated output of each pair of antennas collects a fringe because of Earth's rotation.

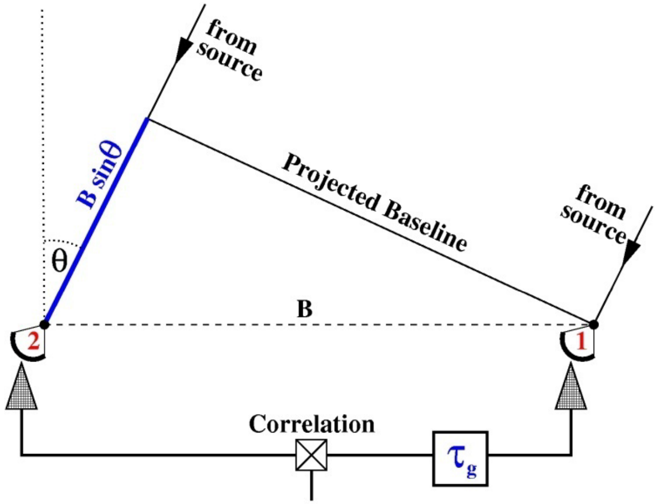
$$\omega_F(t) = 2\pi\,\omega_E \,\{\, u(t)\sin[HA(t)] + v(t)\cos[HA(t)] \,\}\, \cos[\delta(t)]$$

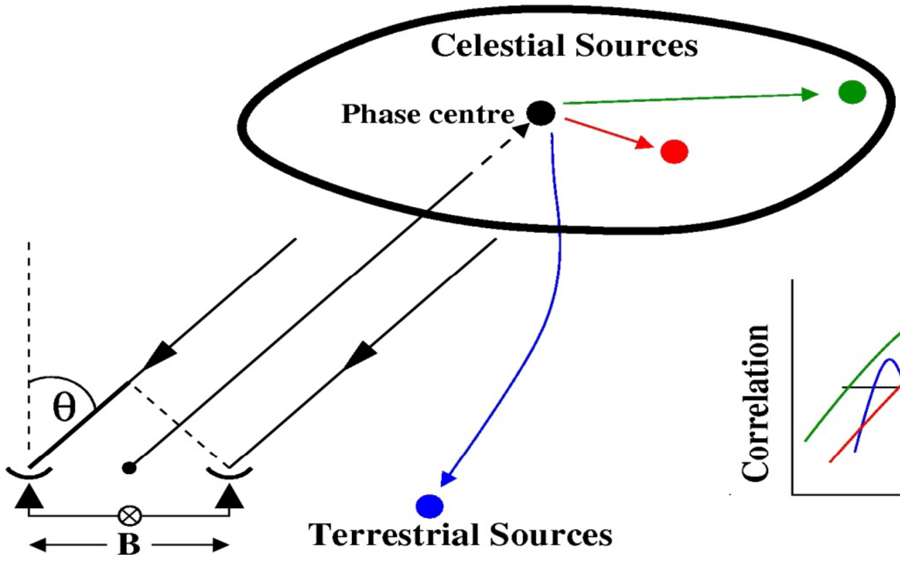


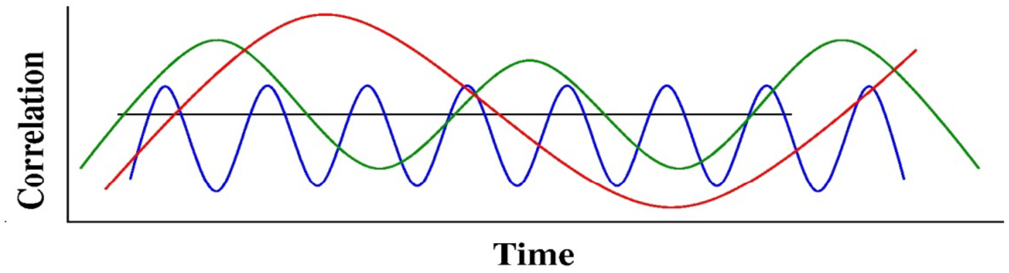


The RfiX Concept

This fringe is killed in the correlator by multiplying the two signals with an inverse pattern, calculated for the phase reference.



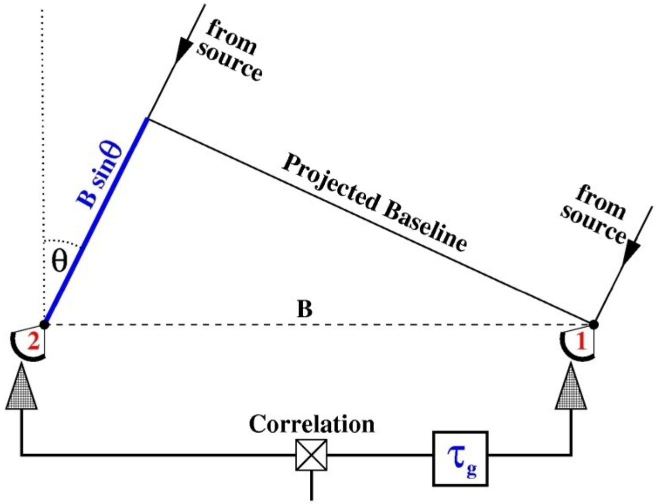


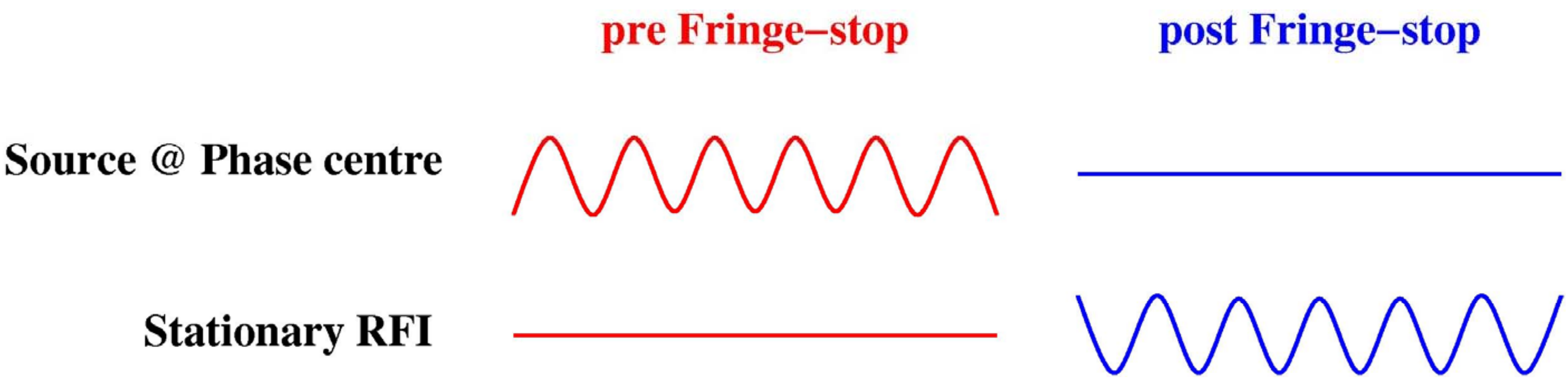


The RfiX Concept

A stationary RFI source will oscillate at precisely the fringe stopping frequency introduced by the correlator

the frequency will be independent of location



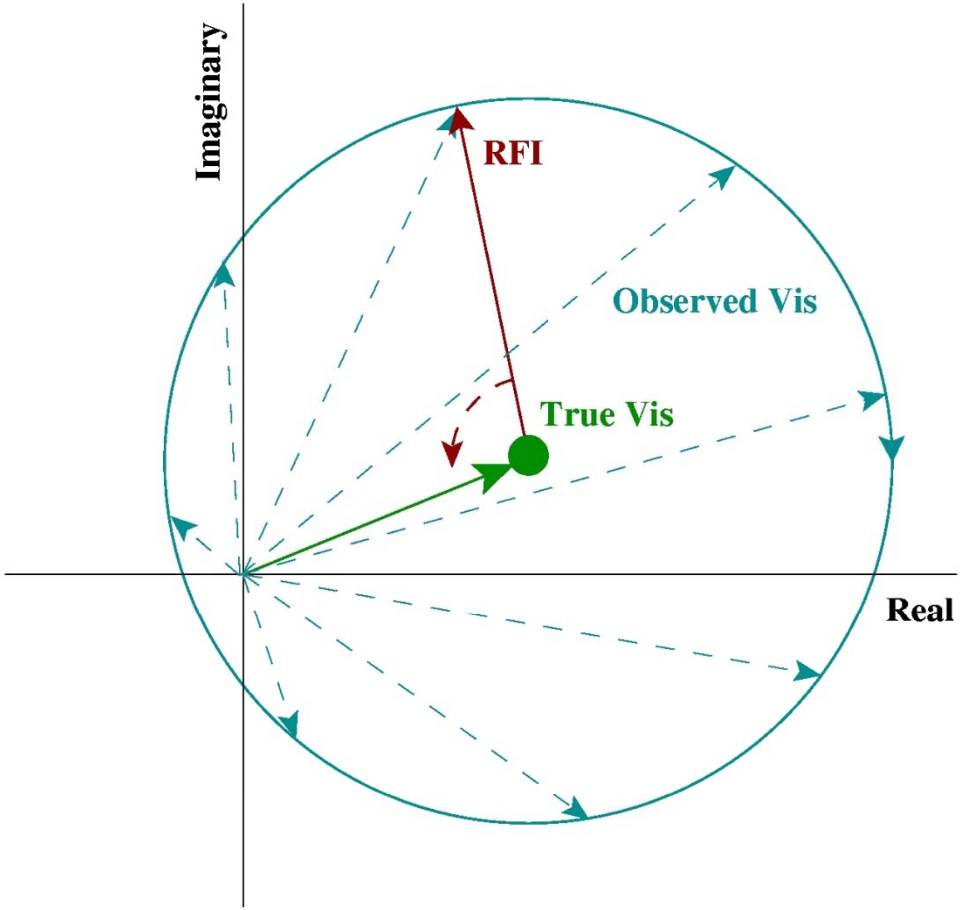


RfiX concept – schematic model

The green spot/vector is the true complex visibility

The red vector is the instantaneous position of the RFI – it rotates with time at the fringe-stop frequency

The cyan vectors are the instantaneous values of the observed visibility.



RfiX concept – actual data

Outer Band of Points

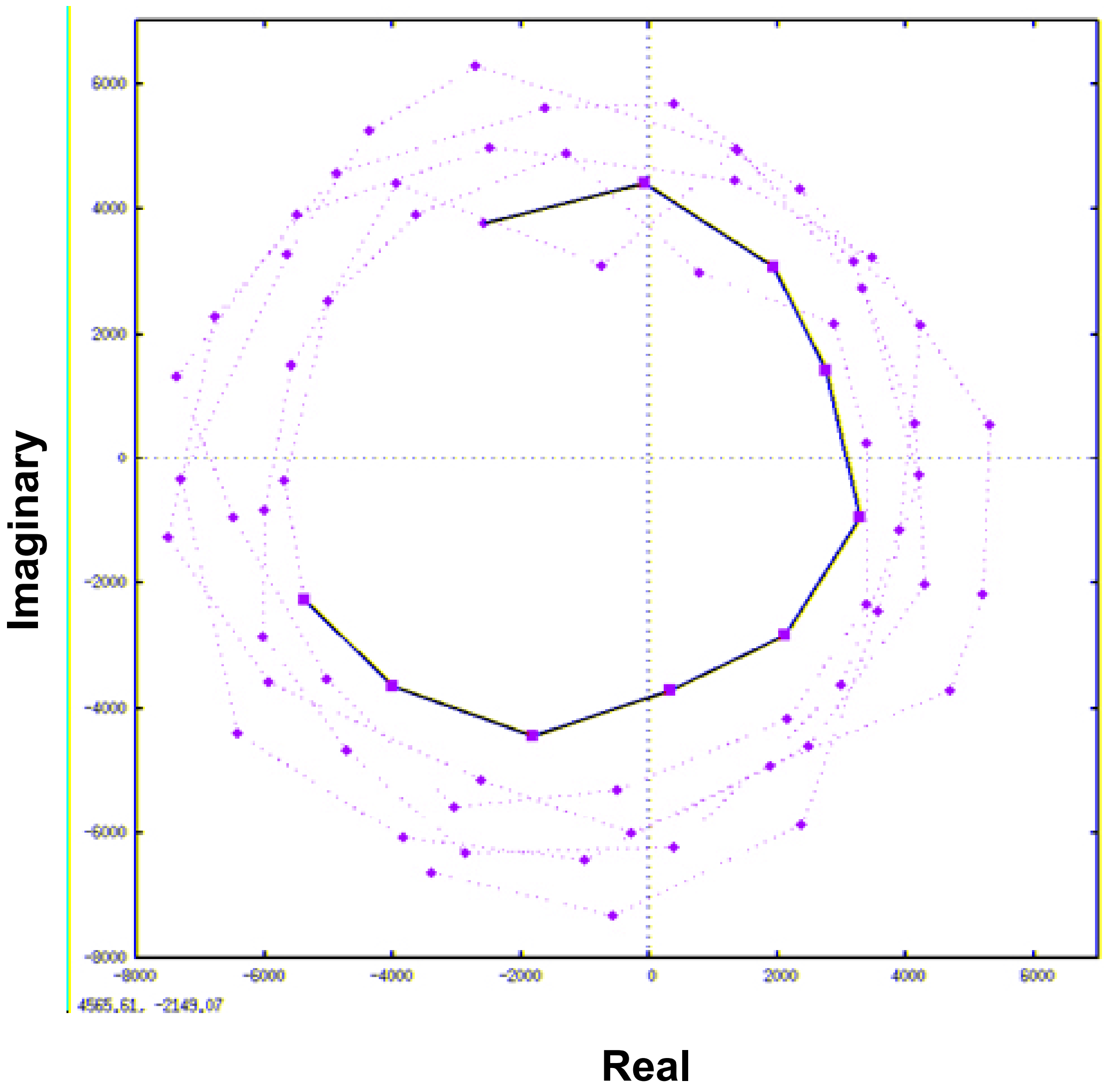
observed visibility values

Connected String

temporal sequence of observed values

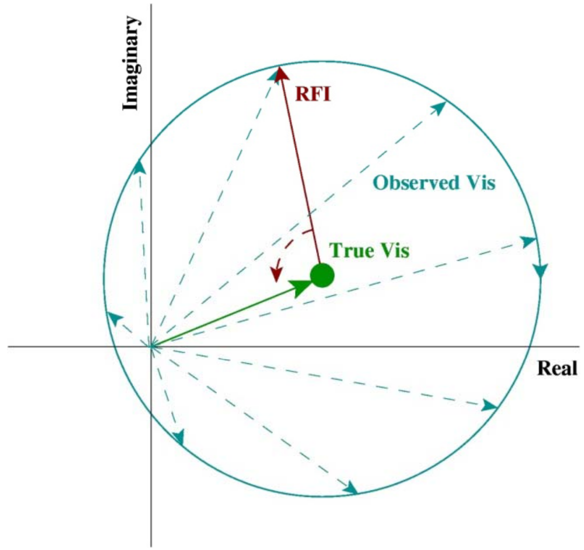
Effective Noise

is now determined by the radius of circulation (RFI amplitude) and not by the system temperature



RfiX concept – equation

$$V_{OBS} = V_{TRUE} + A\,e^{i(\omega_F t - \phi)} + \text{Noise}$$



V : Visibility

A : Amplitude of RFI

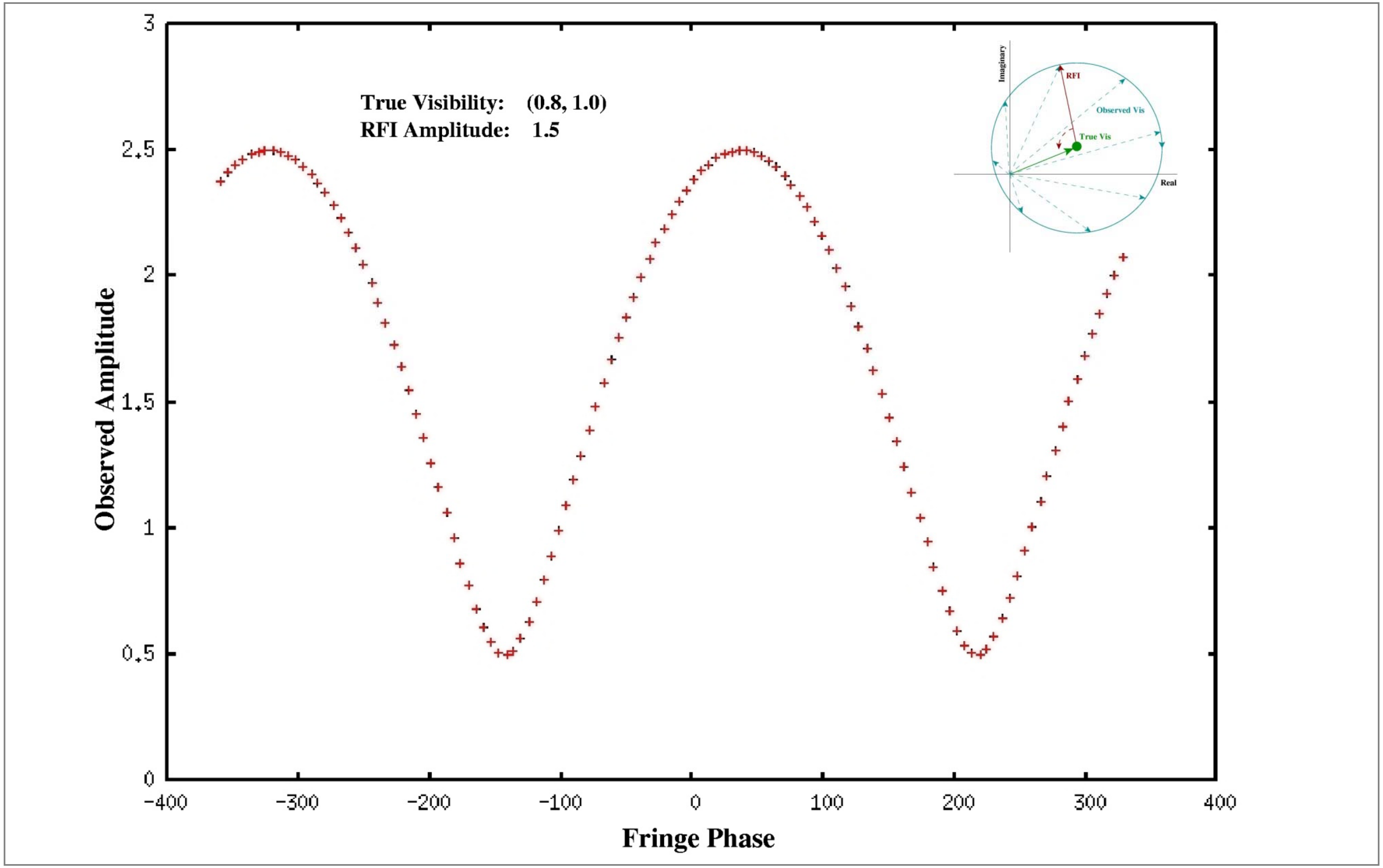
ϕ : Phase of RFI

V : Visibility

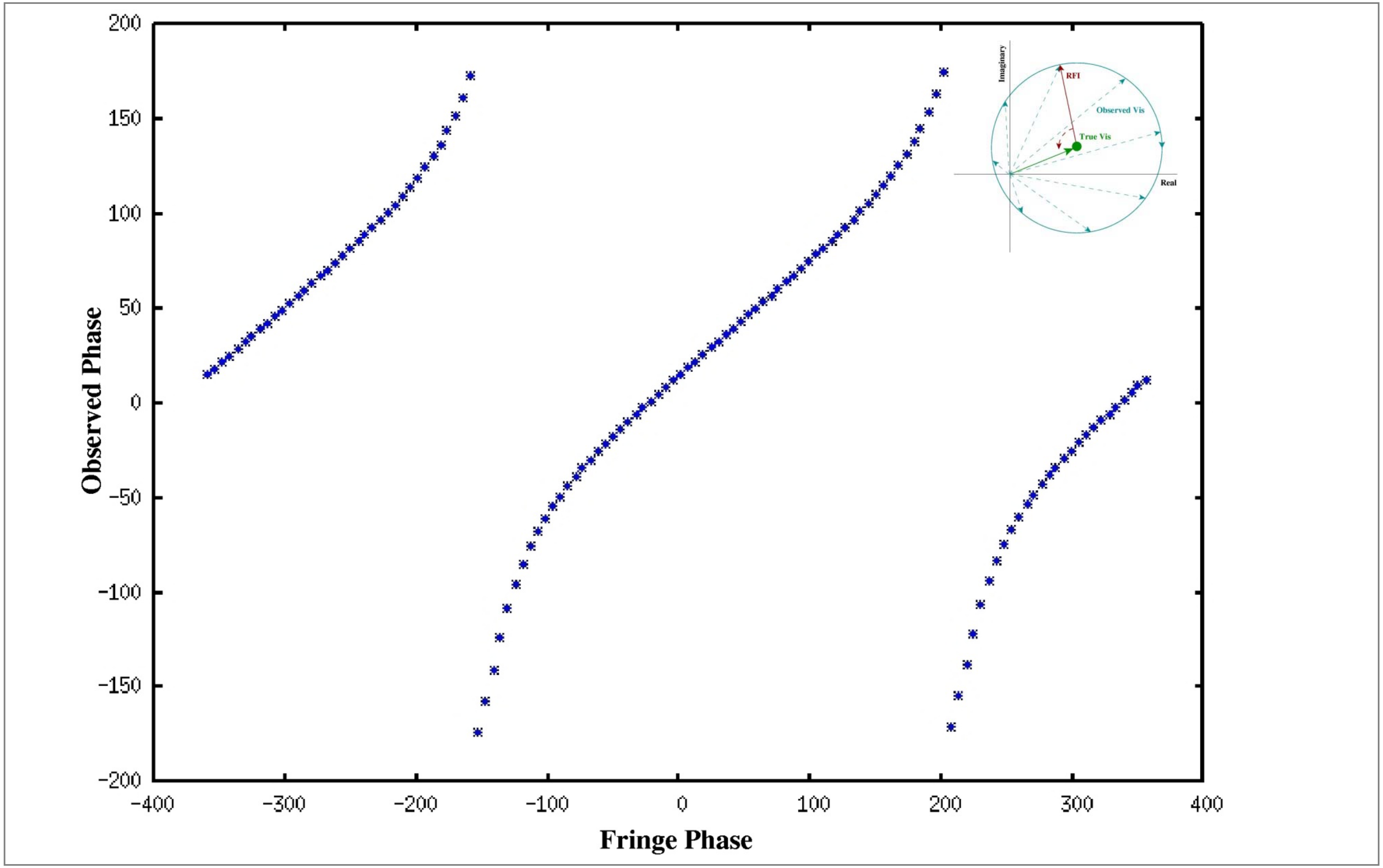
ω_F: Fringe frequency

J : j-th data point

RfiX concept – visibility oscillation (amplitude)



RfiX concept – visibility oscillation (phase)



RfiX concept – solution

$$V_{OBS} = V_{TRUE} + A\, e^{i(\omega_F t - \phi)} + \text{Noise}$$

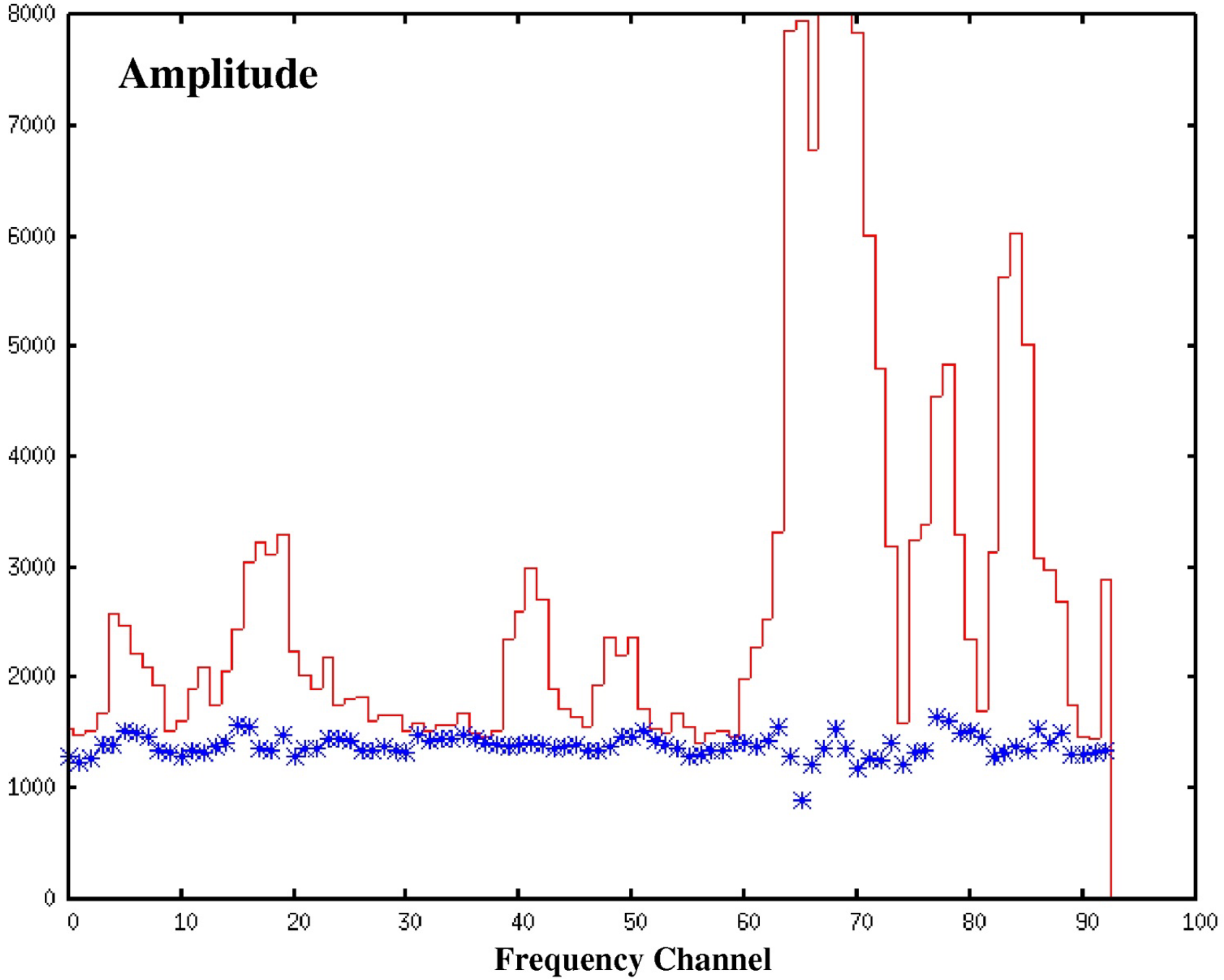
One can estimate the amplitude and phase of the RFI and subtract it from the observed data to obtain the true visibility value

Important: There is no smoothing of data

$$V^j_{RFIX} = V^j_{OBS} - A\, e^{i(\omega_F t^j - \phi)} = V_{TRUE} + \text{Noise}^j$$

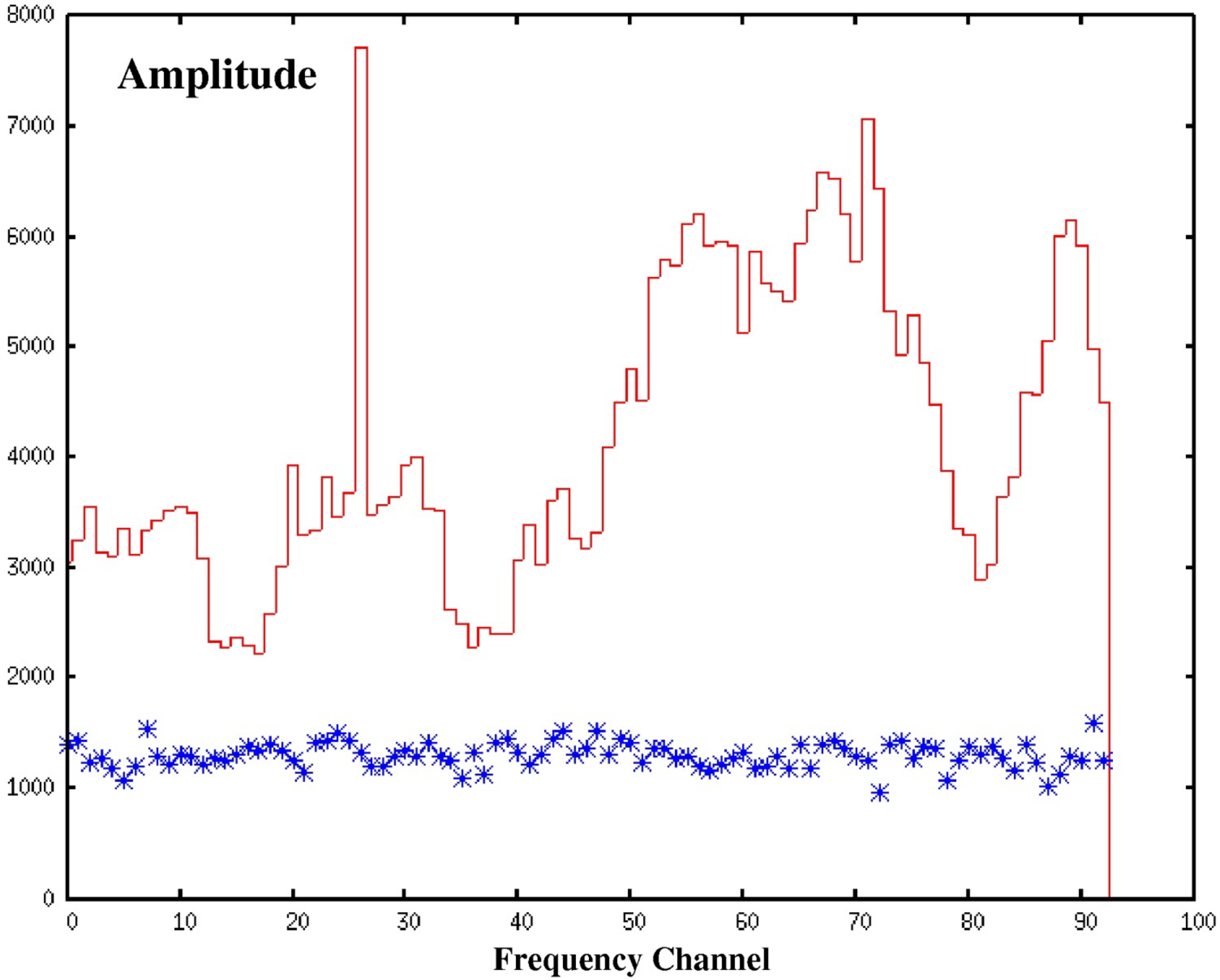
RFI @ GMRT 154 MHz – I

Red line
pre Rfi-X



RFI @ GMRT 154 MHz – II

Red line
pre Rfi-X



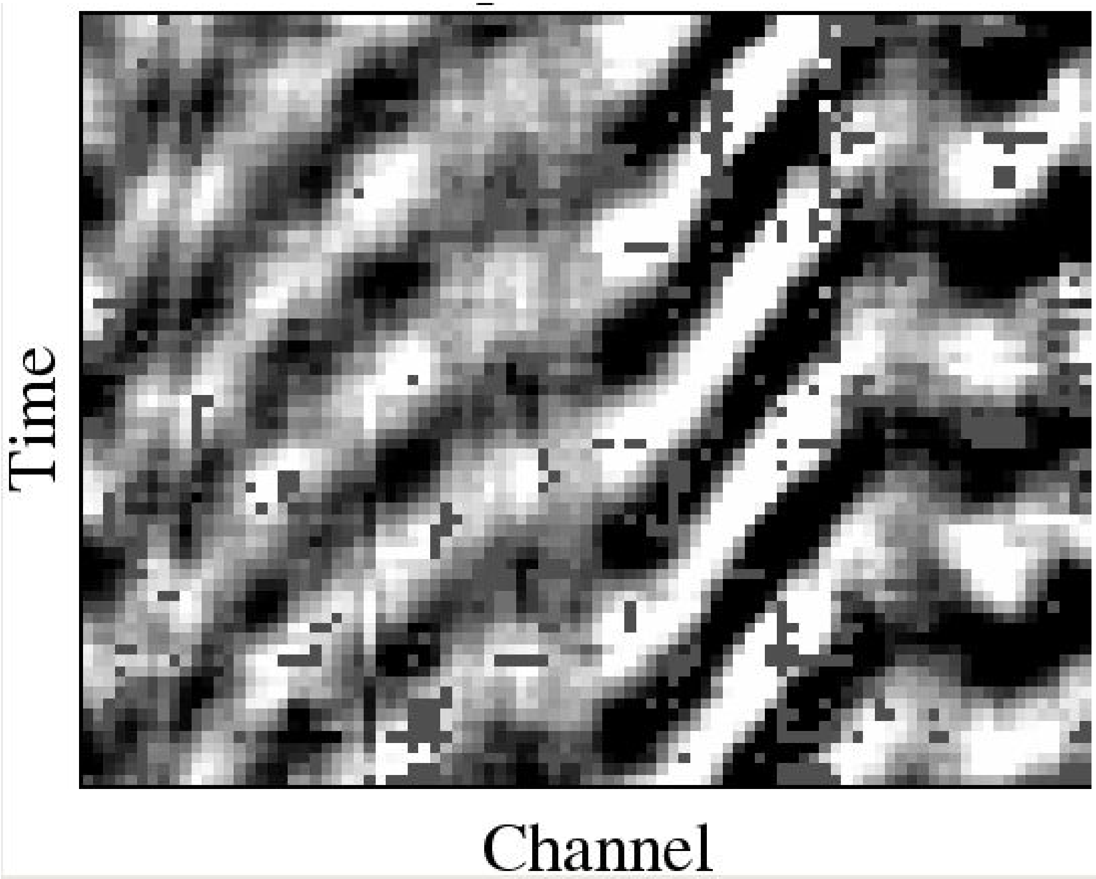
RFI @ GMRT 154 MHz – III

Grey-scale Visibility on frequency-time plane

In the absence of RFI this would have been a featureless plane

Each different gradient represents a different RFI source

- Not narrow-band
- Not broad-band



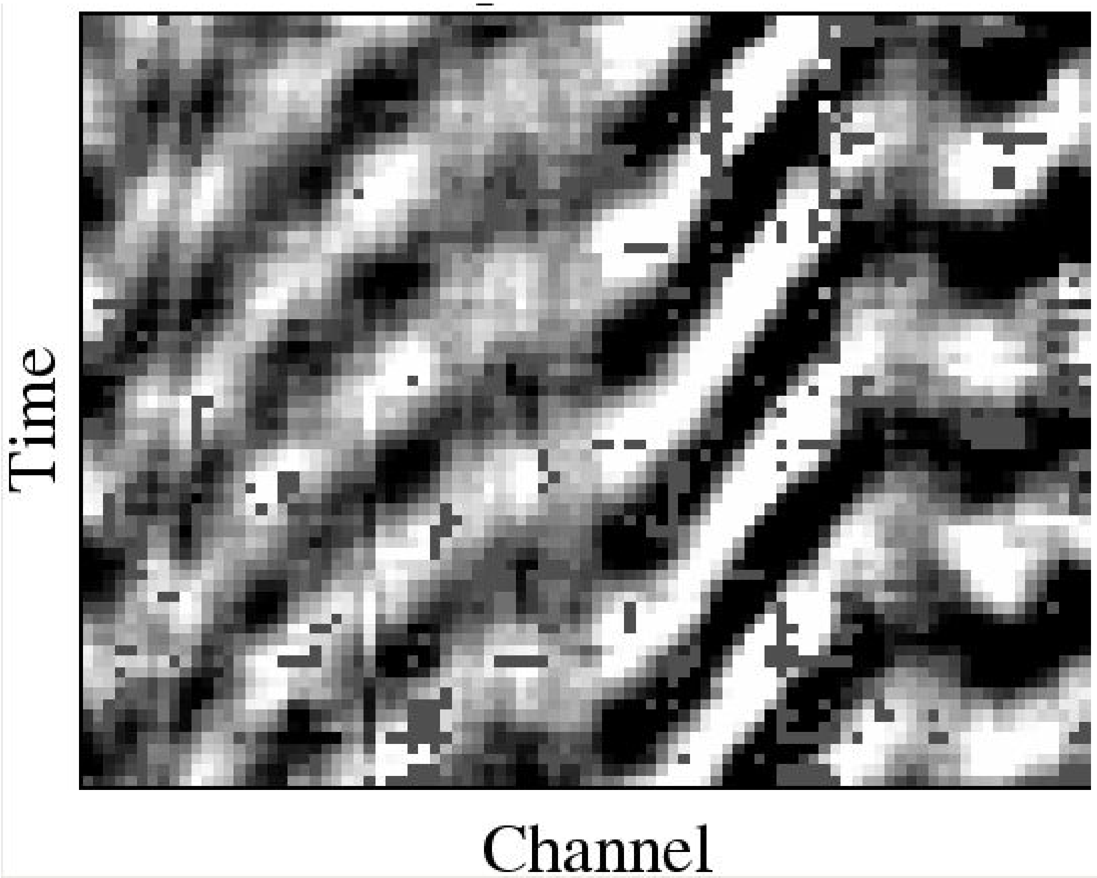
RFI @ GMRT 154 MHz – III

Grey-scale Visibility on frequency-time plane

A Fourier transform to localise and eliminate the ripples ?

With so many abrupt transitions a FT will be noisy

Analyse each channel independently



RfiX concept – algorithm

Fitting a single sinusoid of a precisely defined (fringe) period

- simple linear analysis – well understood error
- only 4 parameters – can fit with just a few points
- shorter fit → higher probability of constant RFI

  Fourier Transform requires dozens to hundreds of points

- longer integration on each point
  - Can detect and eliminate fainter RFI
  - no specialised, expensive, high-speed hardware
  - Manageable data rate – offline analysis
- Relative strengths of RFI and true visibility … not relevant

RfiX concept – caveats

The RFI source is stationary with respect to the interferometer

The RFI source is constant over the fit period

Multiple RFI sources … not an issue

The oscillation period depends only on the baseline

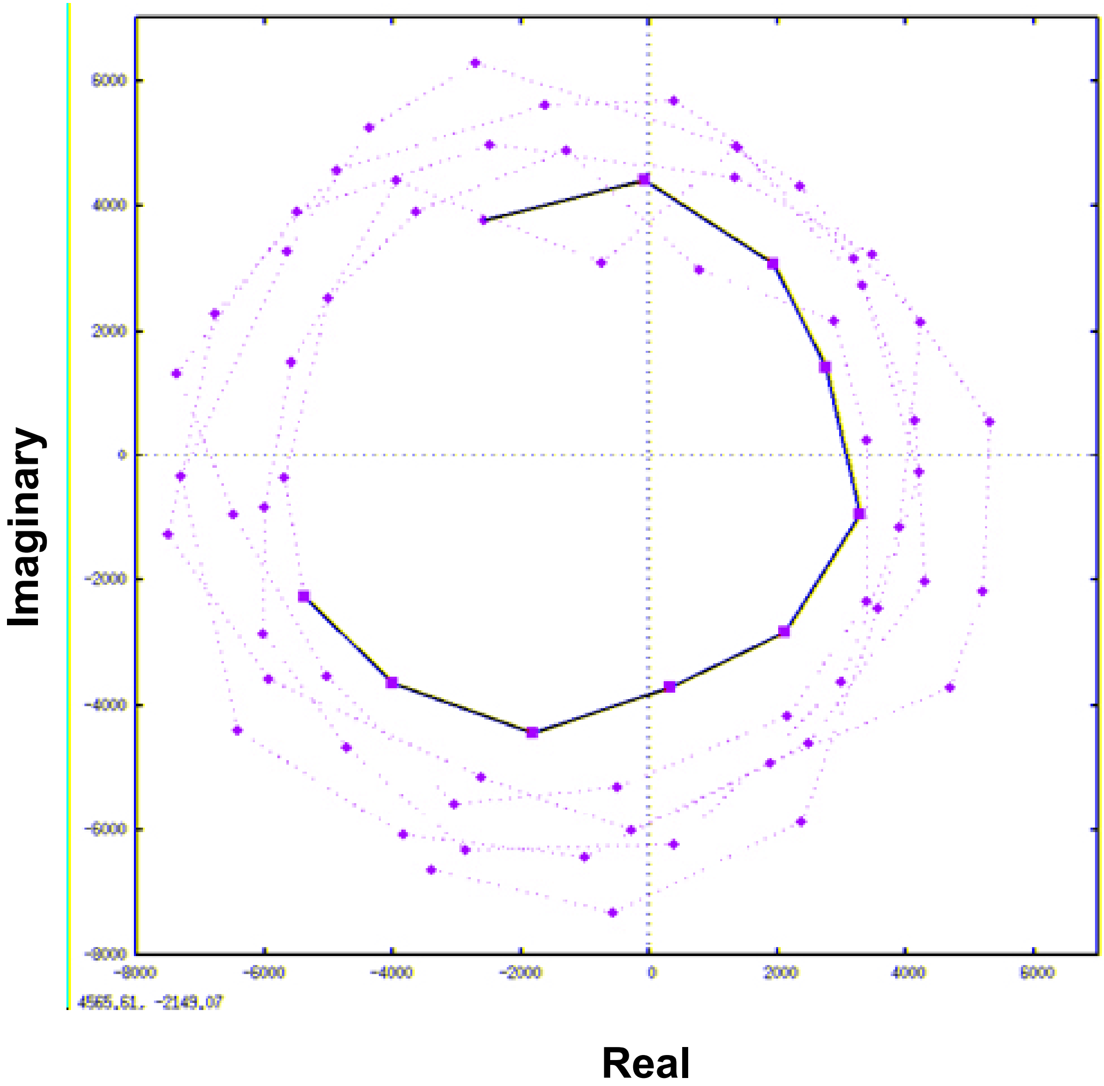
independent of the location of the RFI

resultant RFI $\mathcal{A} \cos(\omega_F t + \Phi) = \sum A_i \cos(\omega_F t + \phi_i)$

Estimate of the True Visibility

Outer Band of Points
observed visibility values

Connected String
temporal sequence of obs-erved values



Estimate of the True Visibility

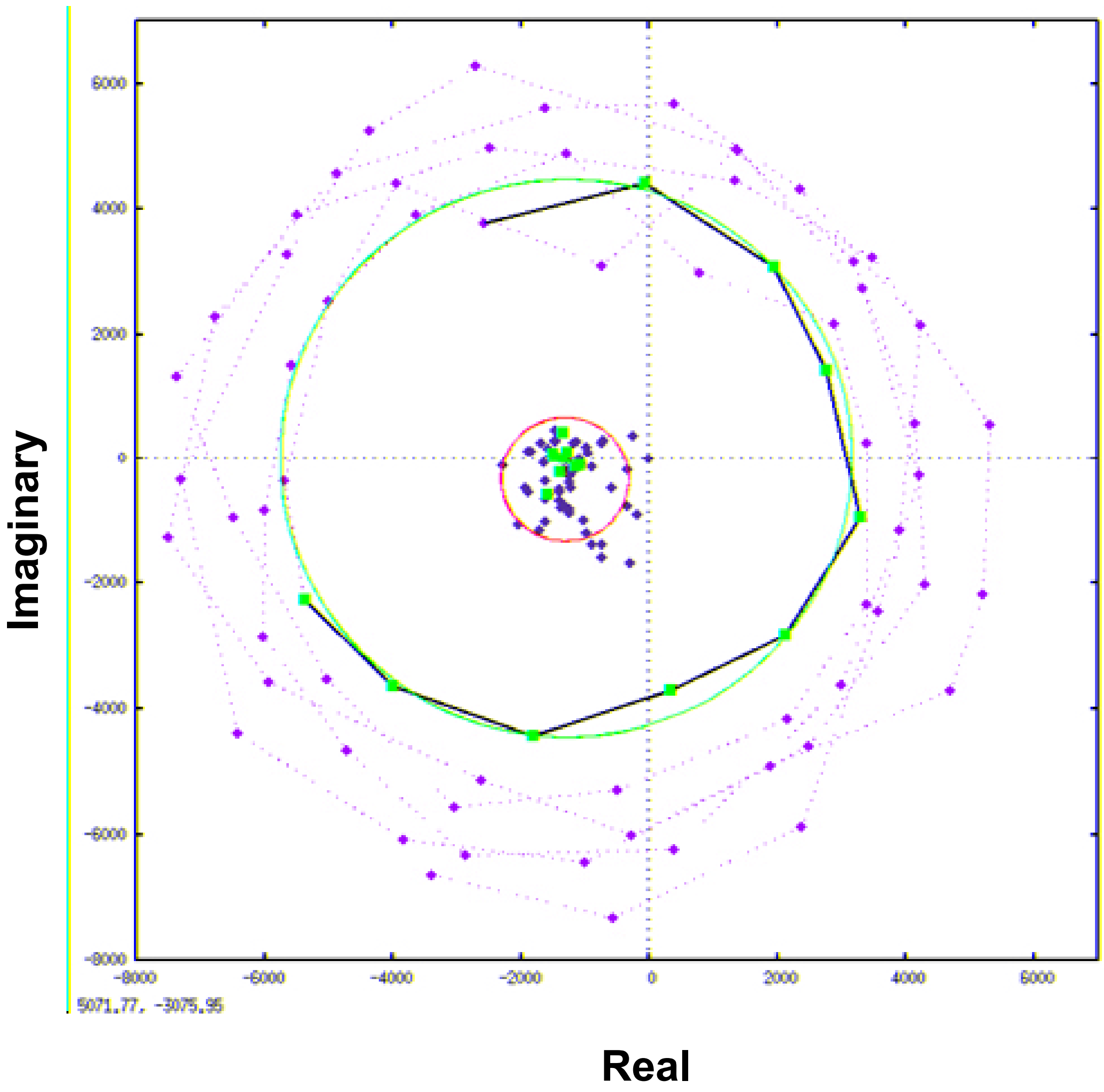
Outer Band of Points
observed visibility values

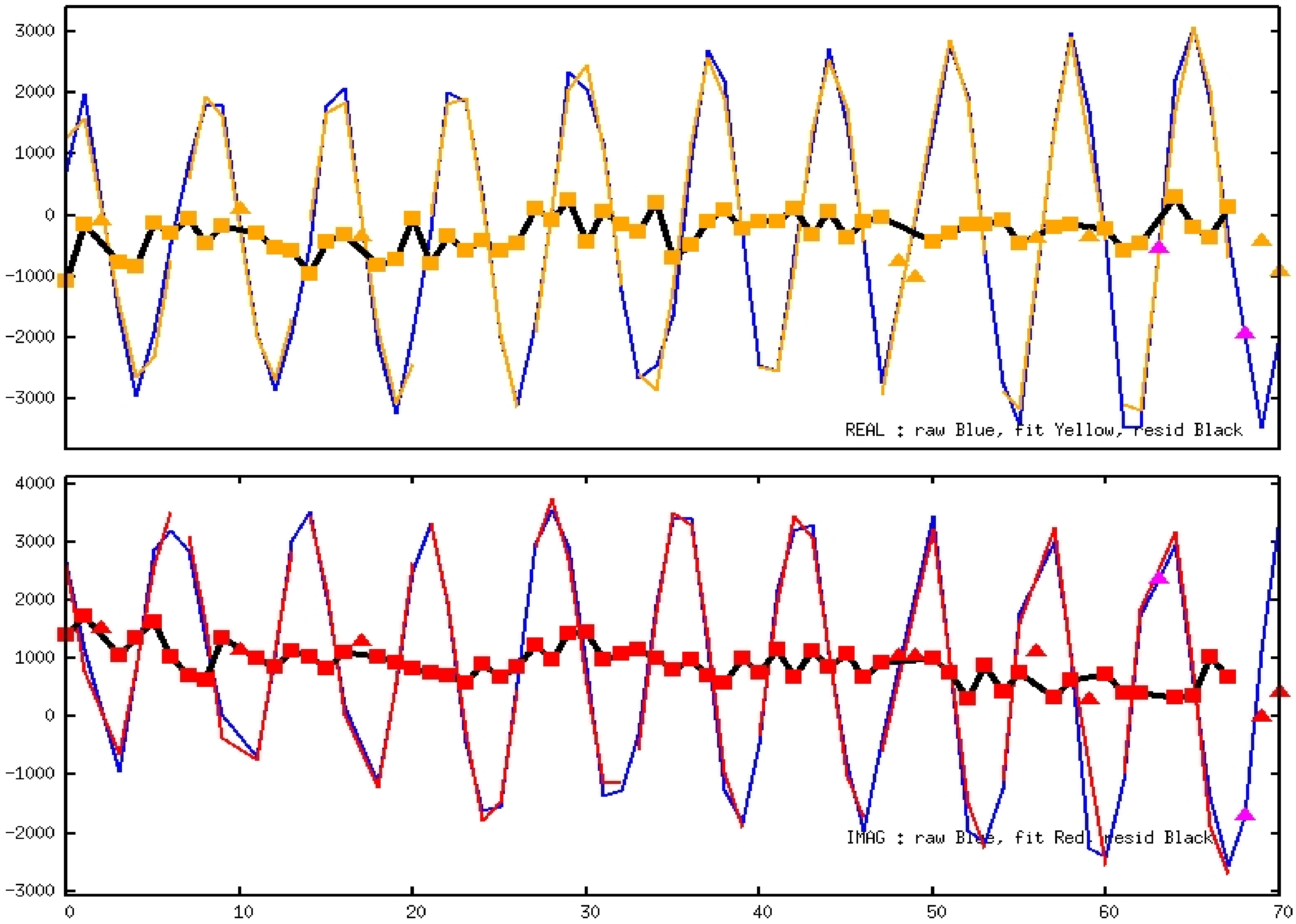
Connected String
temporal sequence of obs-erved values

Large Circles
Fit to RFI + true visibilities

Inner scatter of points
true visibilities

Inner Ring
3σ of the scatter

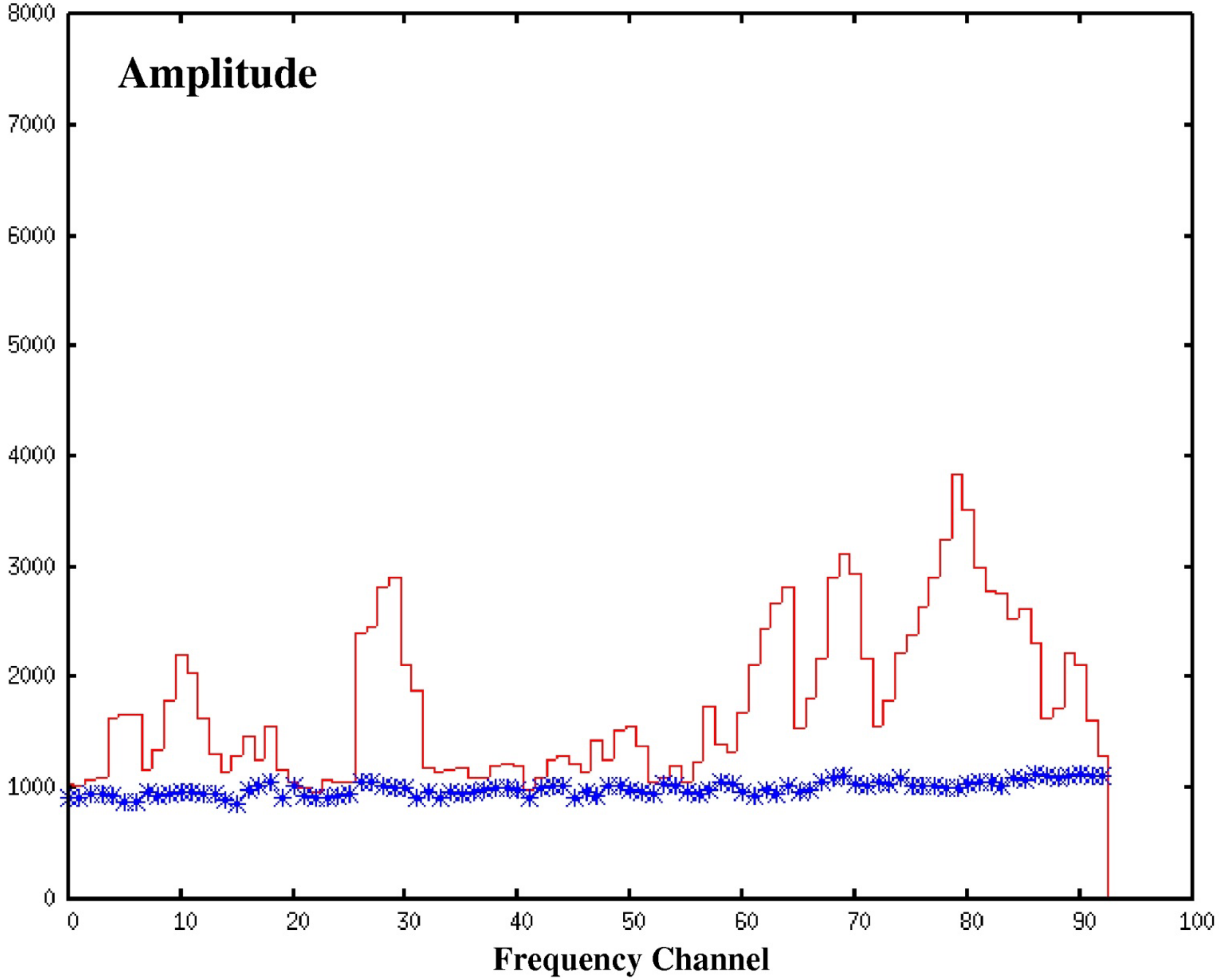



REAL : raw Blue, fit Yellow, resid Black
IMAG : raw Blue, fit Red, resid Black
3000
2000
1000
0
−1000
−2000
−3000
4000
0
10
20
30
40
50
60
70

Efficacy of the Algorithm - I

Red line
pre Rfi-X

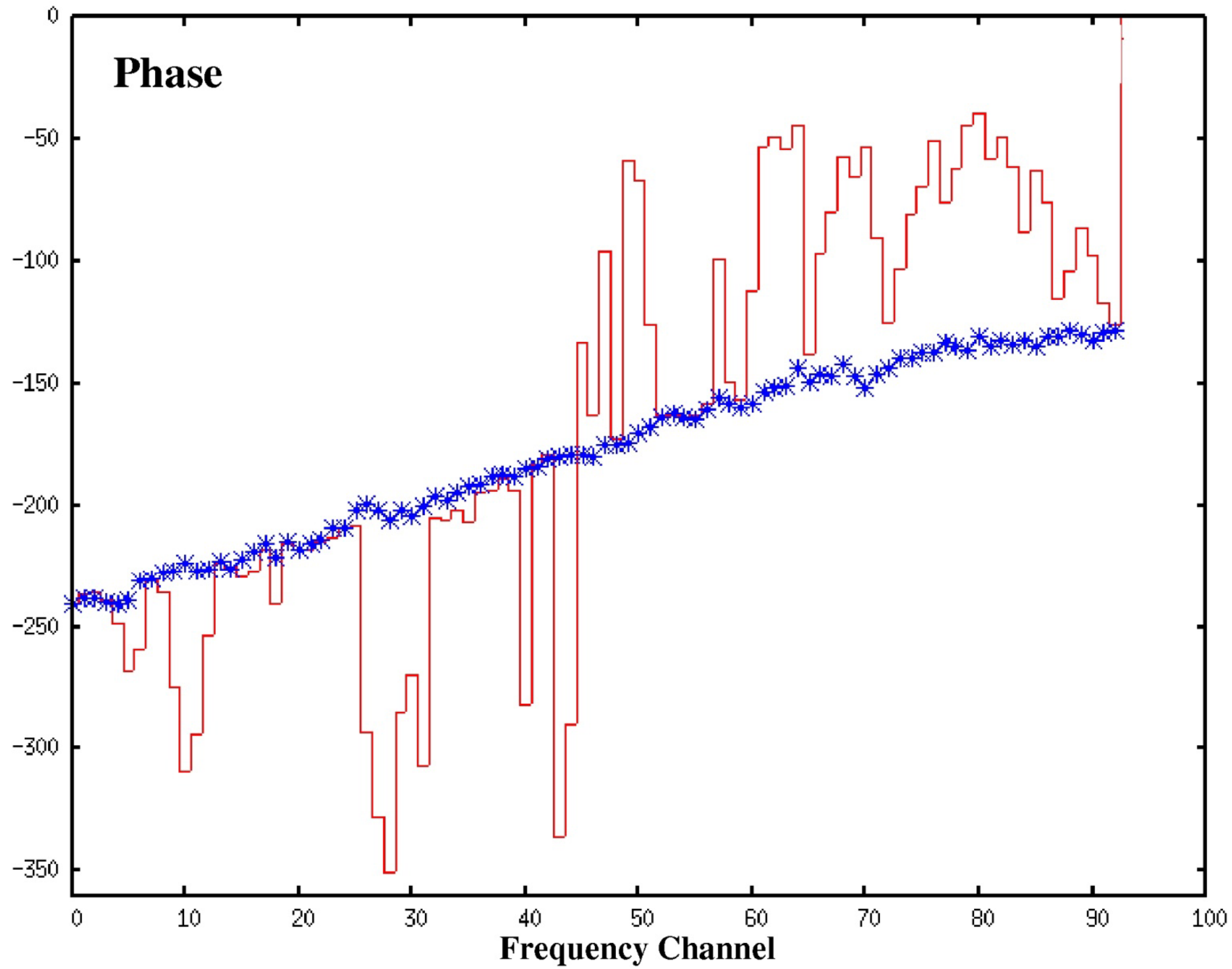
Blue asterisk
post Rfi-X



Efficacy of the Algorithm - I

Red line
pre Rfi-X

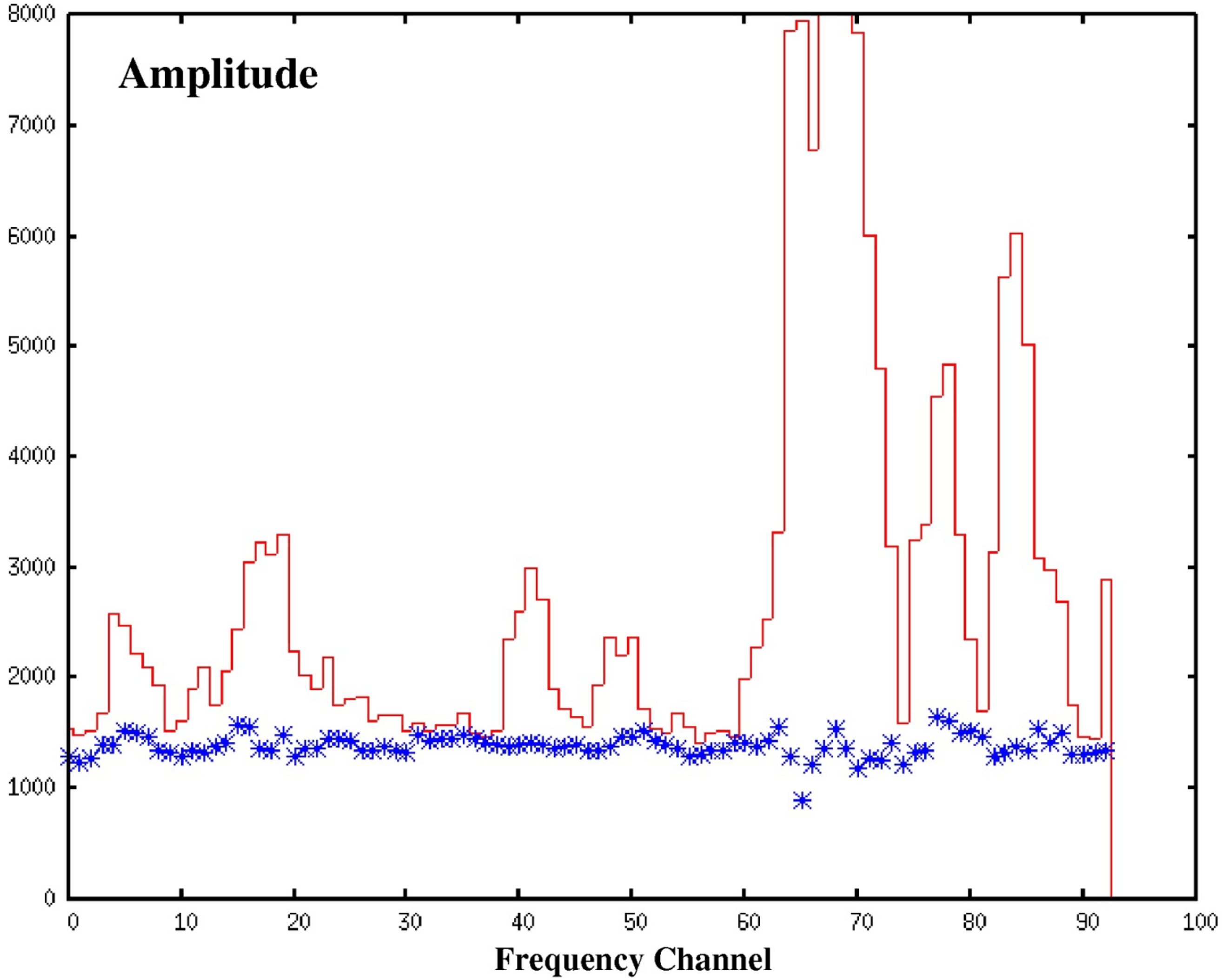
Blue asterisk
post Rfi-X



Efficacy of the Algorithm - II

Red line
pre Rfi-X

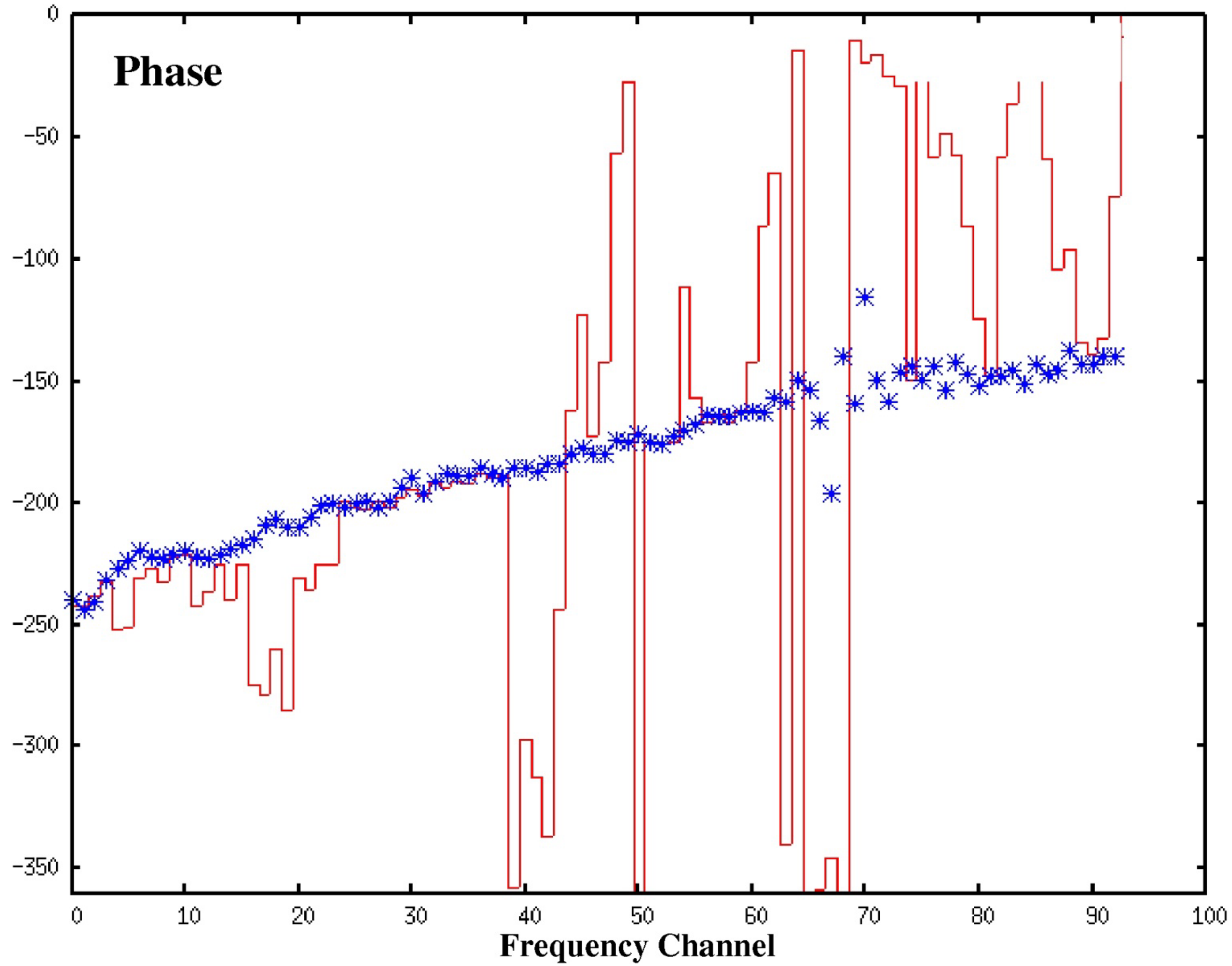
Blue asterisk
post Rfi-X



Efficacy of the Algorithm - II

Red line
pre Rfi-X

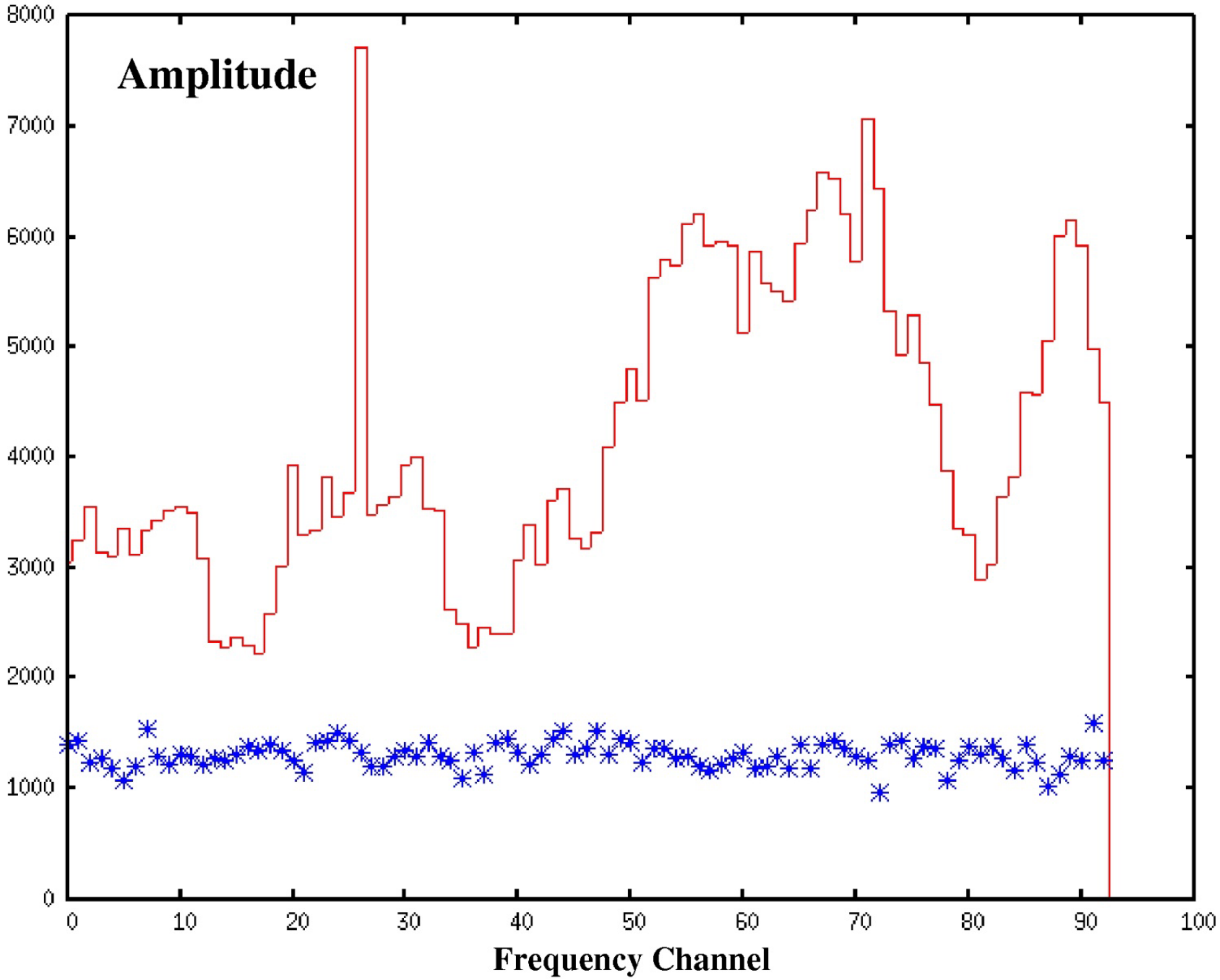
Blue asterisk
post Rfi-X



Efficacy of the Algorithm - III

Red line
pre Rfi-X

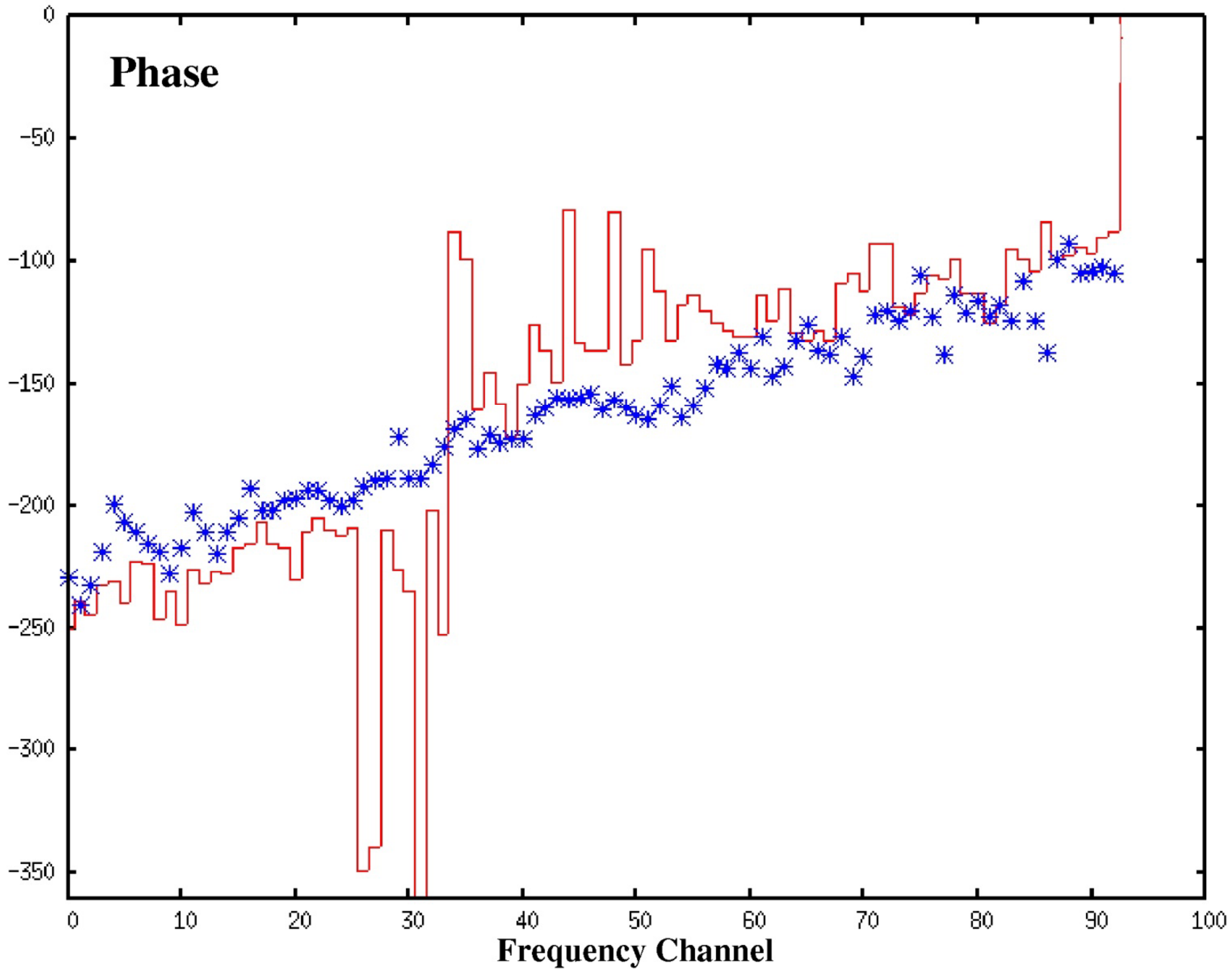
Blue asterisk
post Rfi-X



Efficacy of the Algorithm - III

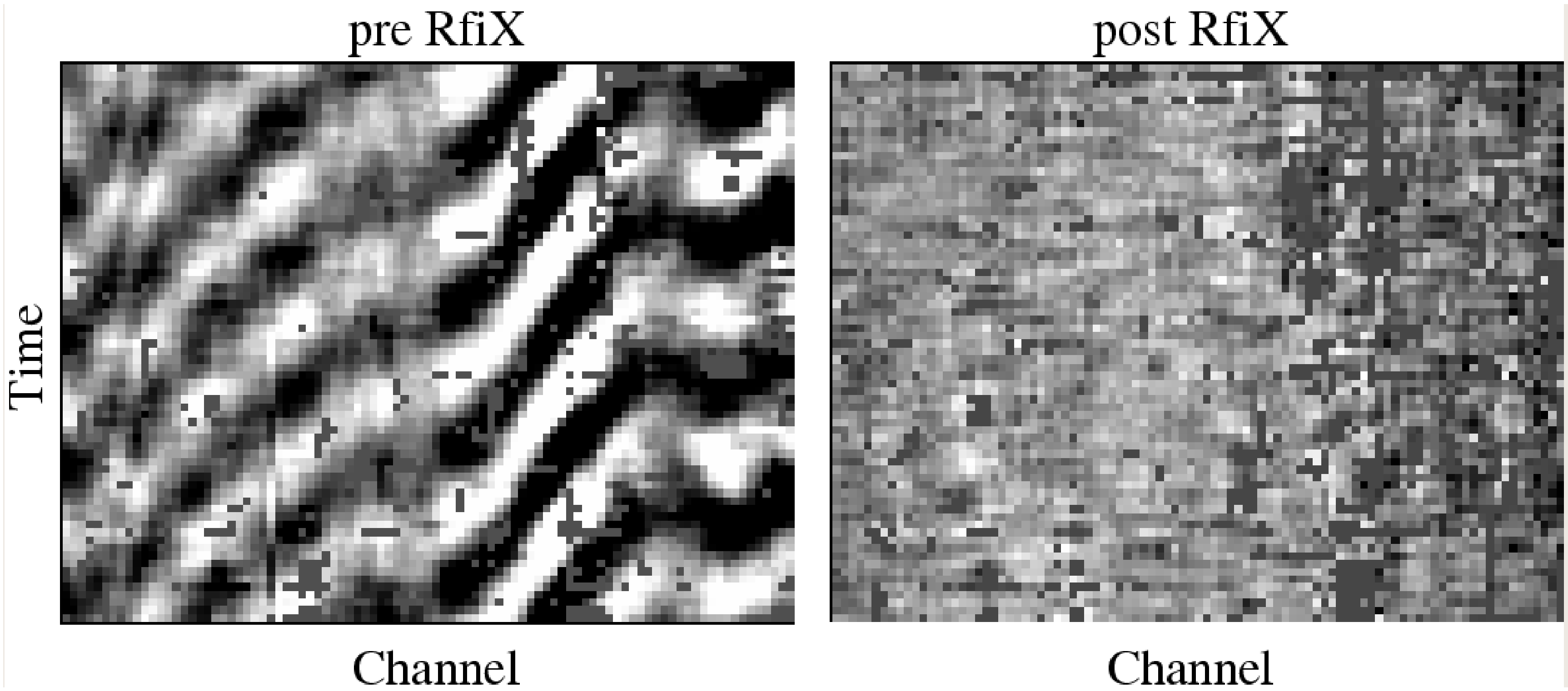
Red line
pre Rfi-X

Blue asterisk
post Rfi-X

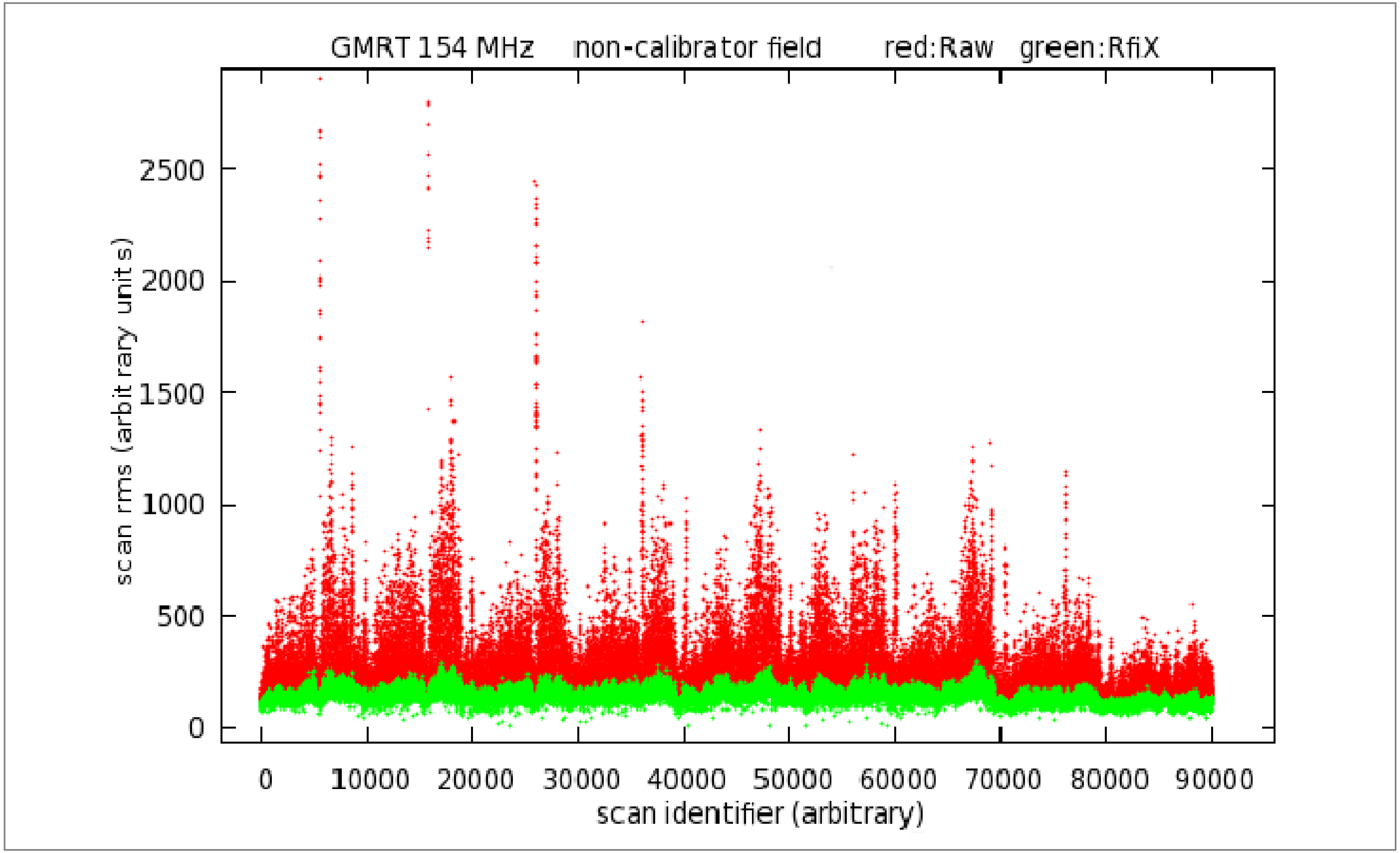


Efficacy of the Algorithm - IV

Grey scale Visibility on frequency-time plane



Efficacy of the Algorithm - V



Efficacy - 3C286 @ 240 Mhz I

3C286 at 240 Mhz

FWHM: 1.9 deg

Field: 2.5 deg

2 hour integration

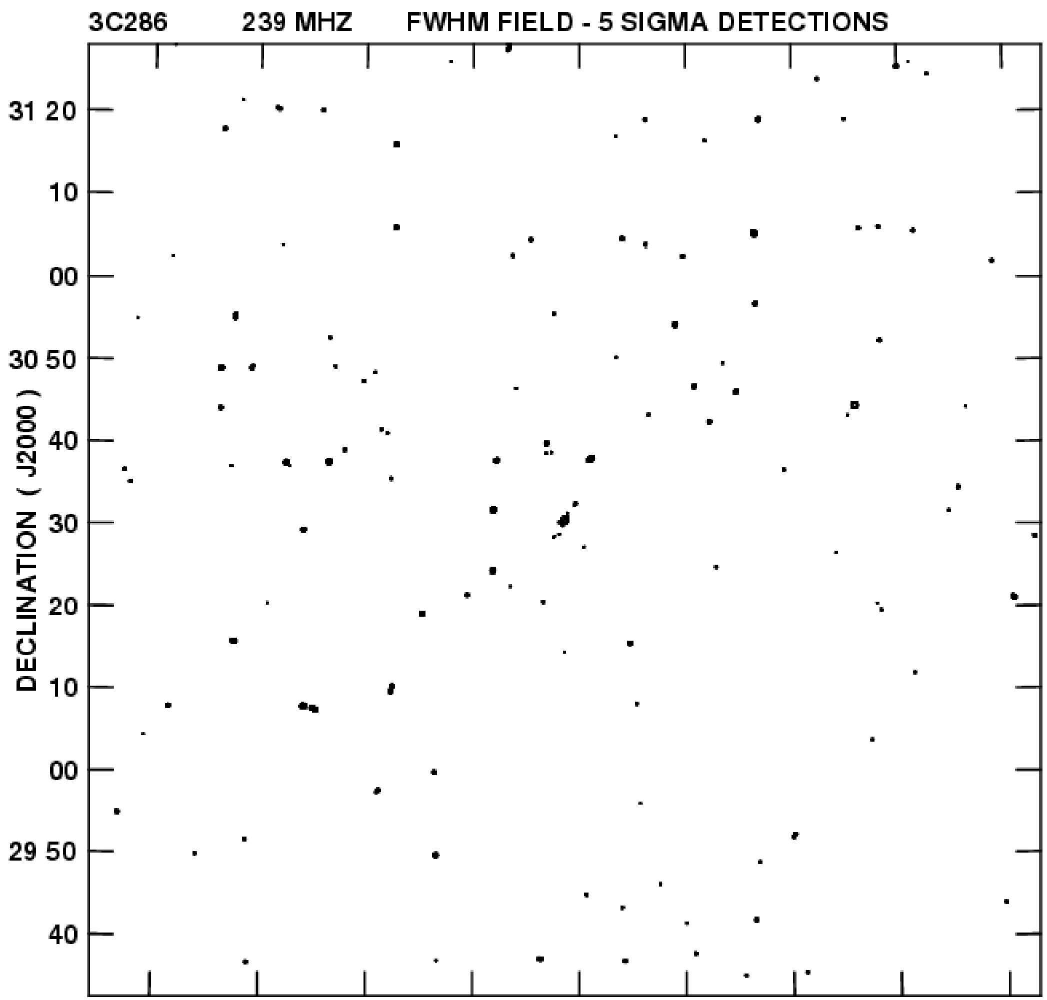
5.6 Mhz bandwidth

Peak Flux: 28 Jy

Noise near peak: 1.9 mJy

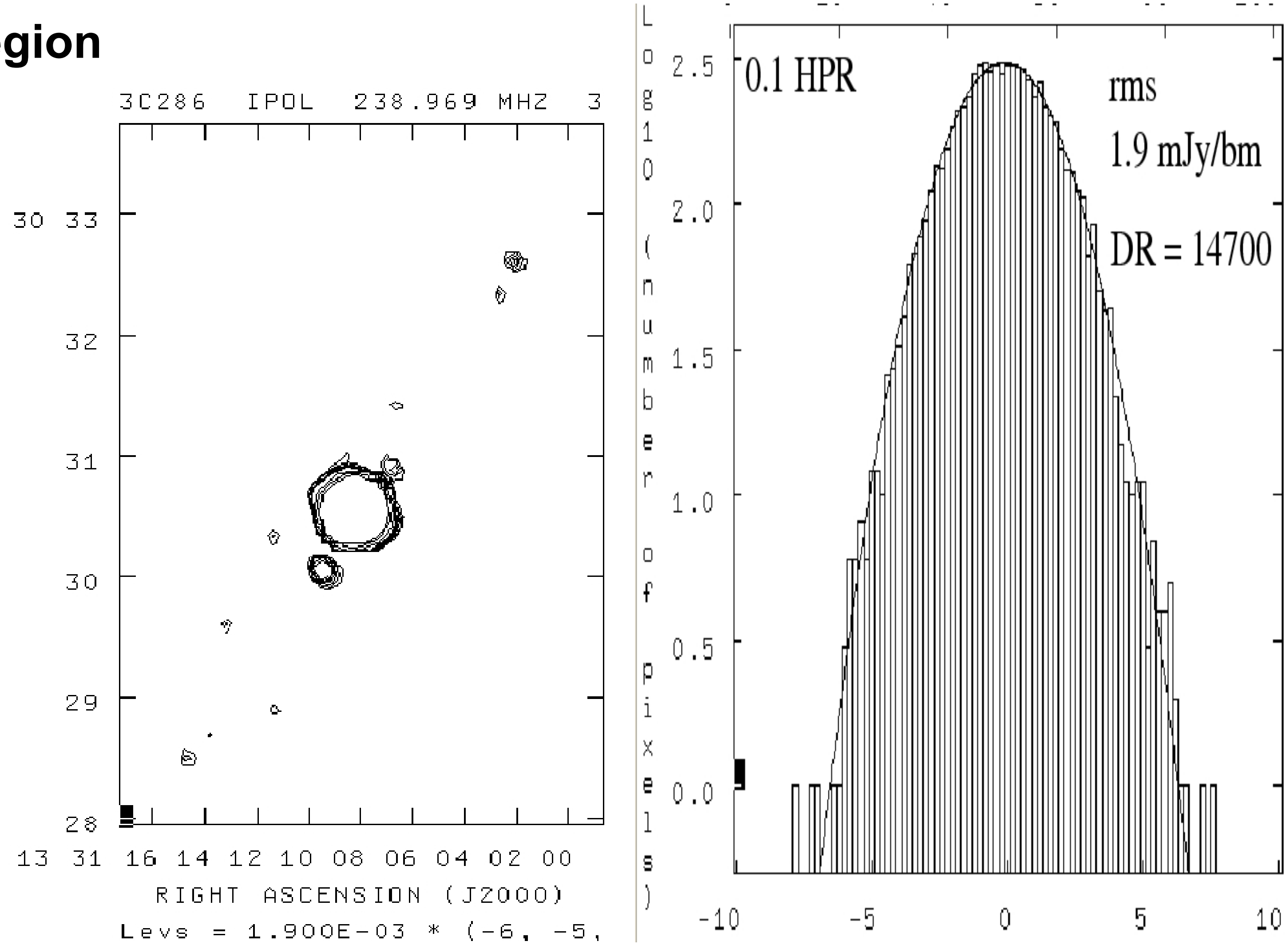
Noise at egde: 0.6 mJy

Efficacy - 3C286 @ 240 Mhz I



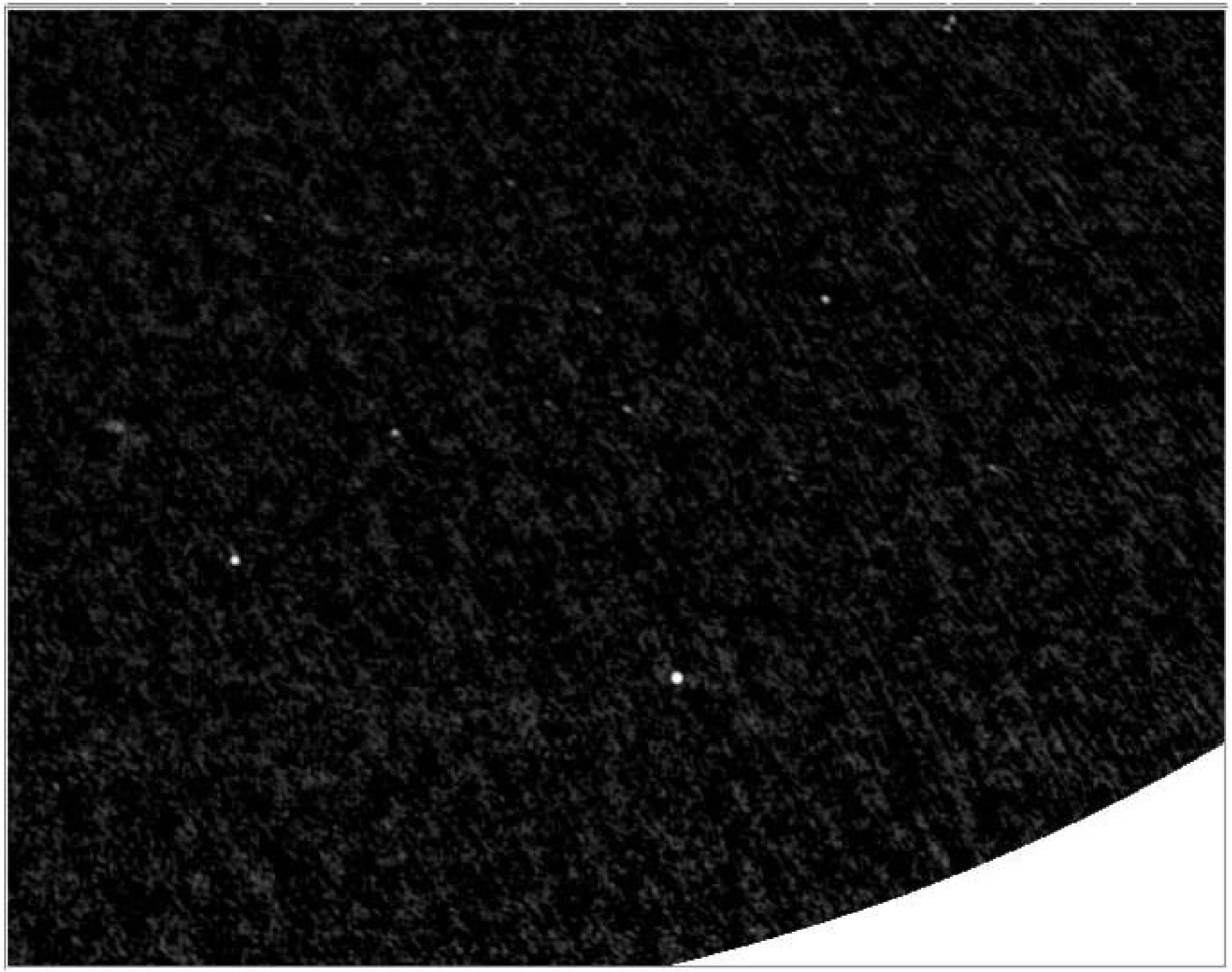
Efficacy - 3C286 @ 240 Mhz III

Central Region



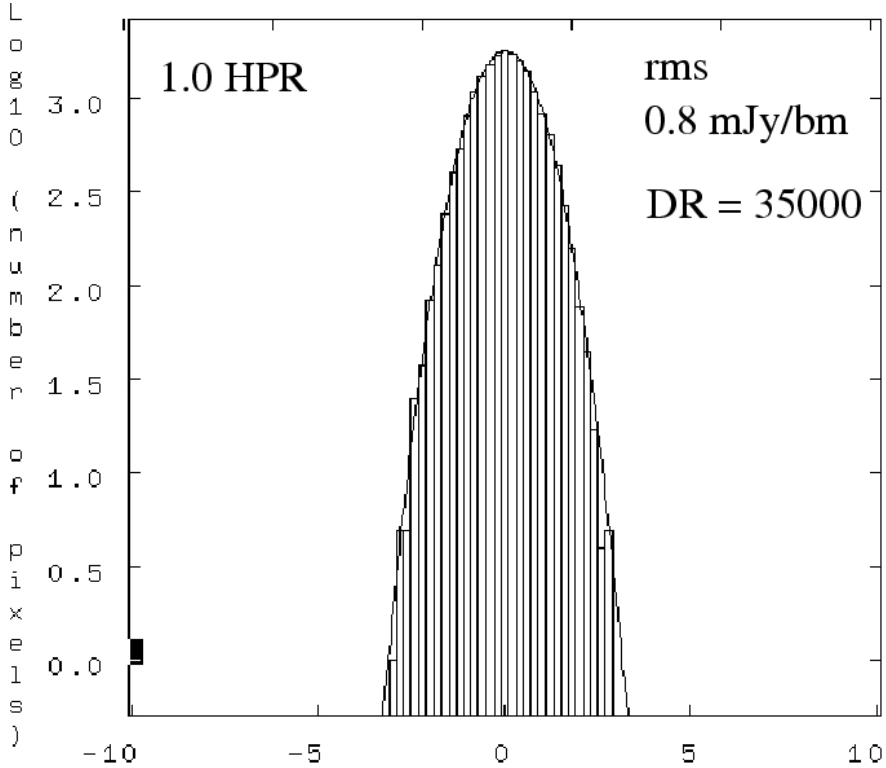
Efficacy - 3C286 @ 240 Mhz II

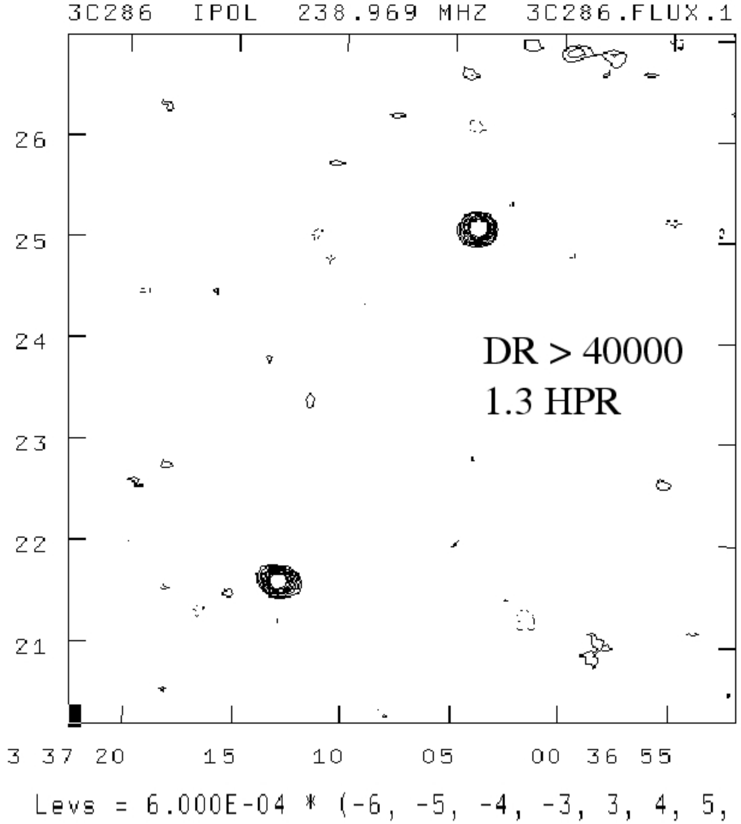
Peripheral Region



Efficacy - 3C286 @ 240 Mhz IV

Peripheral Region





Pros & Cons - 1

- A new approach to RFI excision – conceptually simple and hence its domain of applicability is easily understood
- Efficacy independent of relative strengths of RFI and target
- Requires no special hardware
- More sensitive to weak RFI than high speed sampling techniques
- Can even be applied to archival data (at GMRT)
- Can be implemented for any interferometer

Pros & Cons - 2

- Cannot remove RFI if the fringe period is very large
  - Near the North Pole
  - baselines along a particular position angle
- Will not work if RFI is variable over the fringe period – problem with baselines with large periods (> 600 seconds)
- Will not work if fringe period is similar to the basic integration time of the data – i.e. for long baselines; but long baselines rarely show correlated RFI.

At the GMRT RfiX works for baselines > 35 to 100 λ

i.e. structures < 0.5 to 1.5 deg

Summary

We have an algorithm for excision of RFI from interferometric data in most (but not all) situations

The algorithm salvages signals much fainter than the RFI

The algorithm has been used to make high dynamic range images using the GMRT (up to 40,000 at 240 MHz)

It complements techniques which use high sampling speeds, by dealing with fainter RFI which is constant over few to 100s of seconds.

A combination of the two should go a long way towards the quest for high dynamic range imaging at low radio frequencies

Thank You

Comparison with Map-RFI-to-North-Pole

- MRtNP : RFI has to mimic a celestial source, not true in general
  - Same T_{rfi} in all antennas
  - definite phase and amplitude relationship between contribution to each baseline

RfiX : treats RFI as a baseline issue

- MRtNP : should work for distant sources of RFI, in which situation it will be computationally less demanding