ASTRON Netherlands Institute for Radio Astronomy

THE LAYERS OF RFI MITIGATION

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The Objectives

- Mitigation aimed at wanted signals in non-RAS bands
- Mitigation not aimed at unwanted signals in RAS bands
  - not an excuse for unwanted emissions
- All mitigation of RFI in the data itself leads to Data Loss

- Prevention better than mitigation
- The earlier - the better
  - This gives less downstream system cost and complexity
- Mitigation only possible for significant INR
- Require integration (further into process) to deal with weak RFI

- Prevent RFI or mitigate RFI in data or delete bad data

- Extensively use
- Fridman & Baan (2001)
- Kesteven (2009)
- ITU-R RA.2126 (2007)

- RFI 2010 Proceedings (Baan 2010)
- RFI 2010 presentations http://www.astron.nl/rfi
- RFI 2010 to be published online (Proceedings of Science)

RFI signatures

- Type of radio telescope
  single dish telescopes
  connected interferometry (Array RT)
  Very Long Baseline Interferometry
- RFI (in-)coherently enters the system => baseline dependence => calibration affected by RFI noise power

- The type of observations
- continuum or spectral line
- continuum observations can sacrifice certain time slots
- spectral line damage depends on location of RFI

- Type of RFI
- Impulsive bursts, narrow- or wide-band
- superposition of patterns

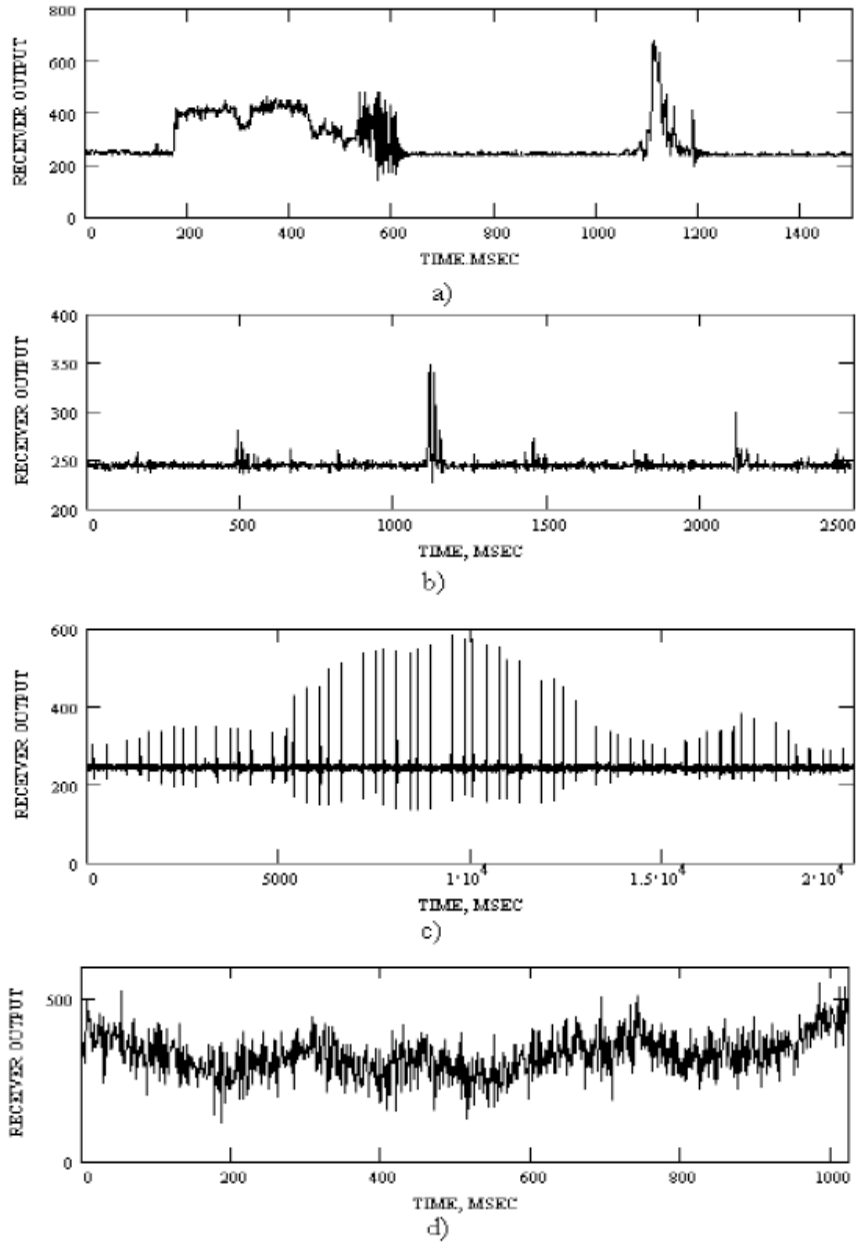


Fig. 1. Examples of *RFI* waveforms in the receiver output versus time: a) and b) impulse-like *RFI*; c) radar impulses; d) narrow-band *RFI*.

Sources of RFI

- Satellite RFI
  - Some sources always present
  - Main-beam coupling – example Cloudsat at 94 GHz
  - Side-lobe coupling
- Aircraft RFI
  - Direct emissions (mobile and network traffic)
  - Reflection of ground-based transmissions
- Ground-based RFI
  - Tracking population density (remote sites)
  - Reflecting windmills
- Observatory-based RFI
  - Computing and electronics
  - Screen or eliminate sources

Evaluation of methodologies

- What is level of suppression of the RFI signal ?
- What is loss of signal-of-interest (SOI) as a result of RFI mitigation and the amount of data loss ?
  - 1. Interference to noise ratio INR (how much RFI dominates the noise)
  - 2. Occupied bandwidth => ratio of SOI bandwidth and RFI bandwidth
  - 3. Processing gain after RFI suppression => ratio of SNR(after) and SNR(before)
  - 4. Loss from RFI processing => ratio of SNR(after) and SNR(no RFI)

Reality Check

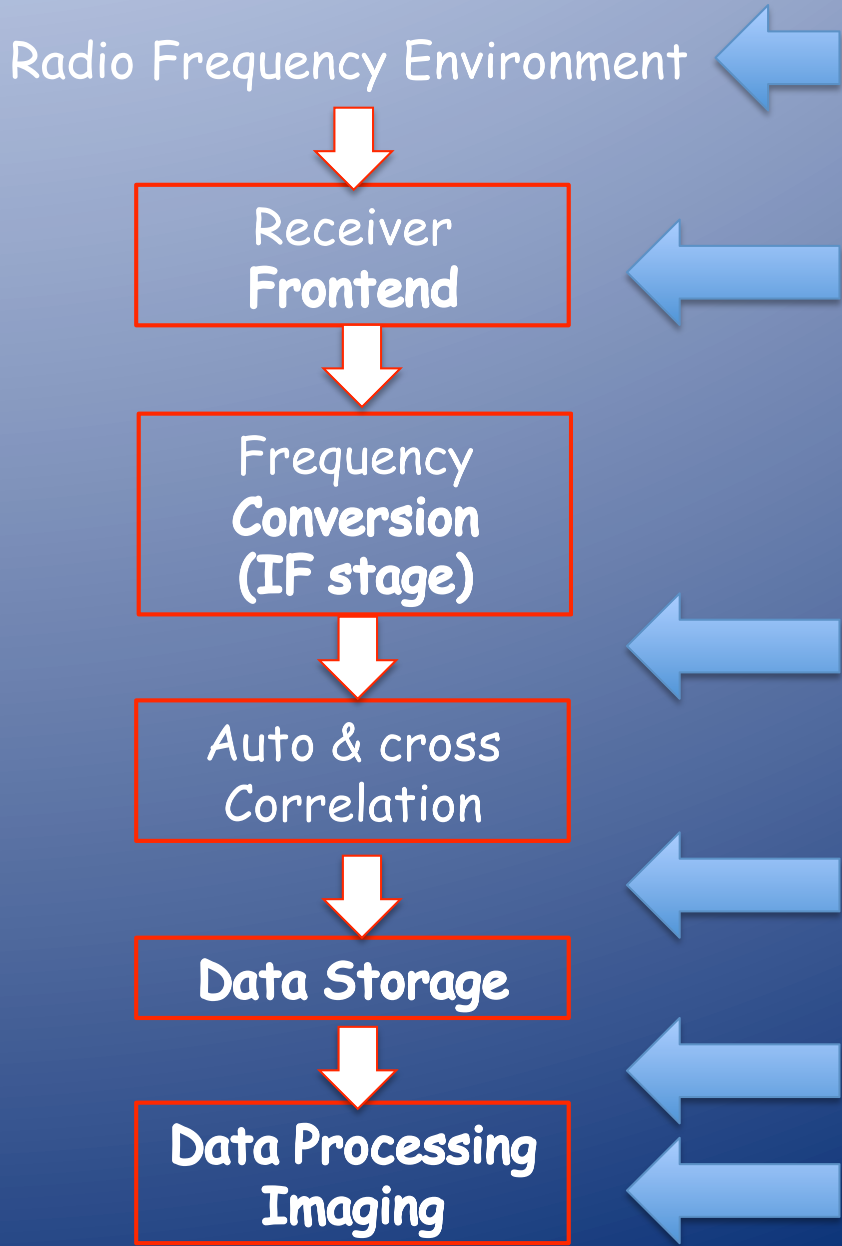
- ITU Standards for spurious and out-of-band (unwanted) emissions not sufficient for protection passive services
- General philosophy: Rather than RFI prevention better to fill the spectrum with users and afterwards solve conflict issues
  - RAS generally first victim
- Increasing RAS bandwidth use at lower & higher frequencies
  - covering RAS allocated bands
  - covering non-allocated and non-protected bands
- Increasing intensity and density of spectrum use increases OOB and spurious emissions
- Introduction of spread-spectrum broadband systems
  - low-power but unlicensed & mass-produced devices
  - requires creative solutions to protect RAS bands (spectrum masks not adequate)

Telescope Systems

- *Mitigation at different stages in the process*
- *Different techniques at different stages*

- Integration starts at Correlation => RFI has more S/N

- Places in the data flow where RFI mitigation can be inserted



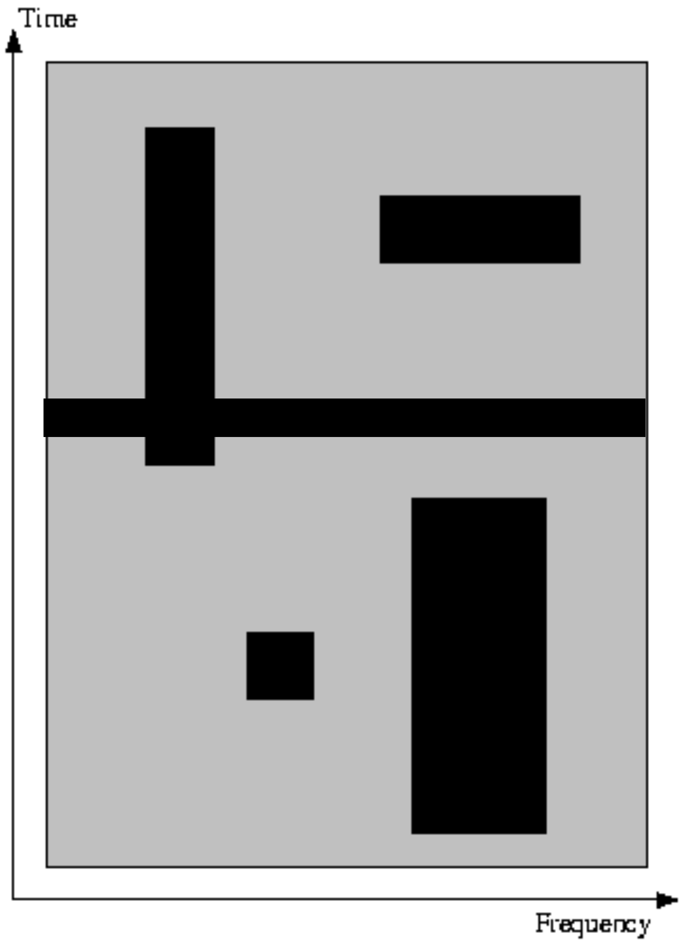
Steps of Mitigation

- Pro-active & Pre-detection
  - coordination & regulation
  - know the enemy – spectral monitoring
- Pre-detection & post-detection
  - filtering, temporal excision (blanking – in correlator), and anti-coincidence (Array systems)
- Pre-correlation
  - ANC, antenna-based digital processing, spatial nulling
- At correlation
  - SD => baseband processing (before or during data stacking)
  - Arrays => anti-coincidence & digital processing & reference antenna
- Post correlation
  - SD => flagging, reference spectrum
  - Arrays => flagging, use fringe stopping, identify/subtract non-celestial RFI sources

Pro-Active ⇔ Pre-Detection

- Establish coordination & quiet zones
  - use natural terrain
  - examples are GBQZ, WA Quiet Zone, SA Science Reserve, ALMA QZ & PRCZ
- Use national regulations
  - example of new NL Telecom Law – scientific use of the spectrum classified as *essential government use*
- Maintain & improve existing regulation (ITU-R RA.769 & RA.1513 & others)
- Solve issues before implementation (Ch 54 at Arecibo)
- Know your spectrum neighbors - prevention

- Clean up your own observatory act



Time-Frequency Diagrams

Excising in temporal and frequency domain

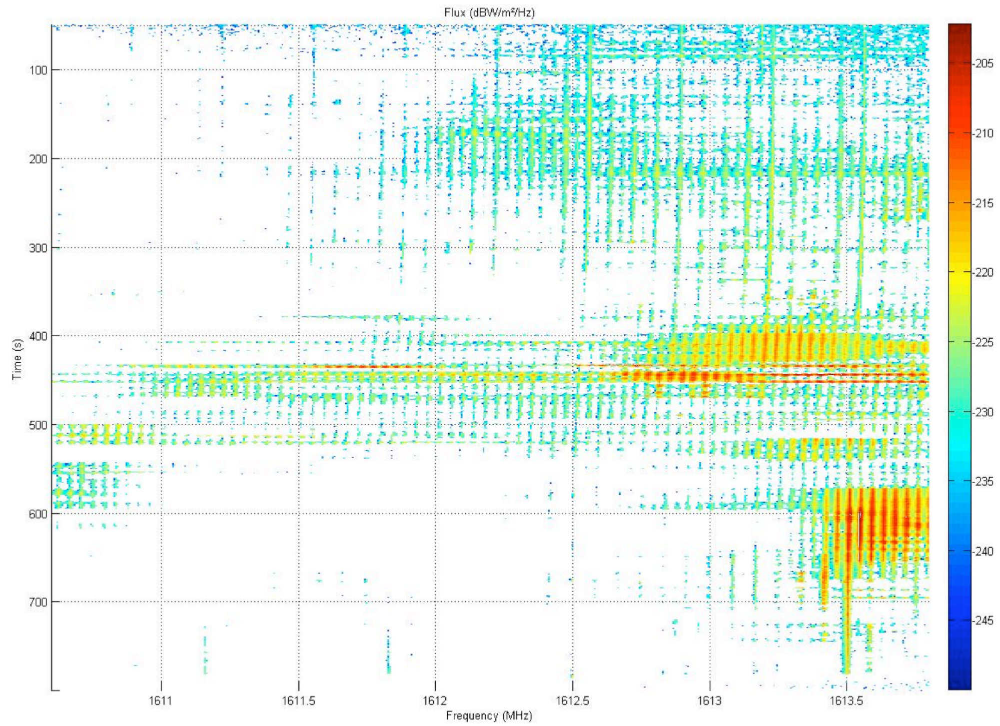
- RFI strong & short => not weak and persistent
- if intermittent & no info in rejected channels
- data loss

Cancellation => subtraction RFI from output

- no impact on science = no data loss

Anti-coincidence => using widely separated RTs

- adds to the noise



Leeheim IRD-82 (MAR 2010)
single passage (Jessner)

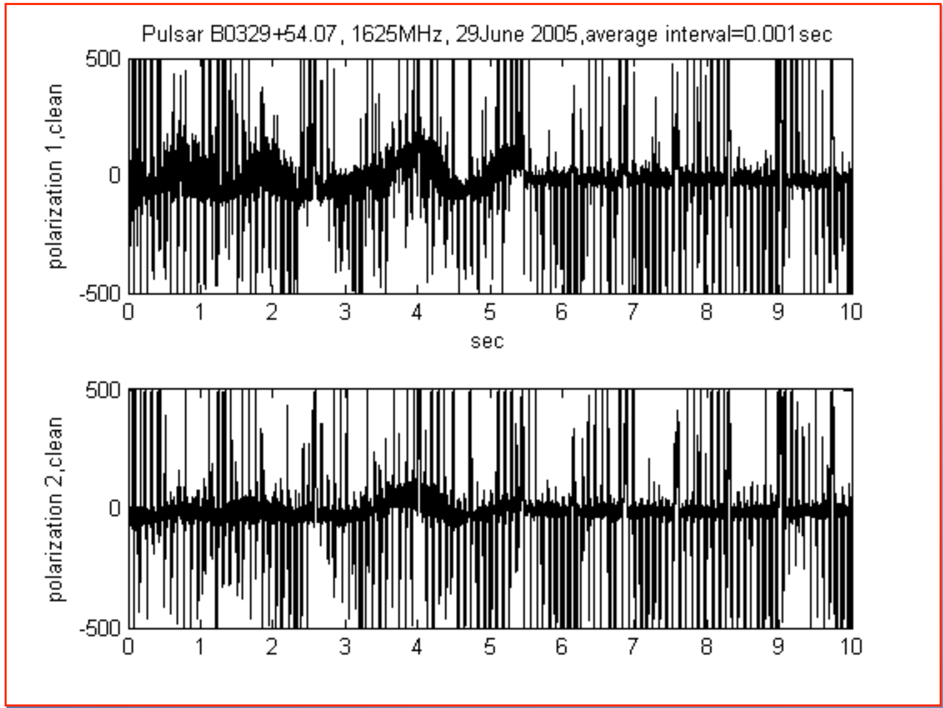
Pre-Detection & Post-Detection

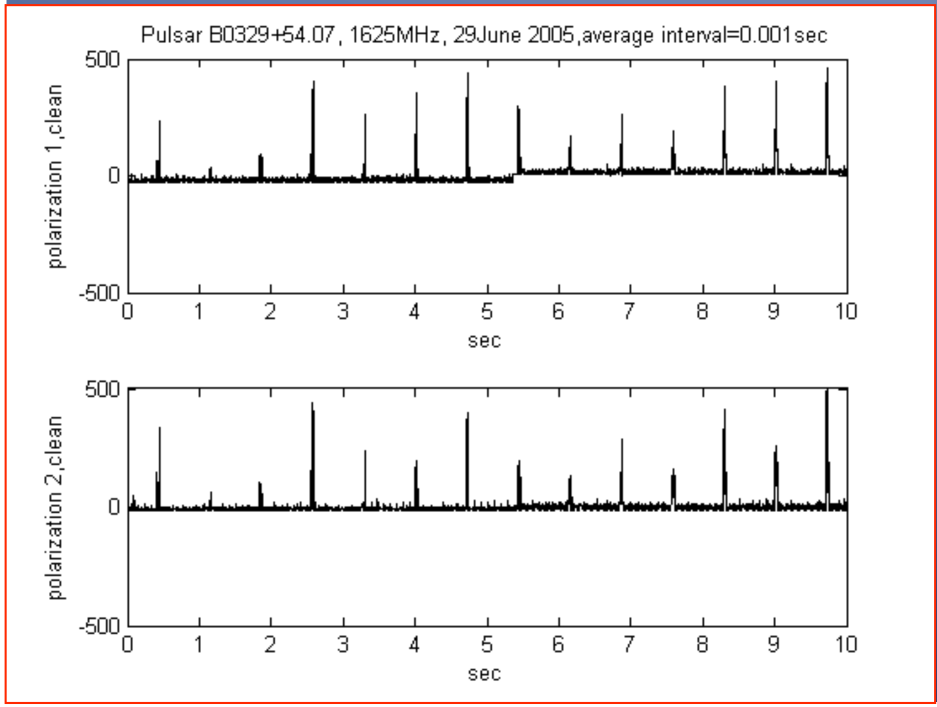
- filtering, *temporal excision (blanking – in correlator)*, and *anti-coincidence* (array systems)

  => data loss and reduction of signal quality
- Robust receivers – receiver linearity

- Filtering results in insertion losses and raises Tsys
  - more significant if close to the band-edge
- Super-conducting filter technology – under development

- Single RT => blanking or stopping correlator
  - example: Arecibo – SJU airport L-band radar and others
  - terrain and multi-path broadens RFI time-window
  - works well for periodic & impulsive signals
  - broad-band possible if linear system & no aliasing



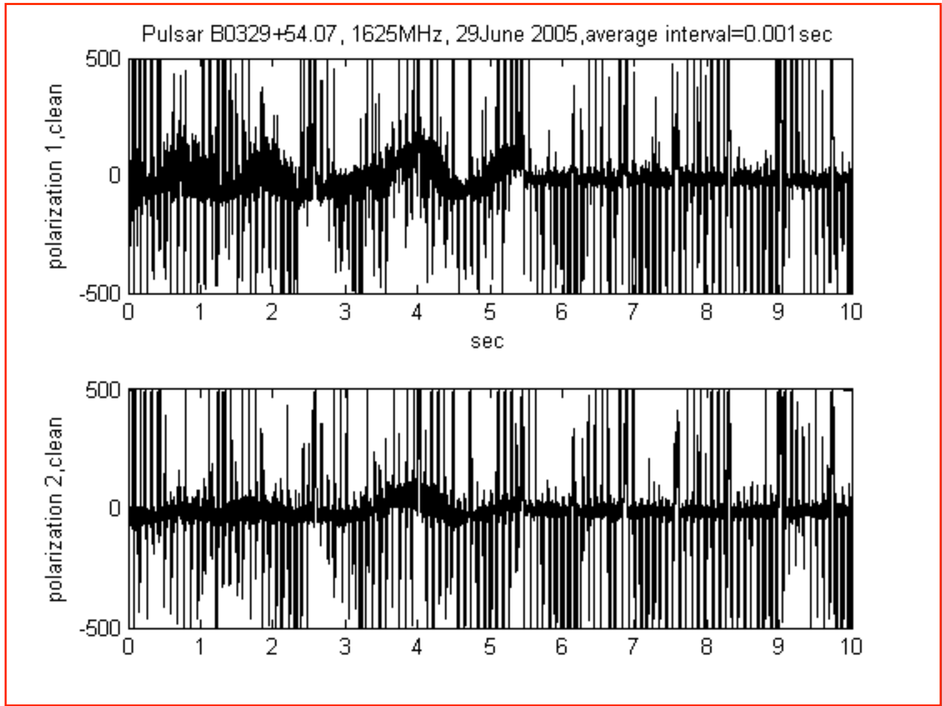


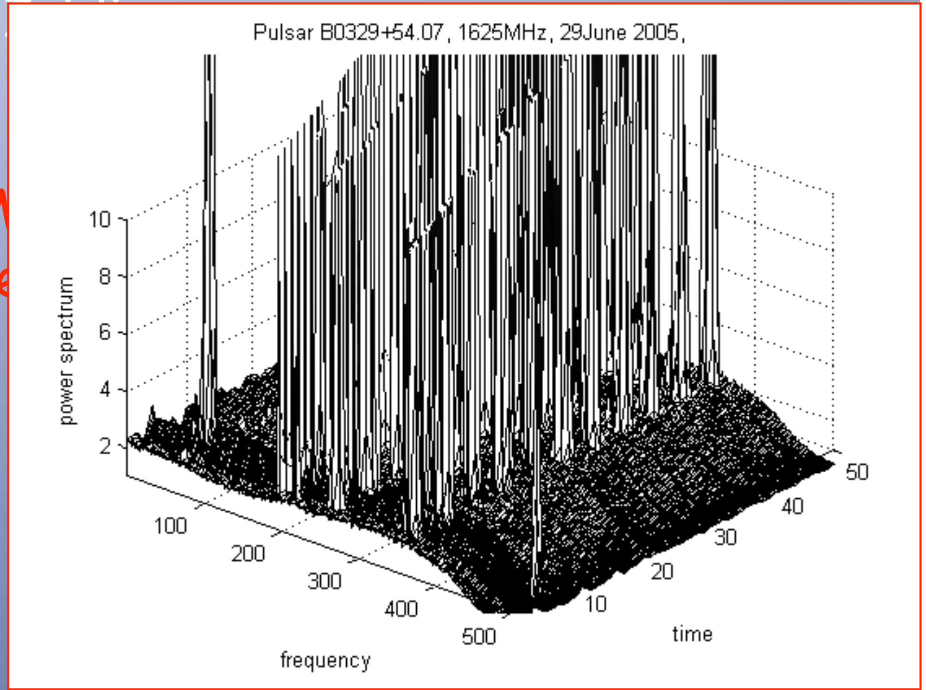
Pulsars
and Iridium

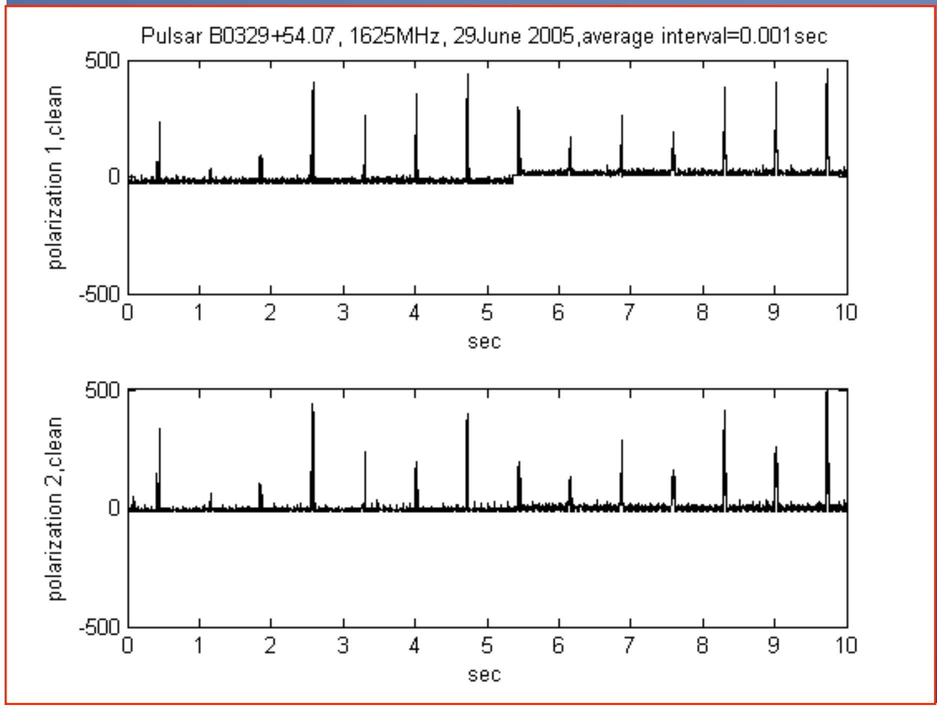
SW processing in Westerbork
PUMA II system
standard excision algorithms

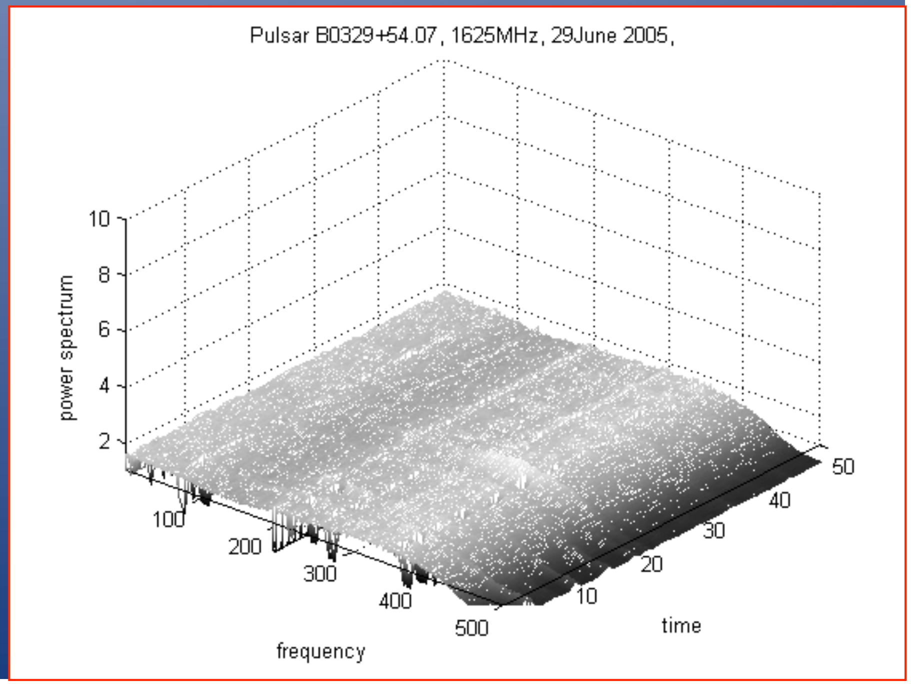
Pulsars
and

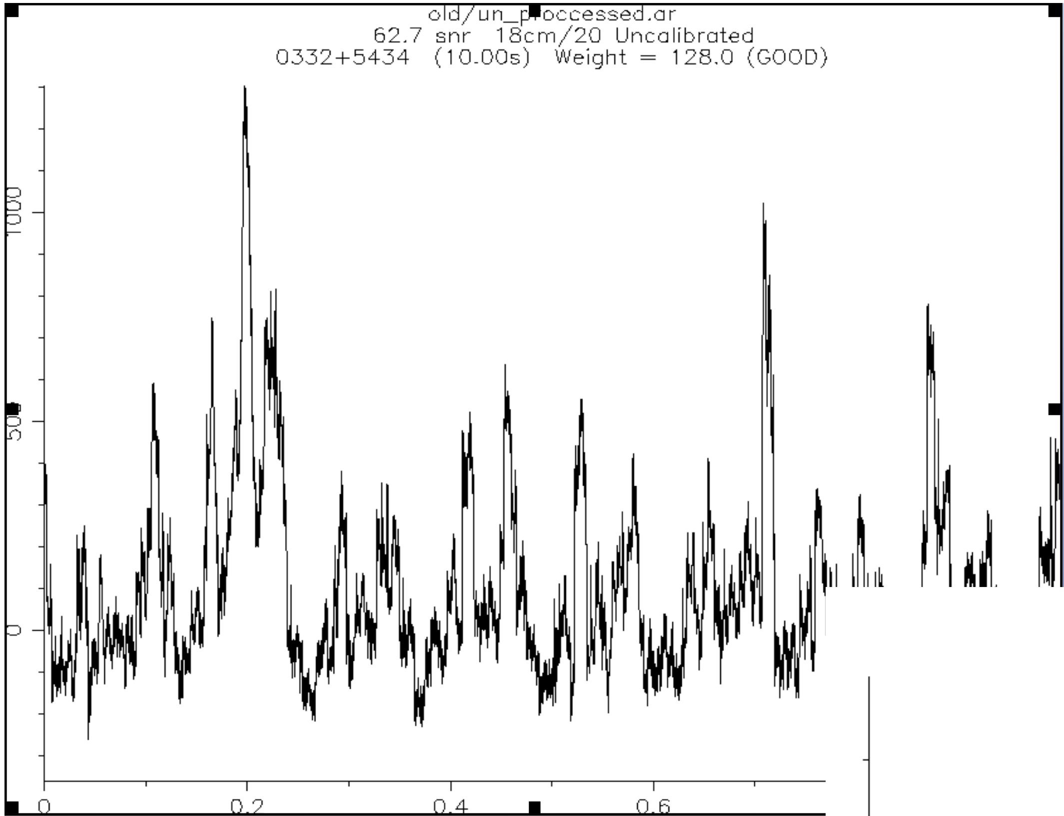
SW
PUM
same







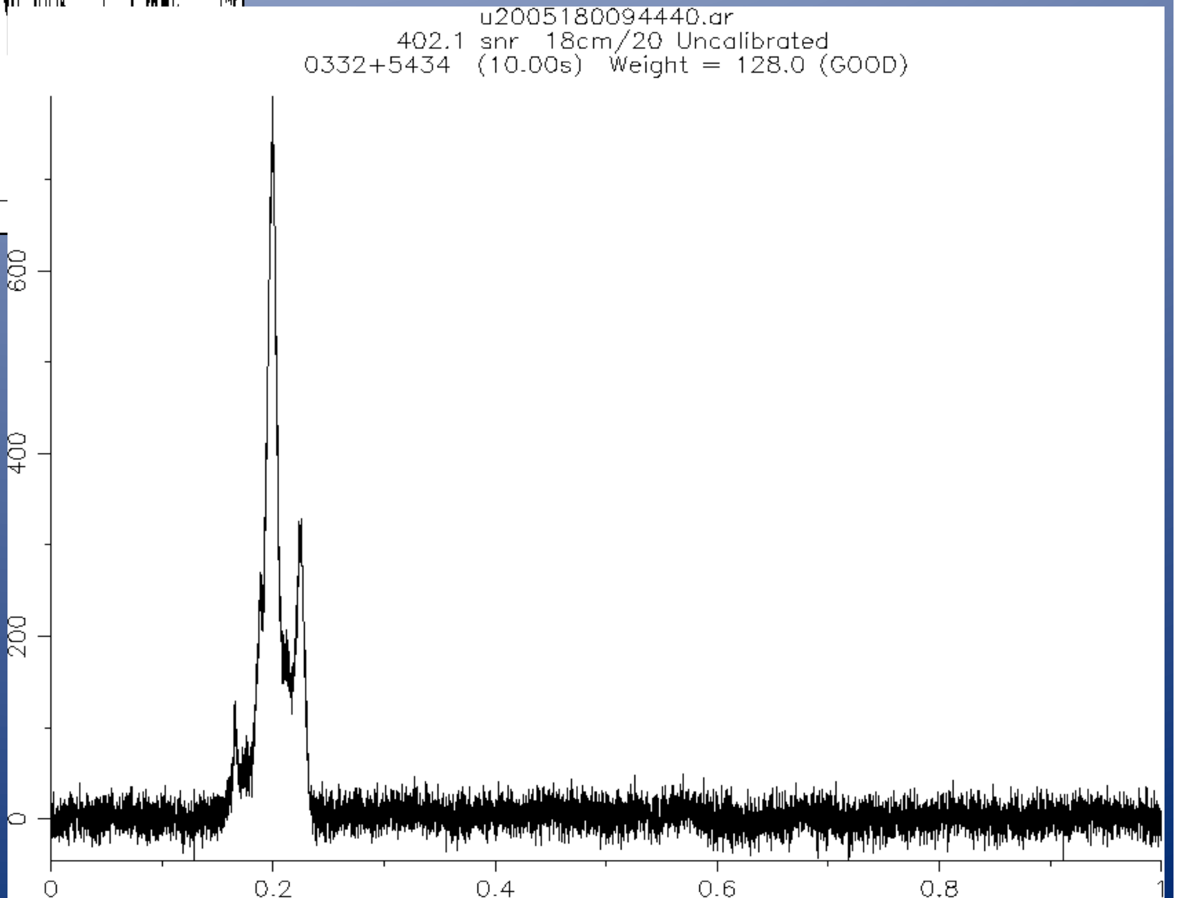




Thresholding of pulsar data before period folding

WSRT PUMA2 data

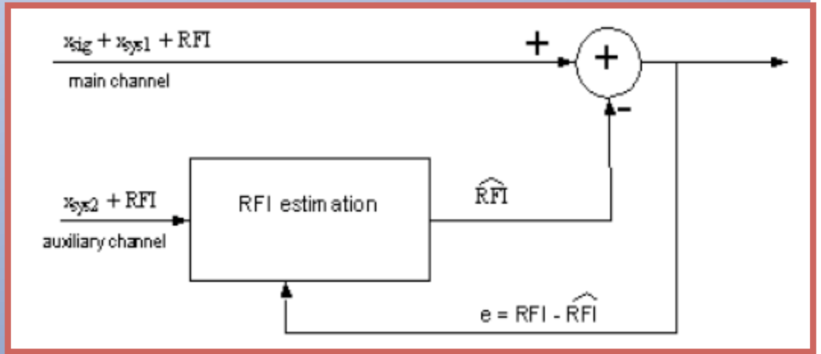
(Fridman & Stappers 2007 and Kesteven for Parkes)

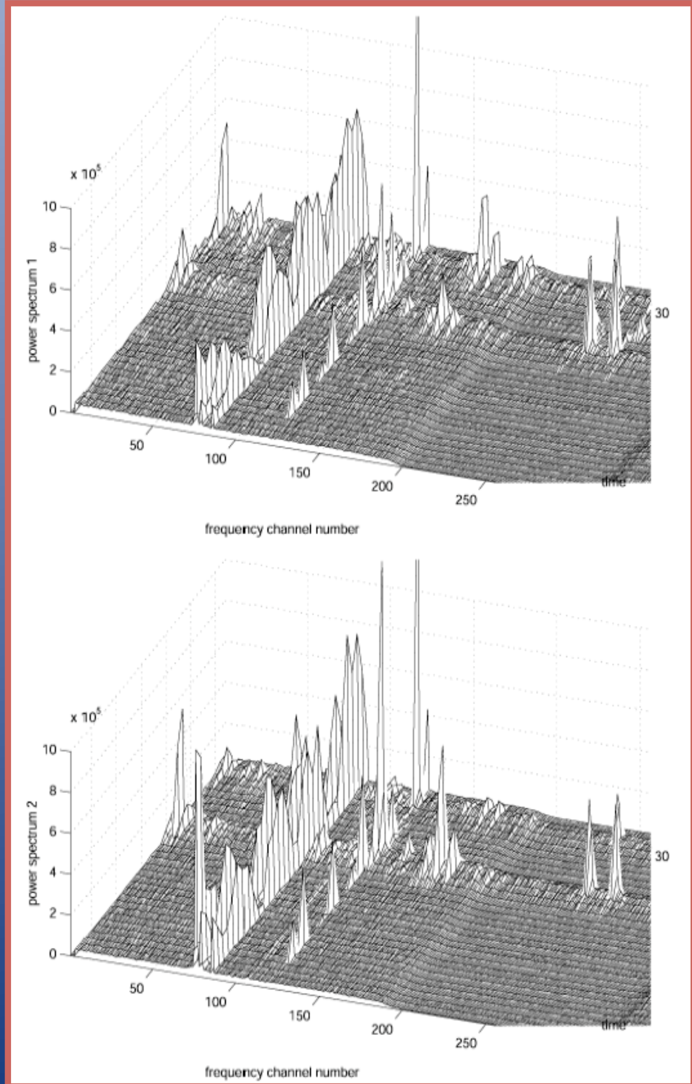


Pre-correlation - ANC

- Adaptive noise cancellation (ANC)
- Adaptive filtering using RFI copy (Haykin 1986)
  - On-source plus RFI signals
  - Off-source plus RFI signals
- Temporal adaptive filtering
  FFT -> adapting in frequency bins
  -> FFT-1 in frequency domain
- Subtract Ref channel & main channel

- Directed reference antenna (Barnbaum & Bradley 1998)
- Subtract RFI power spectrum estimate of RFI from main channel (Briggs et al 2000)
- Effective for multi-feed SD





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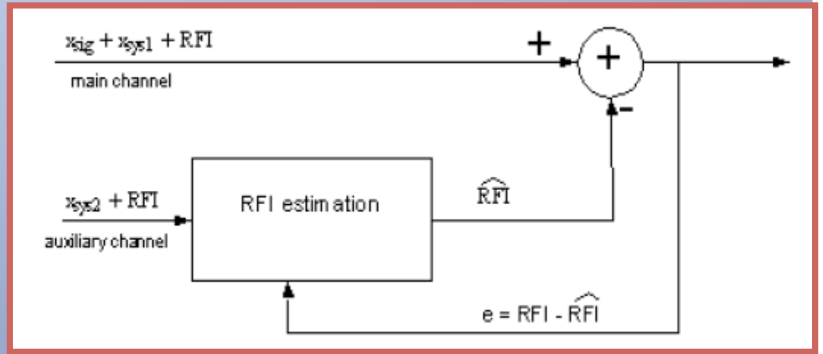
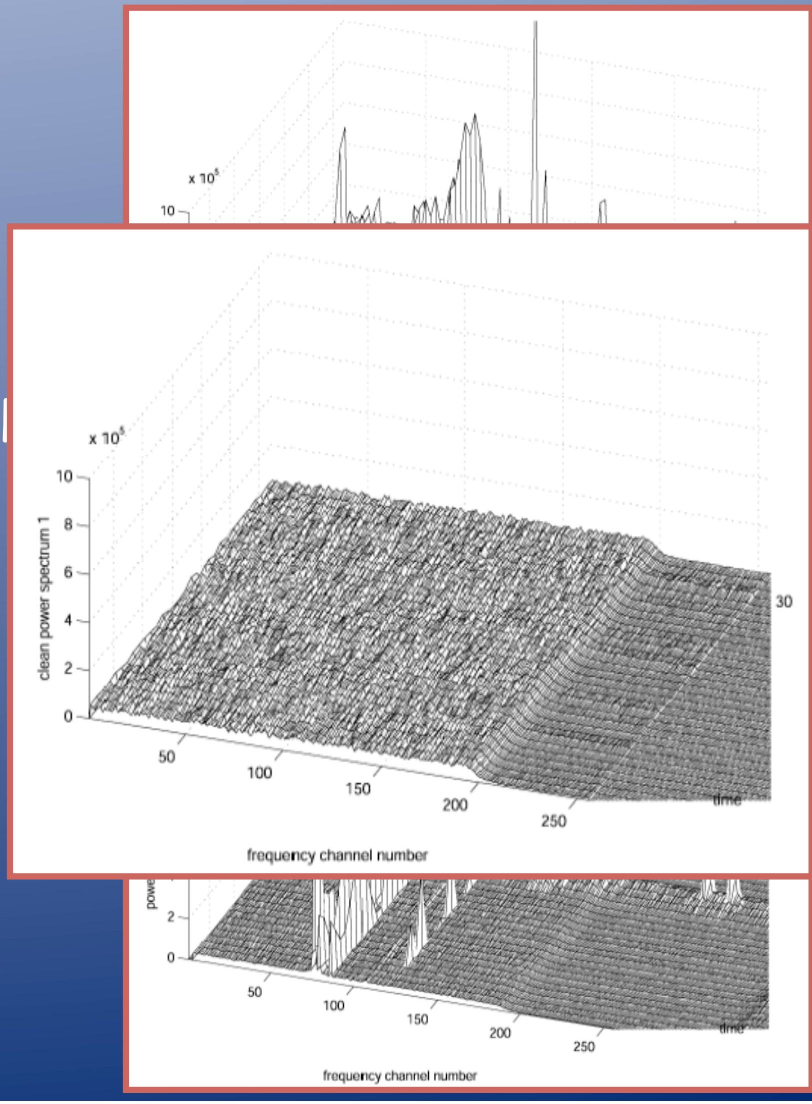




Reference Antennas

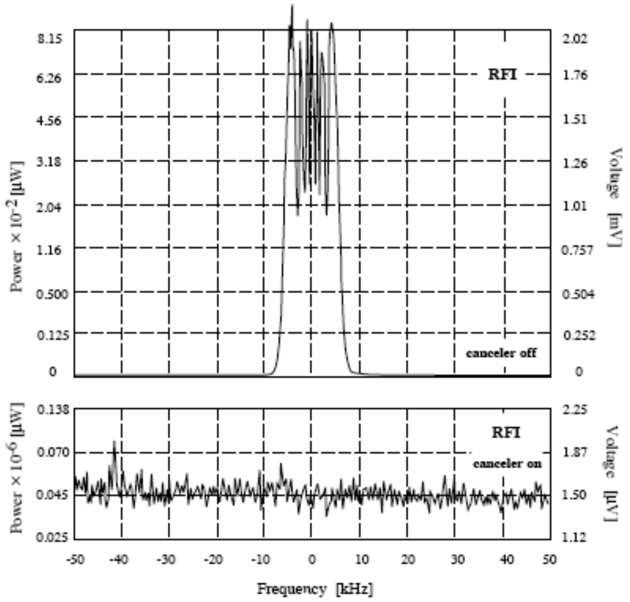
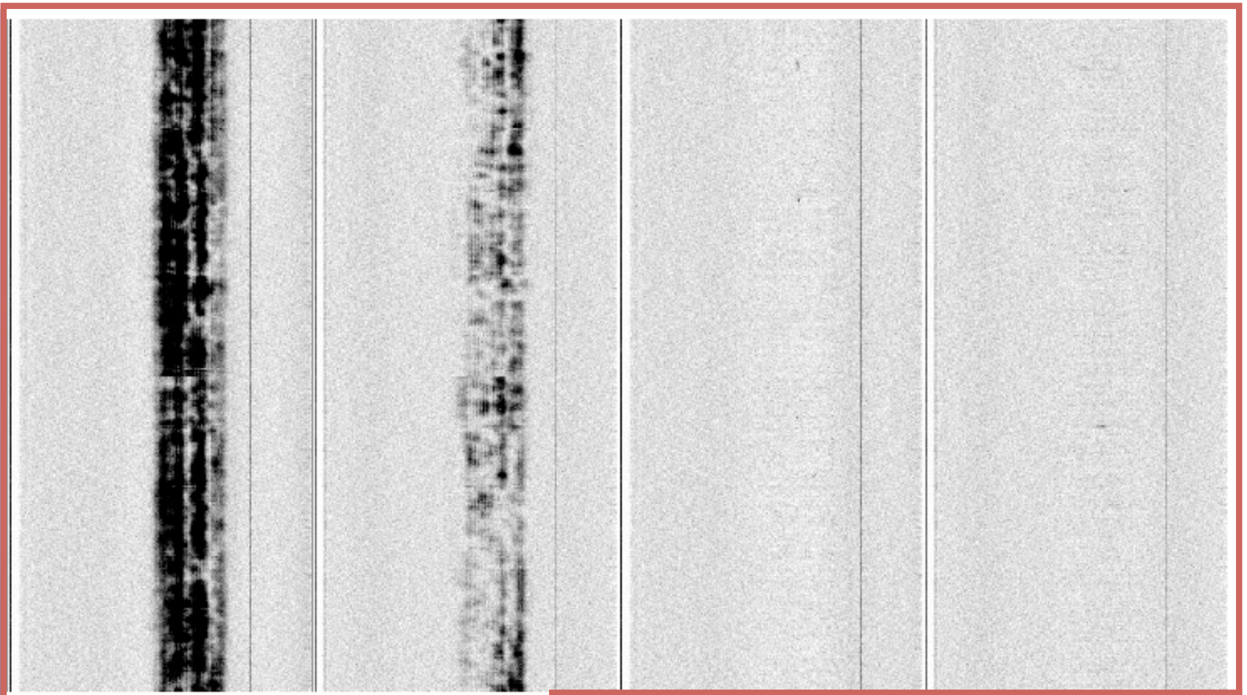
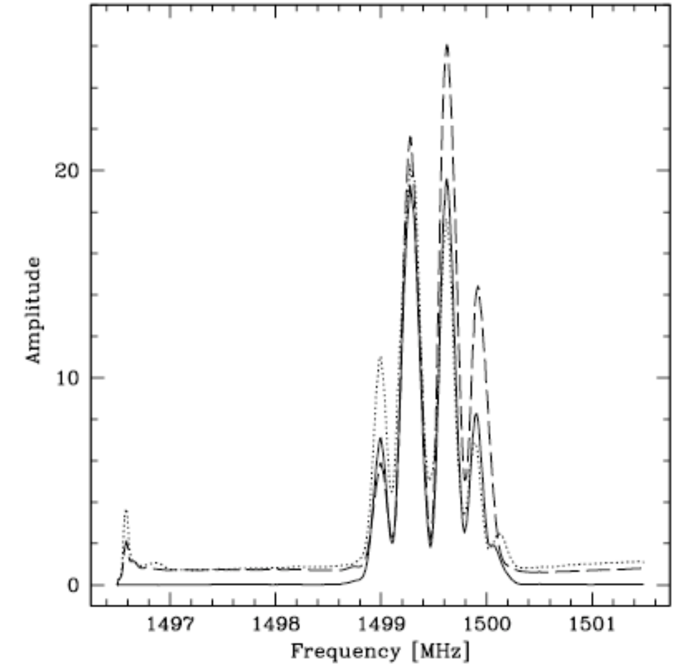


FIG. 8.—High dynamic range test of the adaptive-canceling system under stationary conditions. The data are shown in col. (2) of Table 1. The spectra in this and subsequent figures were recorded in volts. The right axis shows the linear scale in volts, and the left axis is power. Note that the left axis is not linear since power is proportional to the square of the voltage. The top panel shows the RFI at the system output before the adaptive canceler is activated (this spectrum shows a 1 s integration; with a 30 s, the peak of the RFI integrated down to 0.071 μW, which is the value we use in col. [2] of Table 1). The bottom panel shows the spectrum after activating the adaptive canceler and integrating for 30 s.

NRAO 140 ft
Barnbaum & Bradley 1998





Parkes
Briggs, Bell, Kesteven 2000

GLONASS C/A

parametric estimation/ subtraction

using known modulation properties of signal

no additional antennas

cancellation > 20 dB

(Ellingson, Bunton, Bell 2003)

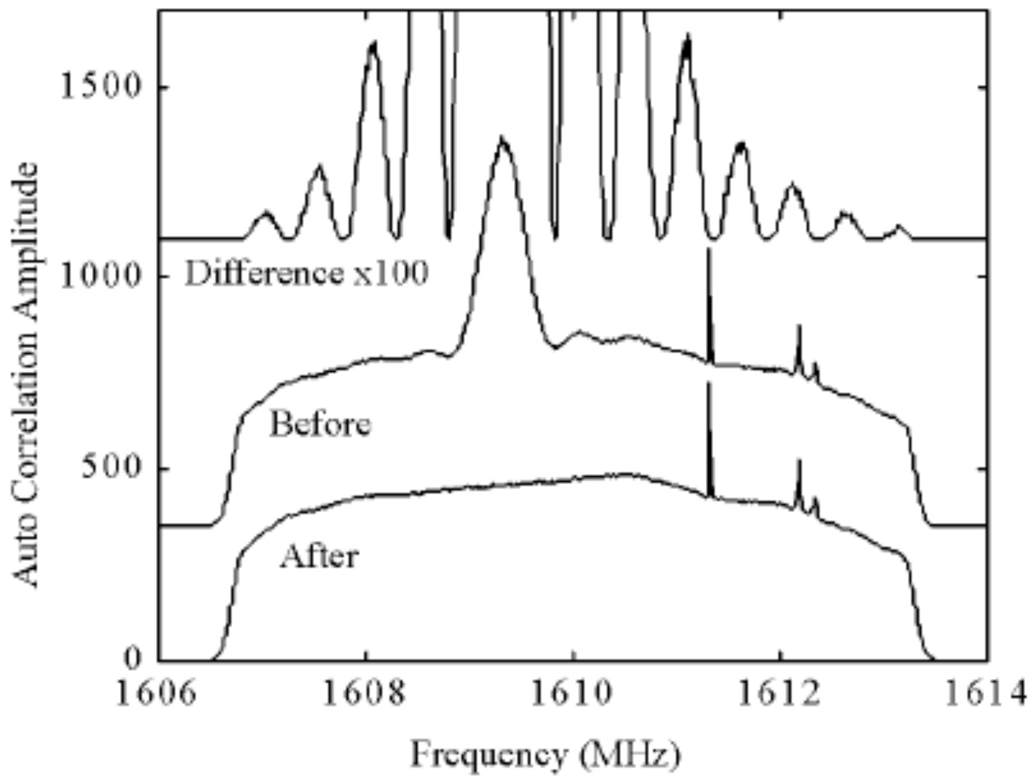
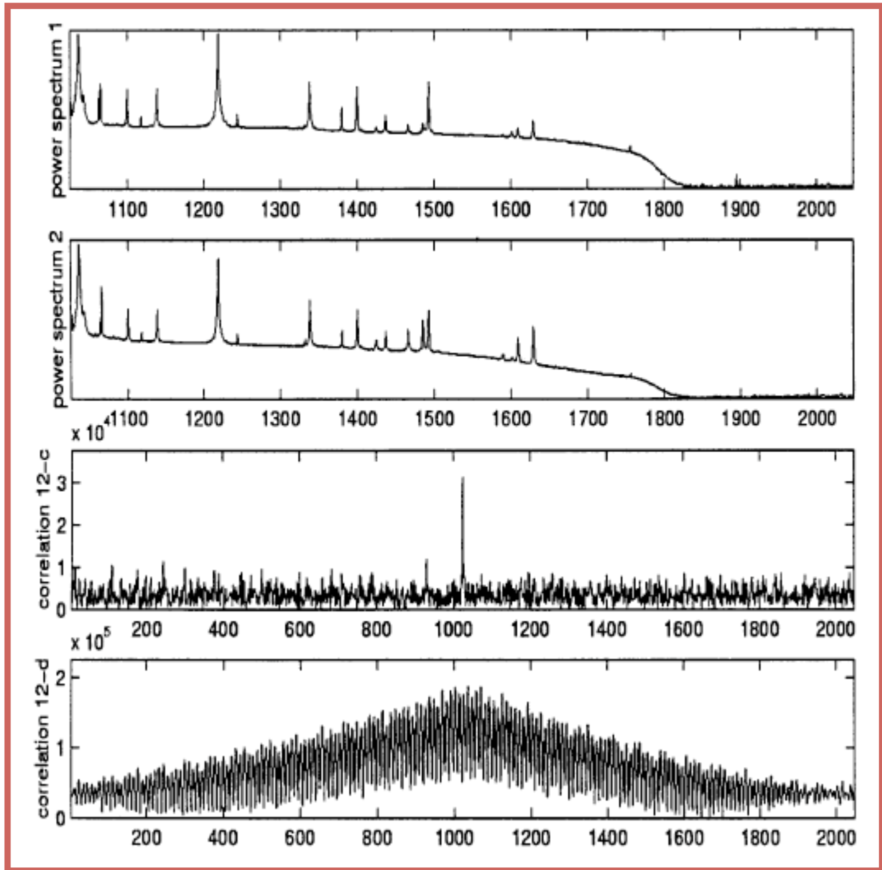


FIG. 2—*Middle curve*: Autocorrelation of raw data, including (*left to right*) *GLONASS*, test tone, and OH maser. *Bottom curve*: Same signal after processing (C/A signal removed). *Top curve*: The cancelled signal (i.e., "before"-"after") multiplied by 100, showing the spectrum of the signal that was cancelled (*curves offset for clarity*).

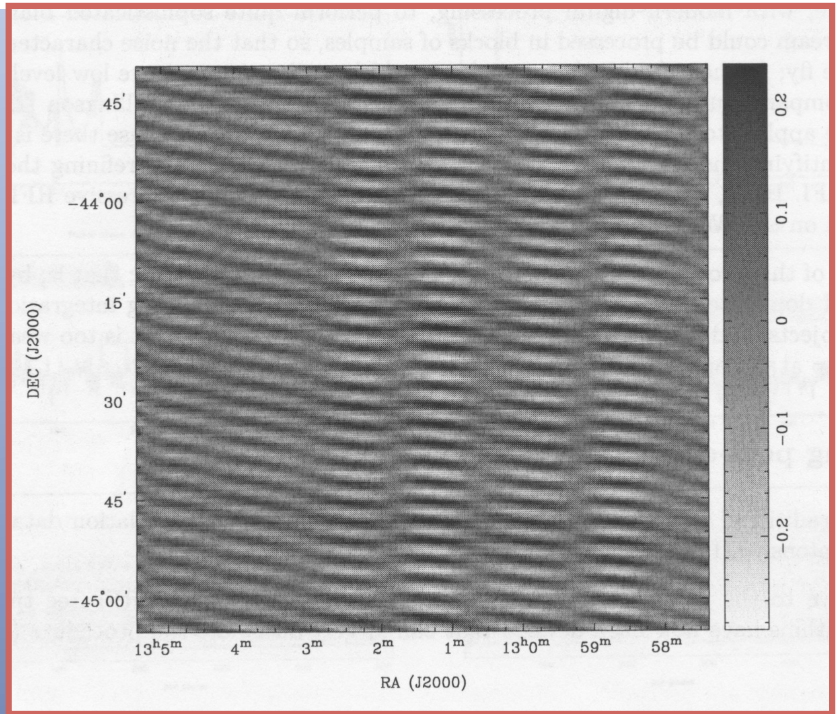
Pre-correlation
Spatial Filtering & ANC nulling

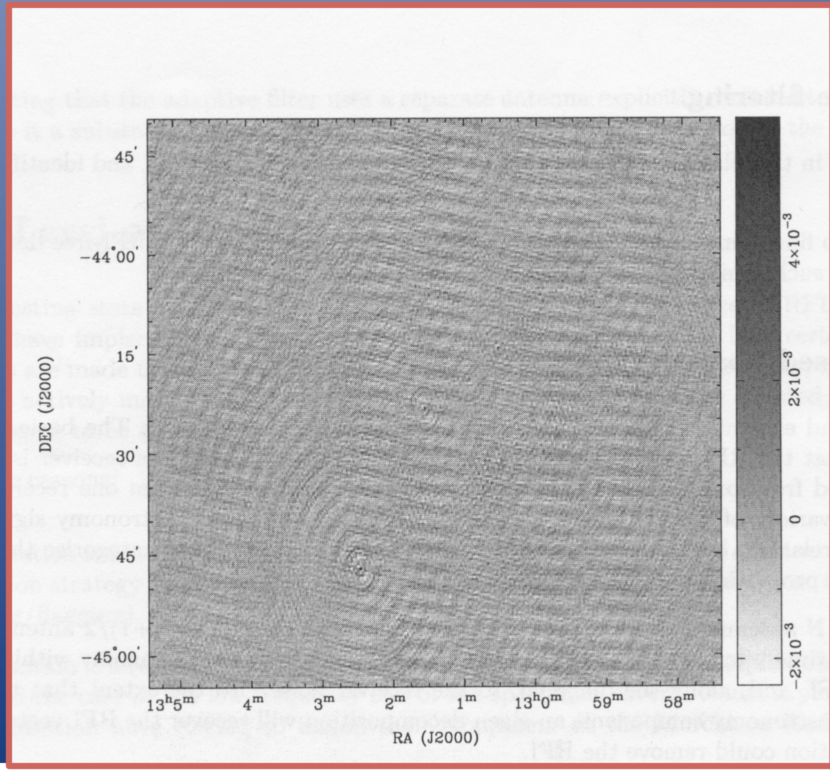
- *Smart antenna* technique in radar and communication system
- multiple sensors (RTs) & view on RFI sources (LOFAR, WLA, etc*)*
- Sparse Arrays => large baselines
  - correlation array & beams synthesized afterwards
  – RFI suppression afterwards using small time intervals & complex weighting during image processing (Leshem 2000)
- Assuming that RFI sources are localized

- Real-time adaptive nulling in phased-arrays for new generation telescopes (van Ardenne et al 2000; Bregman 2000)
- Spatial filtering using outstanding properties of the RFI (Leshem et al. 2000)



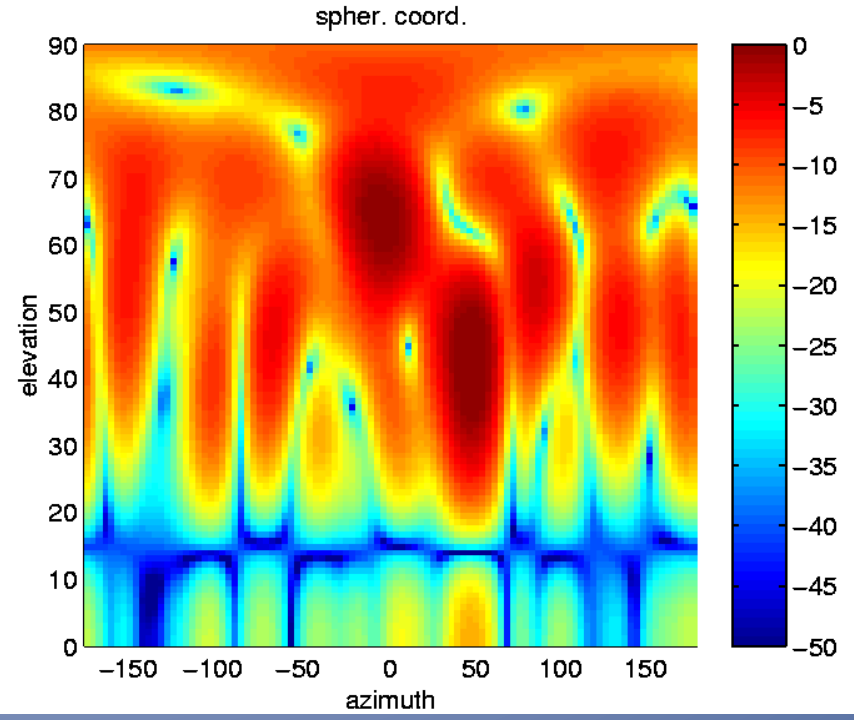
WSRT spatial filtering using
adaptive complex weighting
(Fridman & Baan 2001)





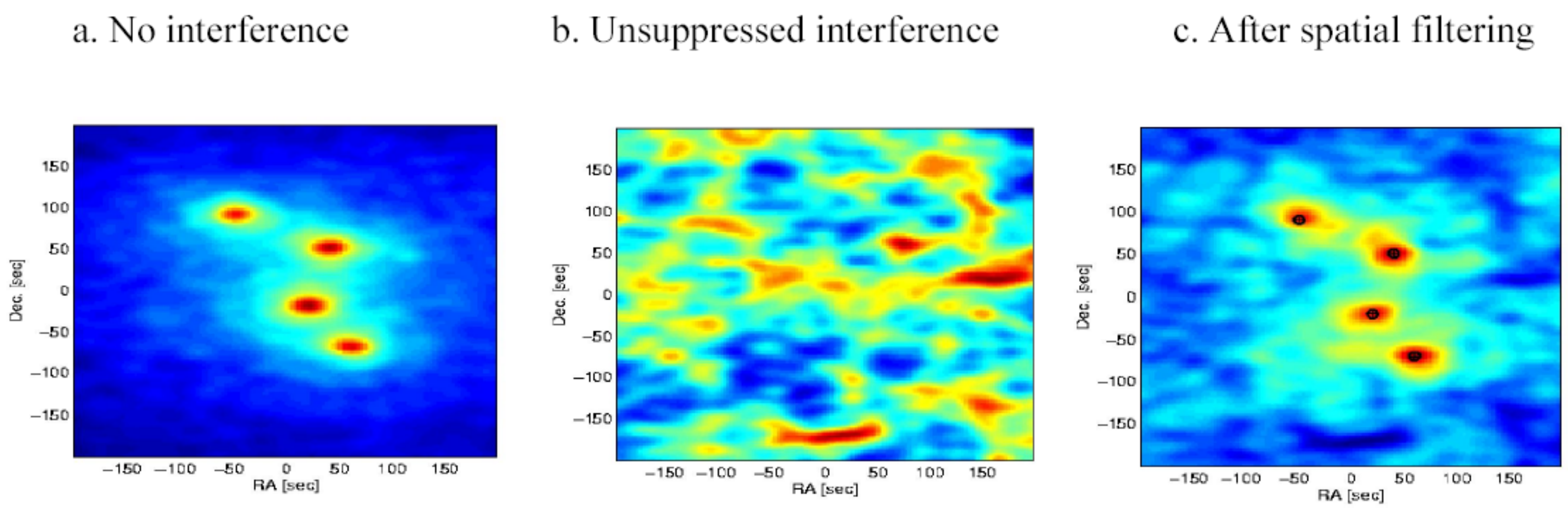
Adaptive filtering &
null-steering
(Kesteven 2009)

100 LOFAR stations
two beams and null at 15 deg
(Boonstra & van der Tol 2005)



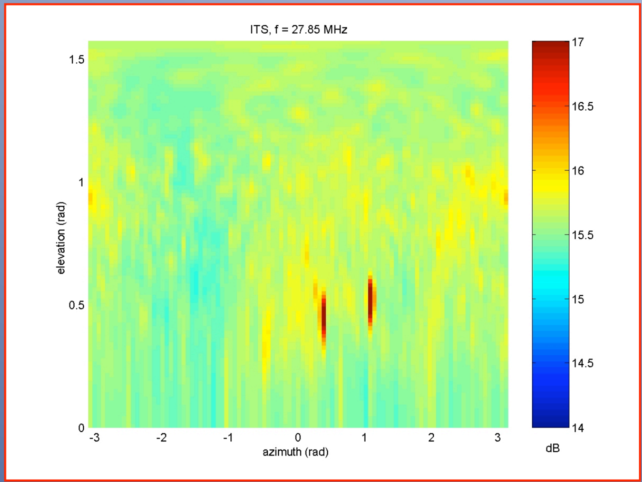
Spatial Filtering

Computer simulation of post-correlation spatial filtering, adapted clean with RFI beam distortion removal
(Leshem & van der Veen 2000)

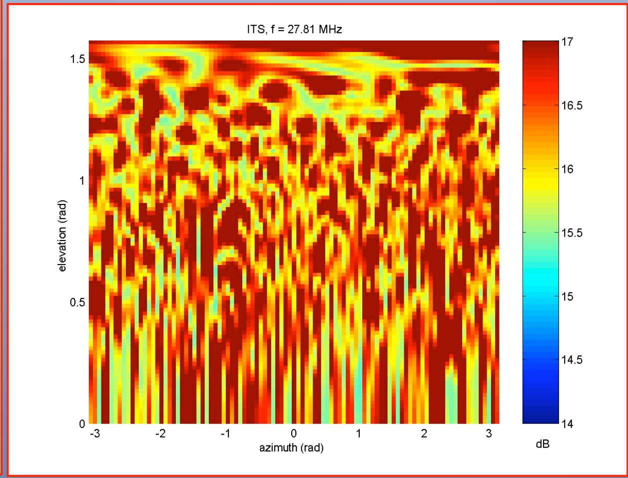


LOFAR ITS spatial filter experiment

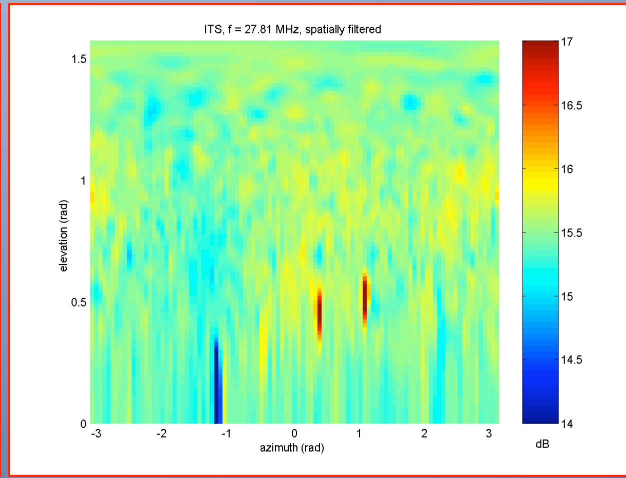
ITS observation, 26 Feb. 2004, 60 antennas, df=10 kHz,
6.75 s integration, A.J. Boonstra, March 15, 2004.



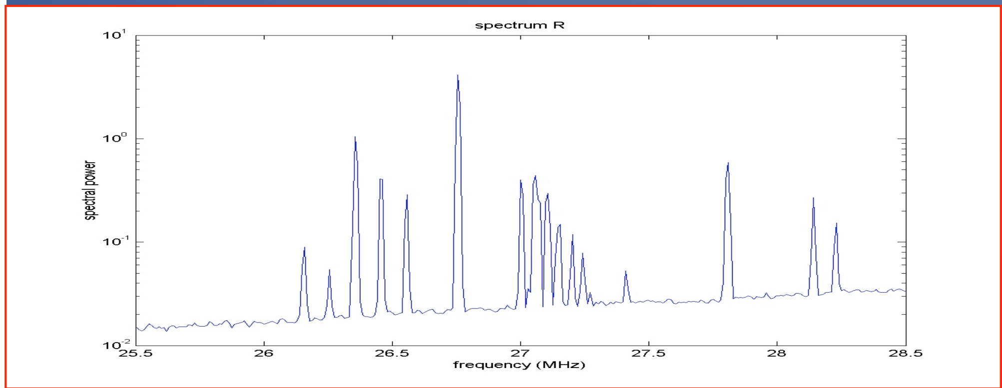
ITS sky map 27.85 MHz,
no RFI
Cas-A, Cyg-A visible



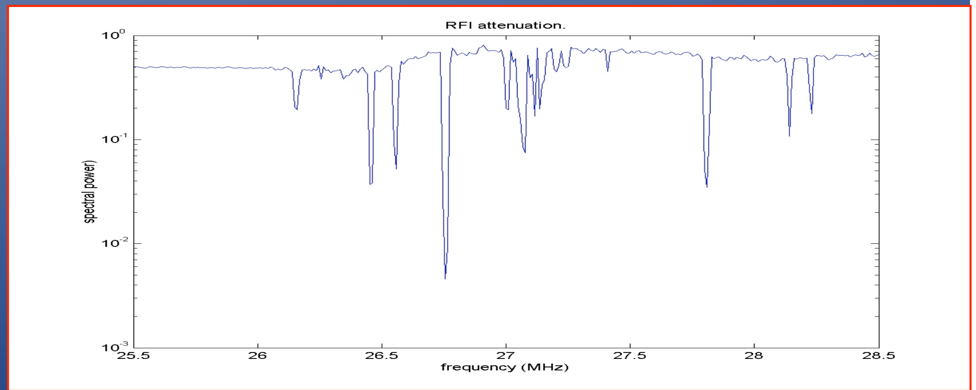
ITS map 27.81 MHz,
strong RFI at (Az,el) =
(-1.3,0) rad



ITS map 27.81 MHz,
fixed null at
(Az,el) = (-1.3,0) rad



ITS observation, spectrum



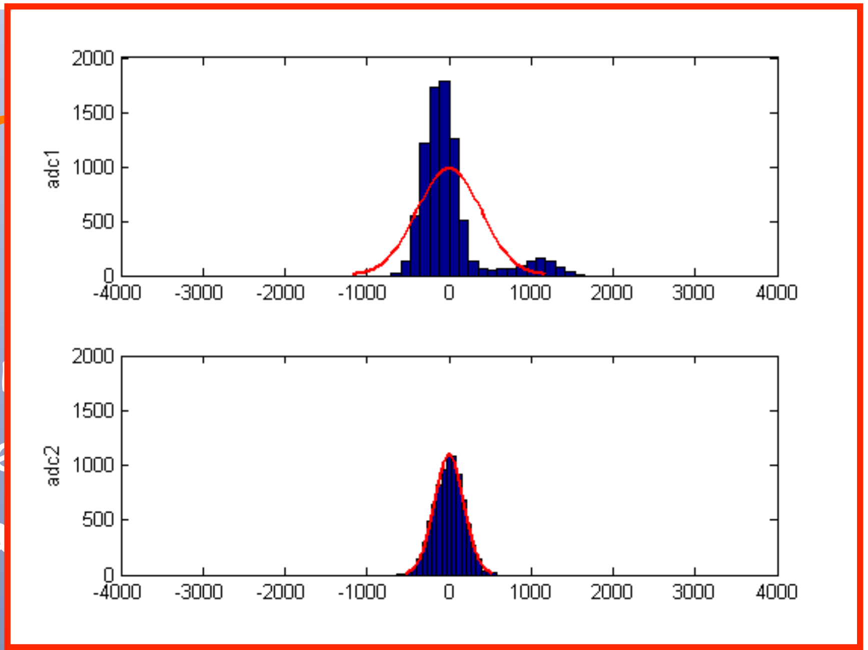
ITS obtained RFI attenuation numbers

Pre-correlation & Antenna-based

- *digital processing at IF* (single RT & ARTs)
- Real-time thresholding in temporal and frequency domains
  - Spectral occupancy RFI should be low
- 'Sub-space' filtering => use RFI signature in data
  - cyclostationarity (Nancay; Weber et al)
- Excision of RFI based on probability distribution analysis
  - RFI changes power spectrum to a non-central power distribution (Fridman 2001; Fridman & Baan 2001)

- Data loss => affects gain calibration => accurate bookkeeping
- Ratan 600 (Fridman & Berlin 1996) – many more examples
- SD solar observations (NJIT group)
- WSRT RFI Mitigation System (Baan, Fridman, Millenaar 2004)

Pre-correlation & Ar



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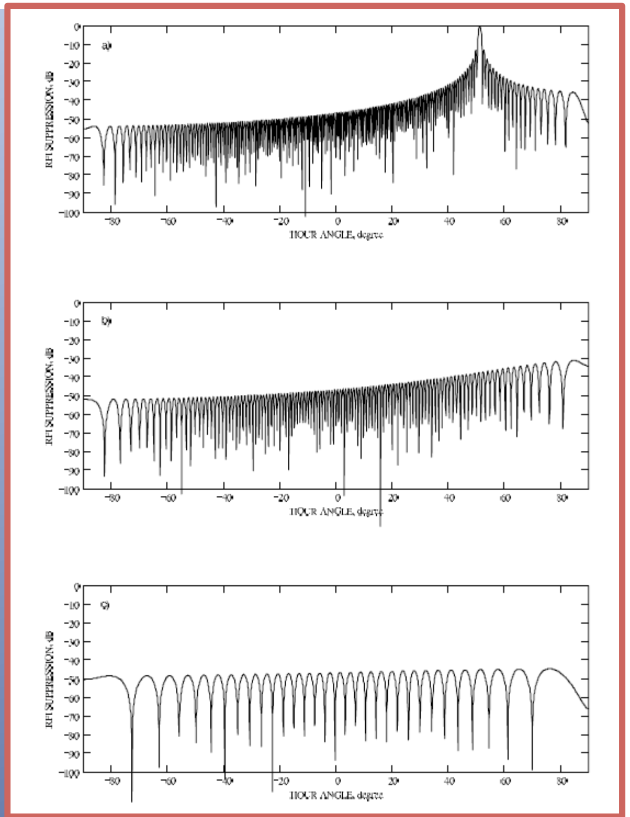
At Correlation

- Real-time post-correlation processing
  - time-frequency analysis before averaging
  - special hardware as part of existing/new backends
  - related to *baseband pre-correlation processing* (before or during data stacking)
- Arrays - anti-coincidence using widely separated RTs & digital processing & reference antenna as part of the array

- Applications integrated into new generation SW correlators (Swinburne)

Post Correlation

- SD – *flagging* & excising => data loss
- SD - using reference spectra
- Array – fringe tracking => spatial filtering
- Array – *flagging* => data loss & time consuming (automation)
- Array - Eliminate 'stationary' RFI sources
  - UVRFI based on RfiX code for GMRT Ramana Athreya (2009)
  - Fringe stopping => stationary (terrestrial) RFI sources fringe faster than astronomical sources, i.e at fringe stopping rate
  - No data loss
- Removal in image-plane using distinct motion of RFI (LOFAR - Wijnholds et al. 2004; VLA - Cornwell et al 2004)



Thompson 1982
Baan et al 2004

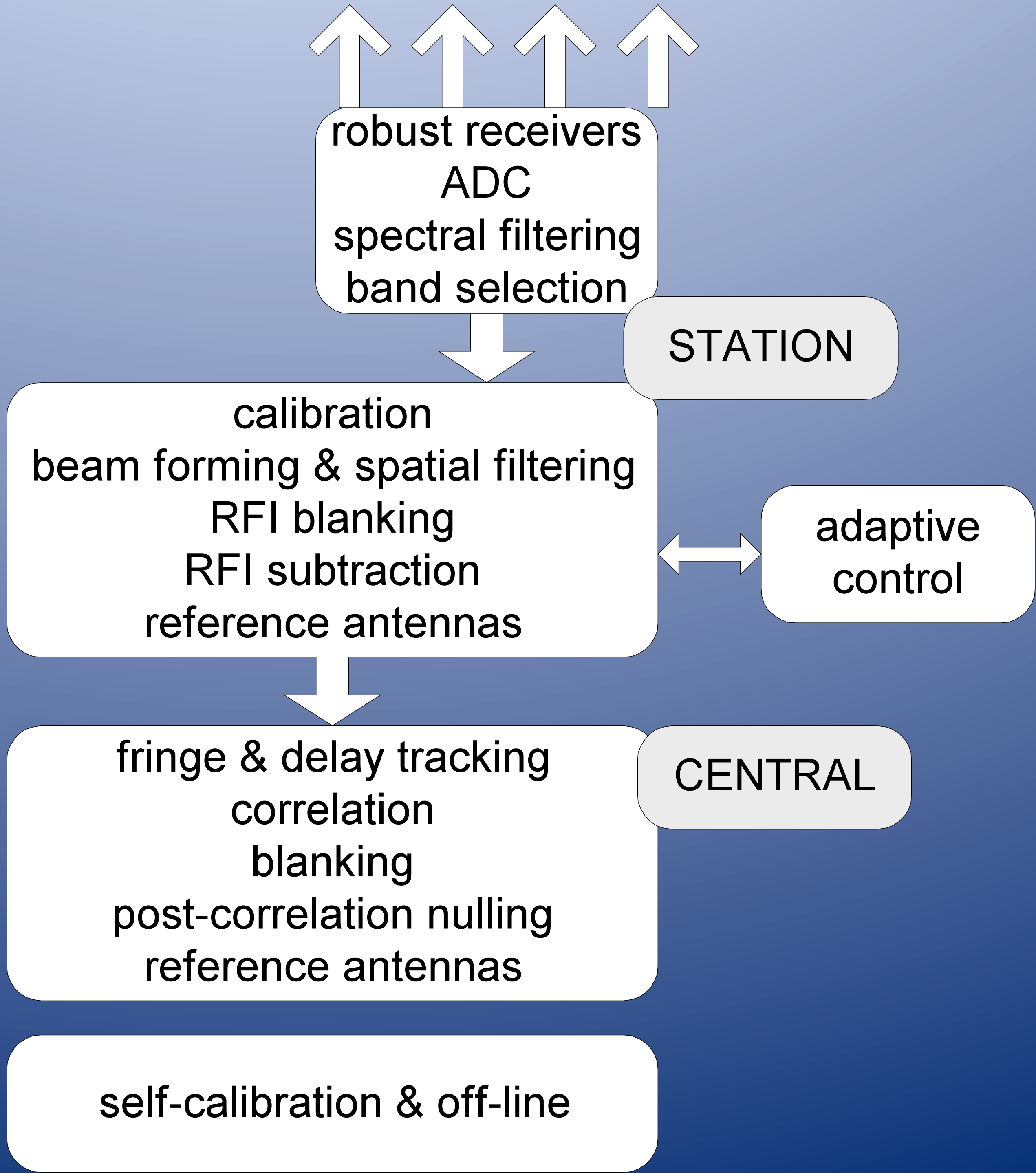
Implementation at Telescopes

- Increased processing capability => filtering (excising) with high temporal (μsec) and frequency (< 1kHz) resolution
- Reference antennas (one per RFI source) require integration
- Requires modifications of current spectrometers
- Future spectrometers need to determine higher moments

- Interferometers less vulnerable
- Auxiliary antennas require system (correlator) integration
- Fringe-stopping and decorrelation by delay-compensation give natural suppression of weak RFI
- Strong RFI adds to system noise and affect complex visibilities
- Accurate bookkeeping of weights for later CLEAN and Self Calibration during mapping stages

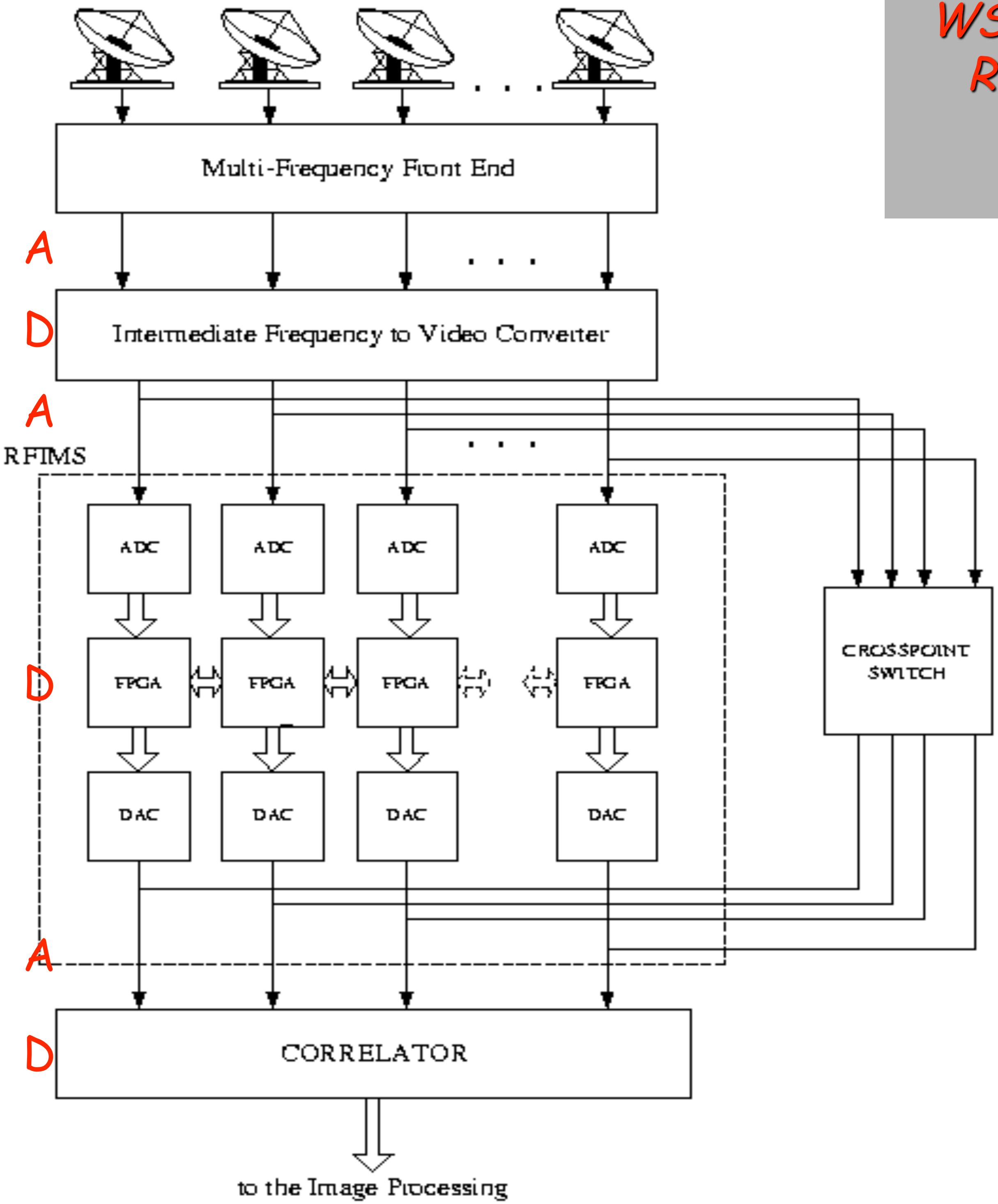
- VLBI - RFI affects calibration data at each site
- VLBI – need RFI mitigation for SD station telescopes

RFI mitigation strategies




Westerbork Synthesis
Radio Telescope

WSRT RFI Mitigation System Real-time pre-detection and pre-correlation baseband processing

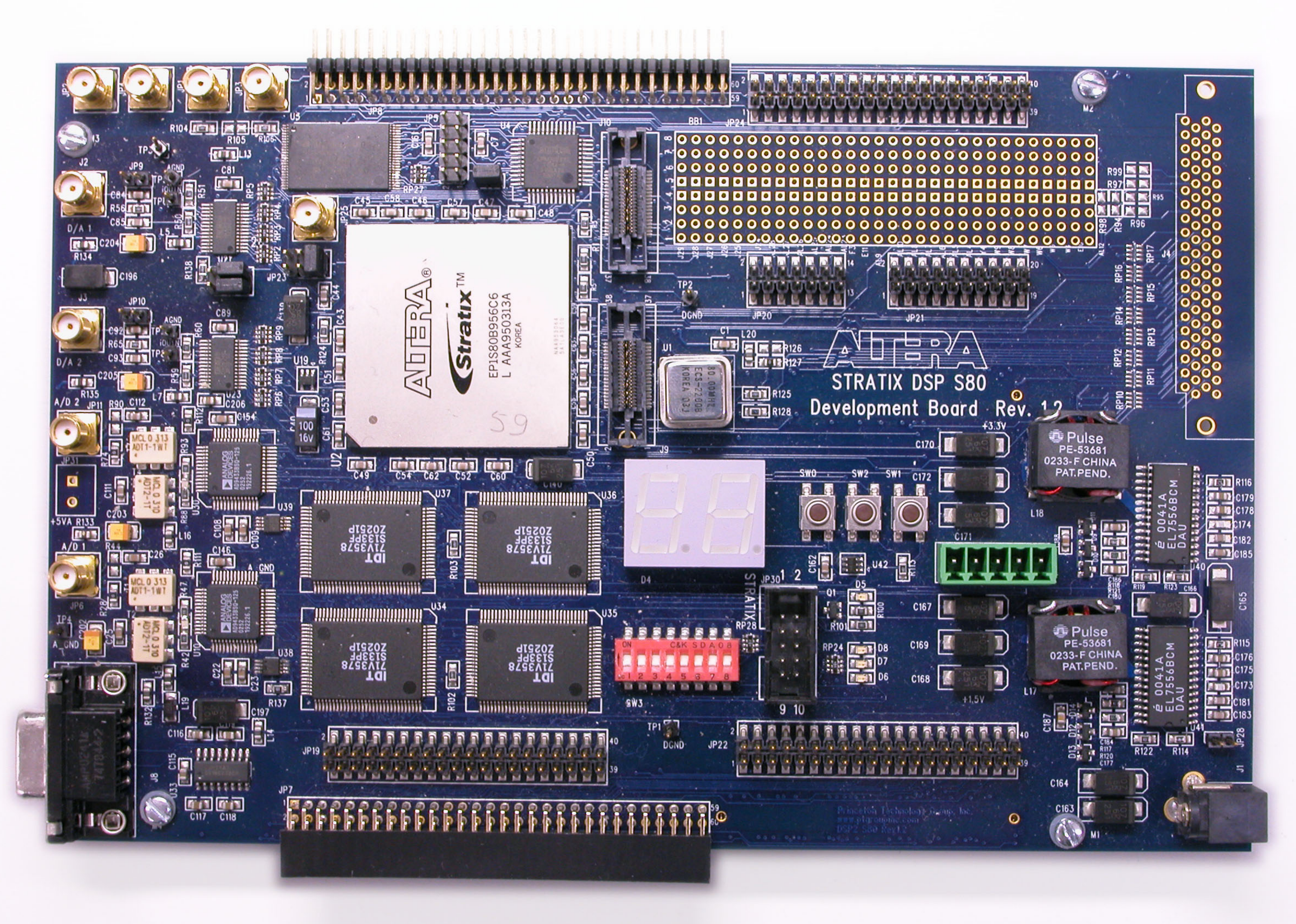


a) 12bit ADC
b) Altera Stratix FPGA
c) 14bit DAC
d) VME control
e) 40Msamples/sec

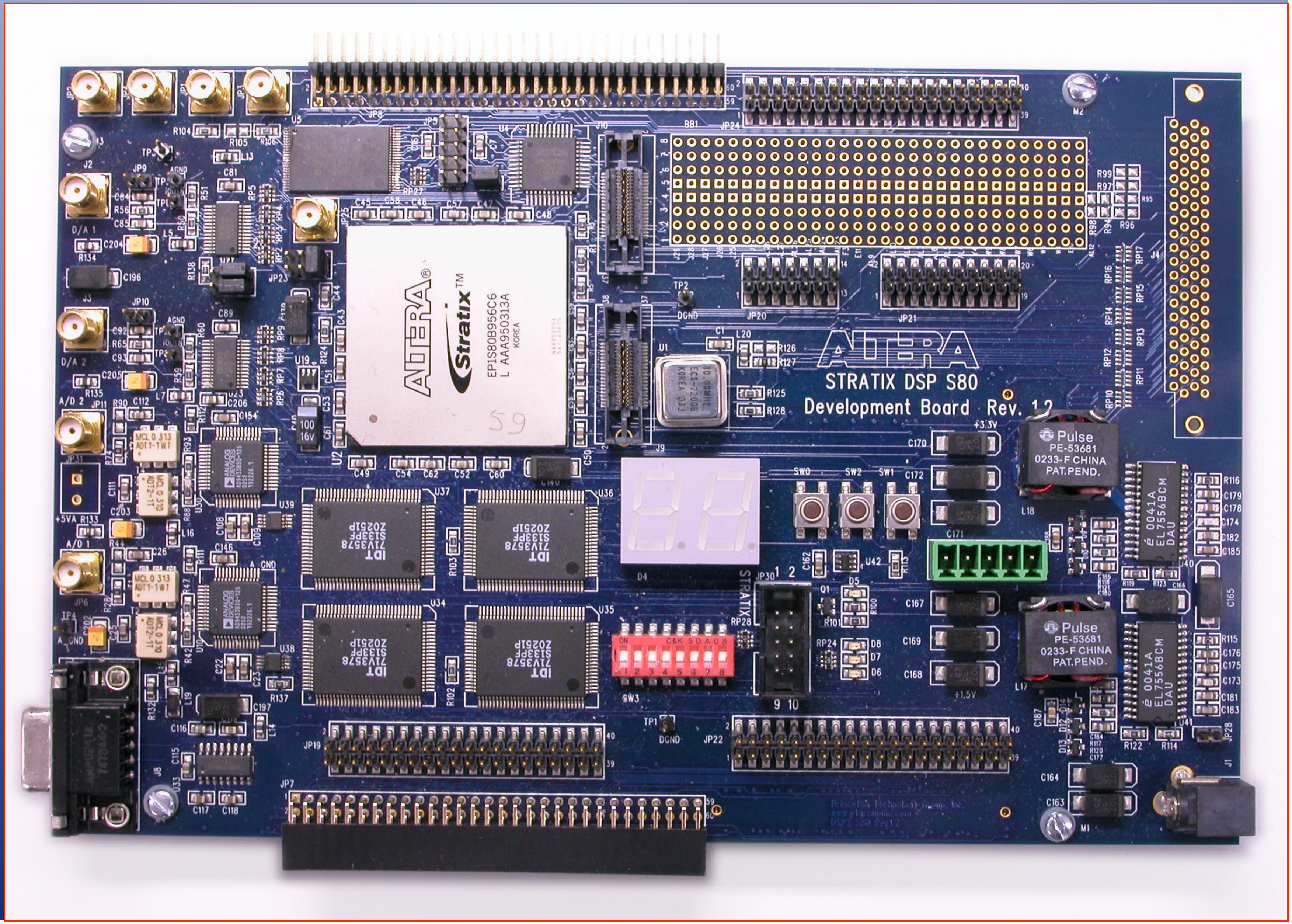
14 RTs & 2 pol
& band 20 MHz

several
A > D > A conversions

RFIMS


ALTERA
STRATIX DSP S80
Development Board Rev. 1.2
Stratix
EP1S80B956C6

RFIMS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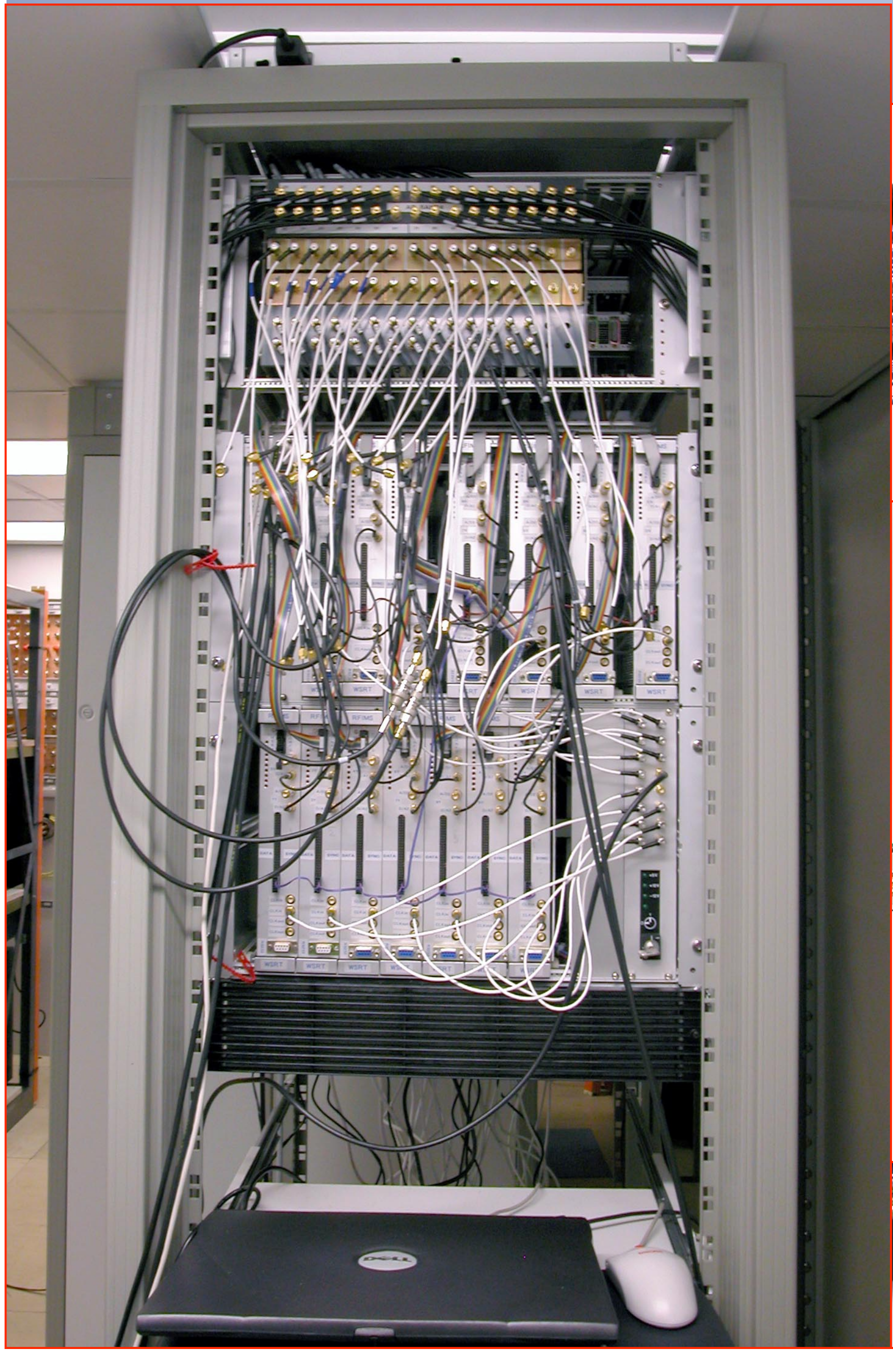
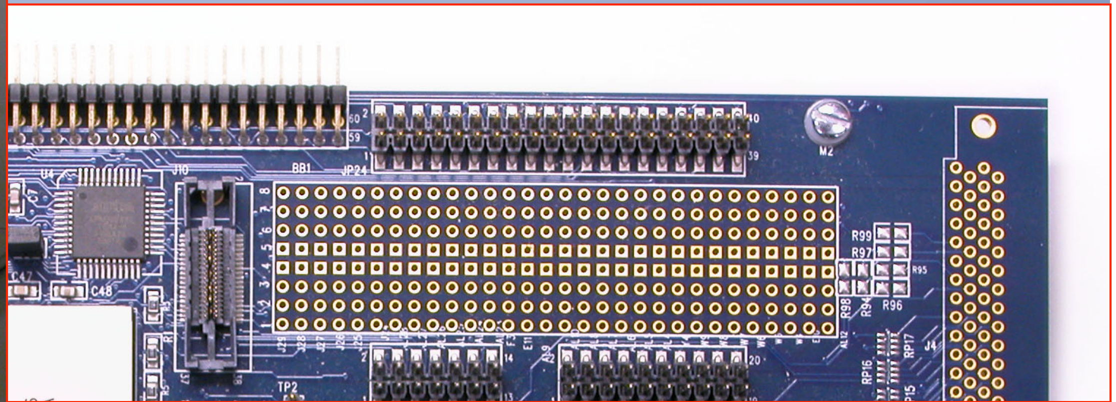
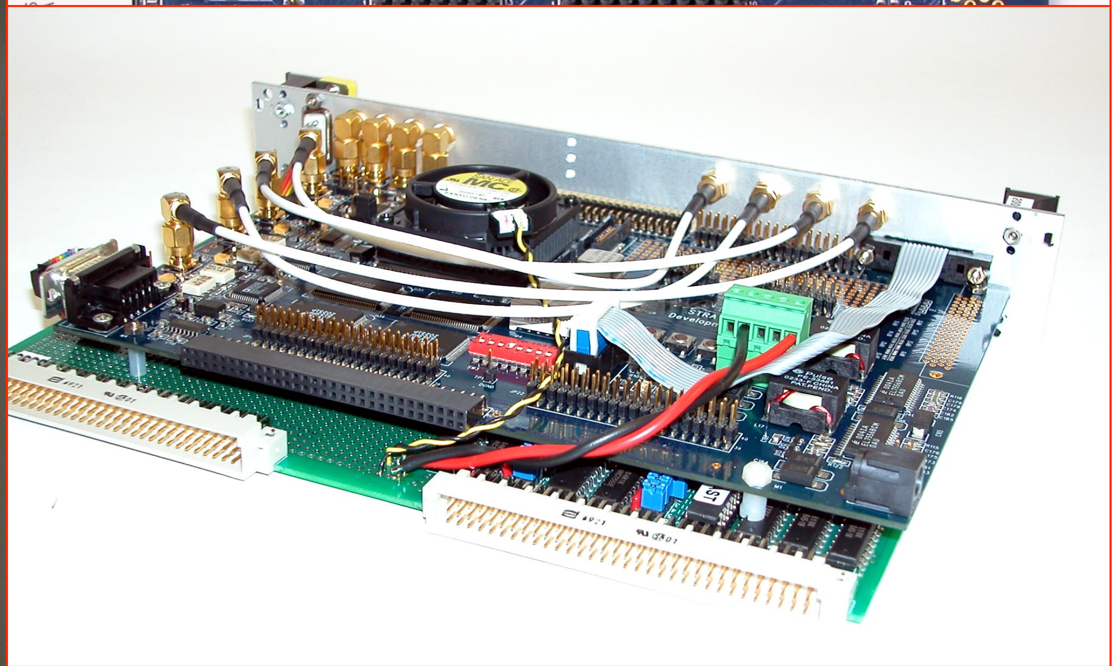
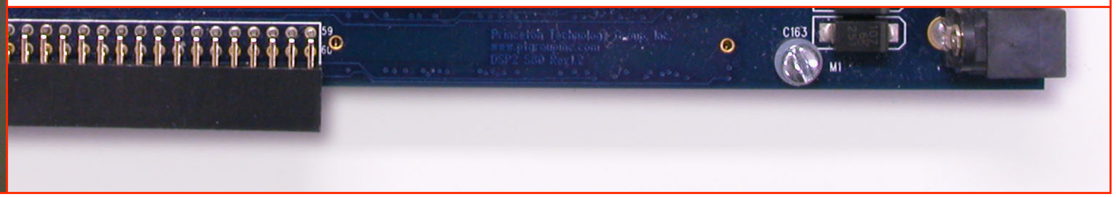
RFIMS





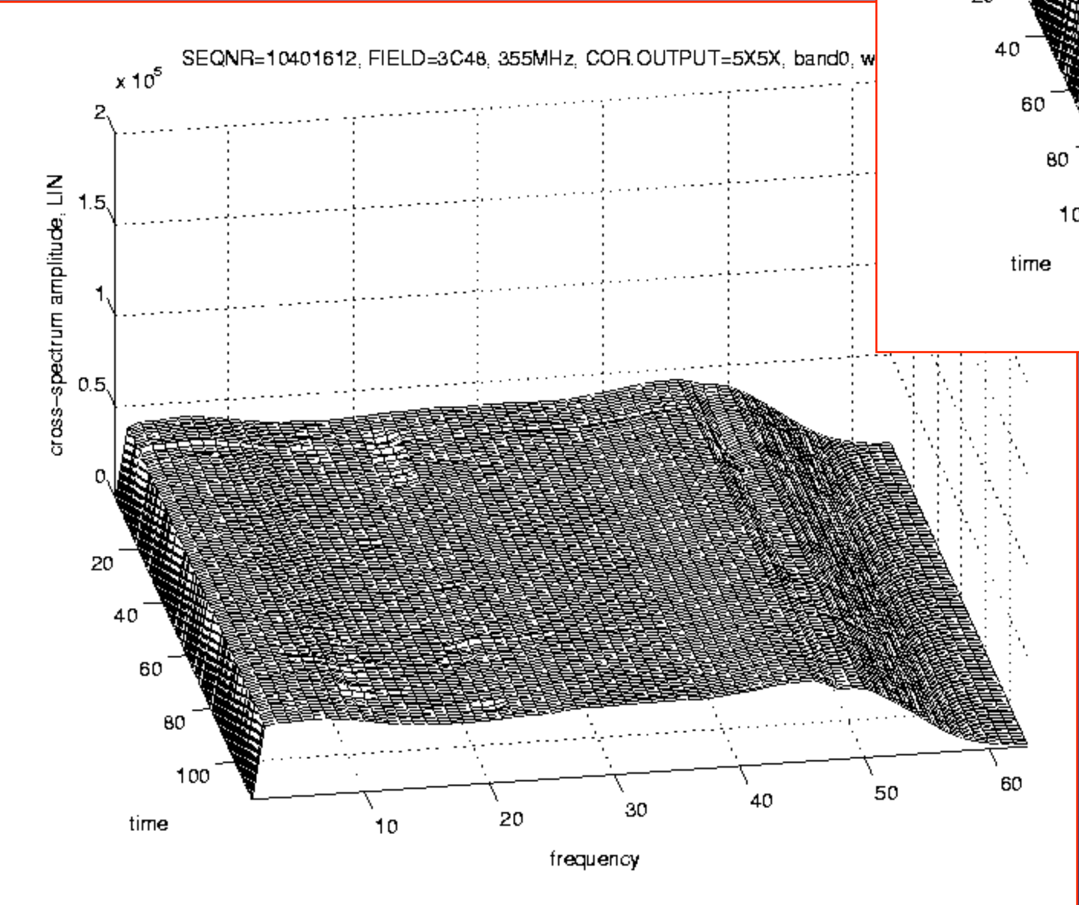


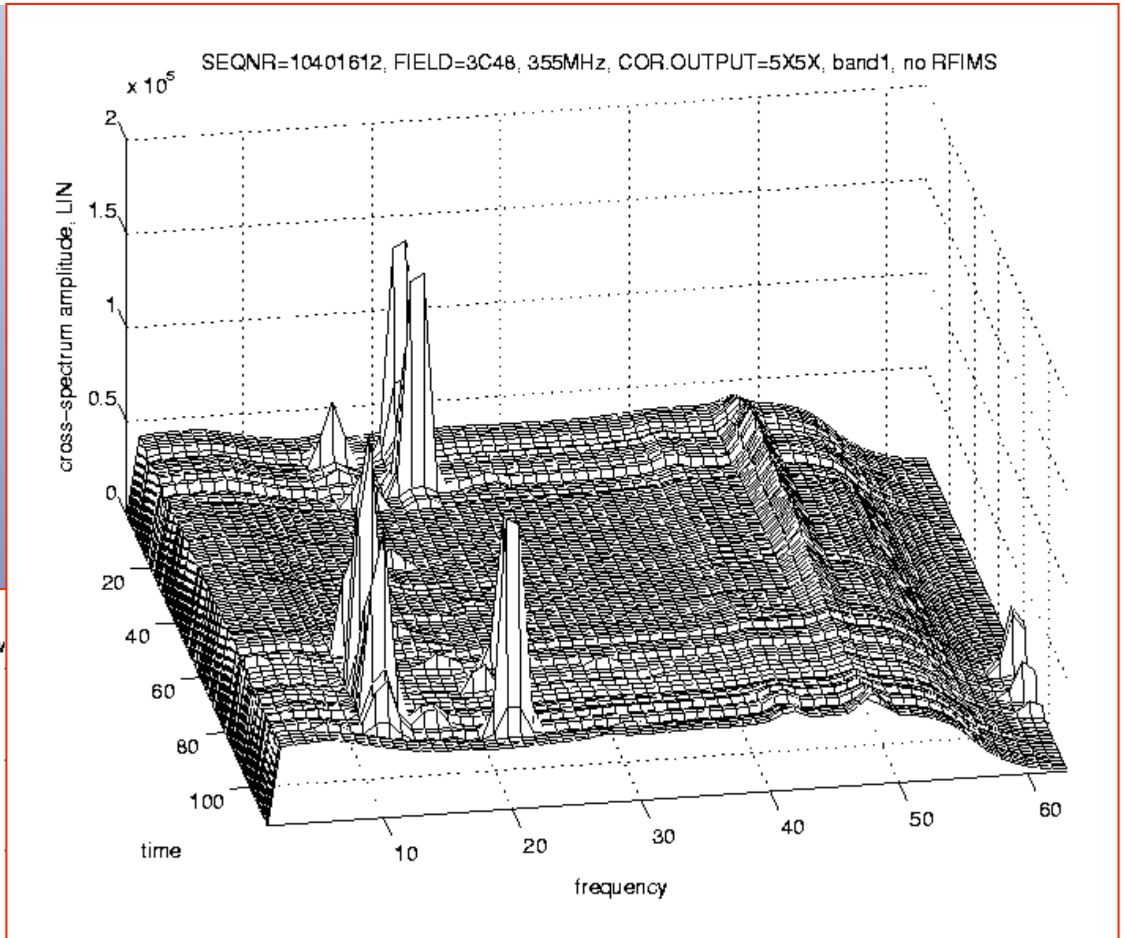


Auto Corr Amplitude

5X5X b0 & b1

rejection in temporal domain
strong & short bursts
rejection in frequency domain

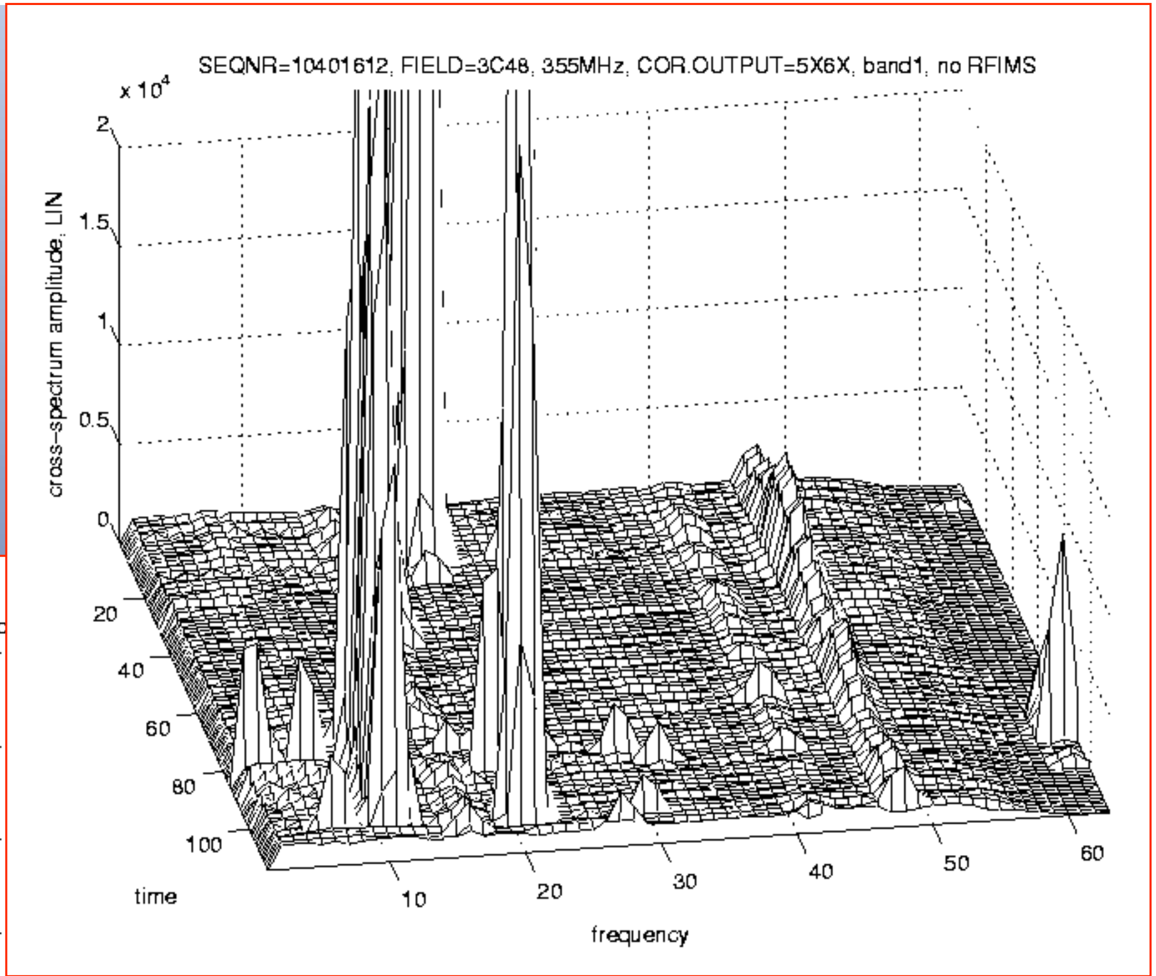


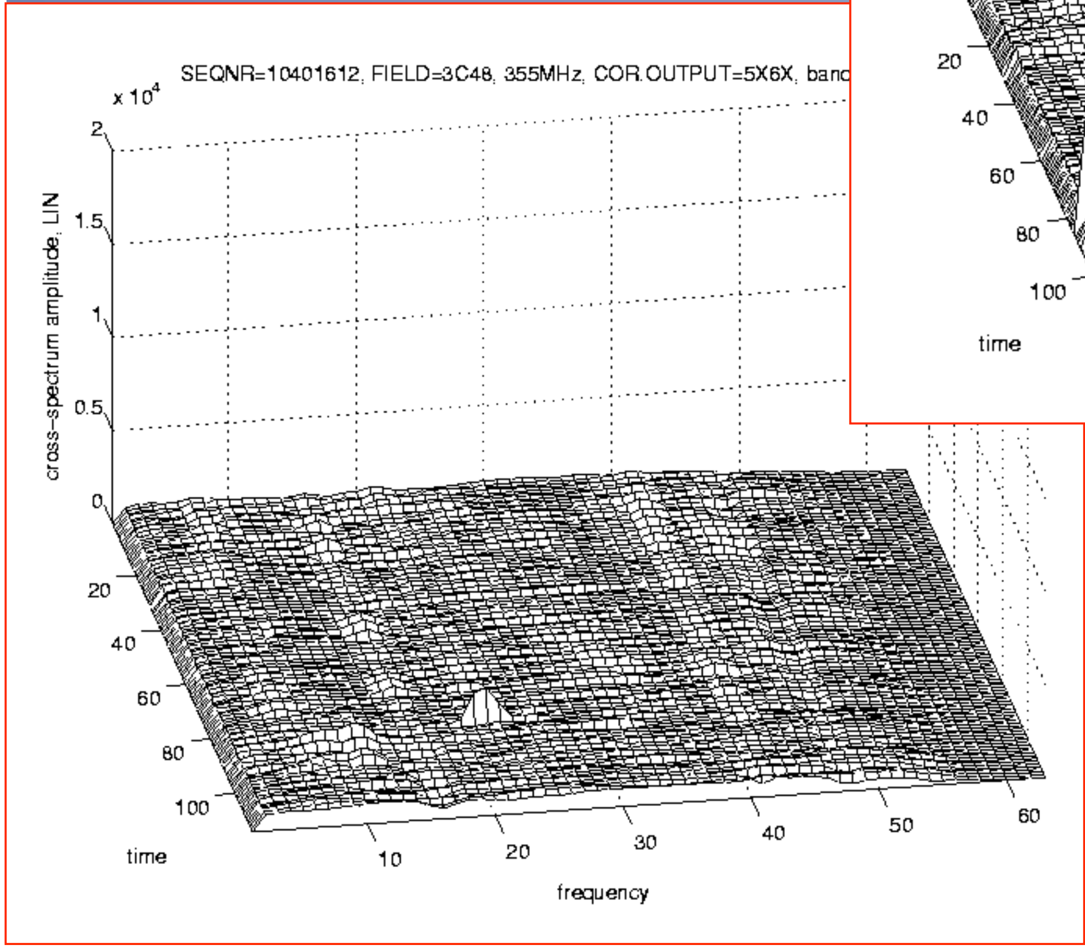


Cross Corr Amplitude

5X6X b0 & b1

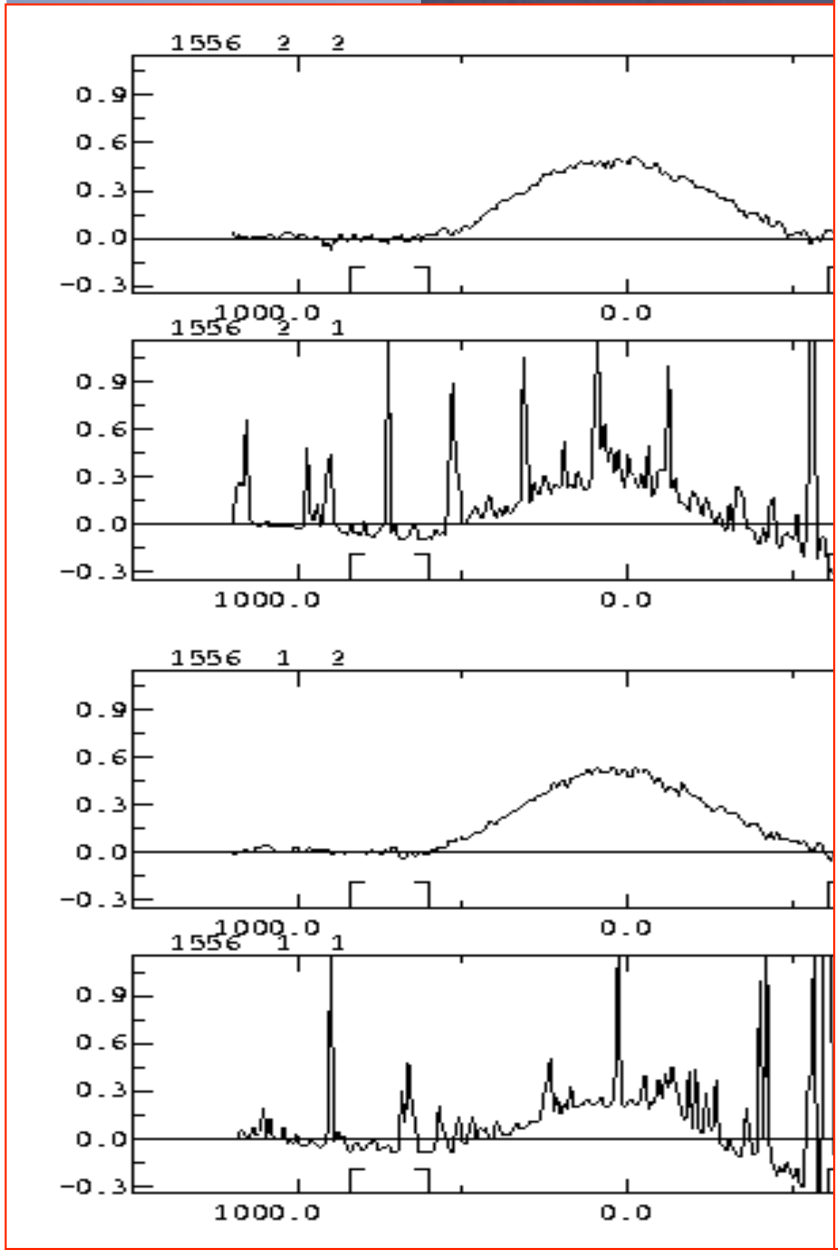
rejection in temporal domain
rejection in frequency domain

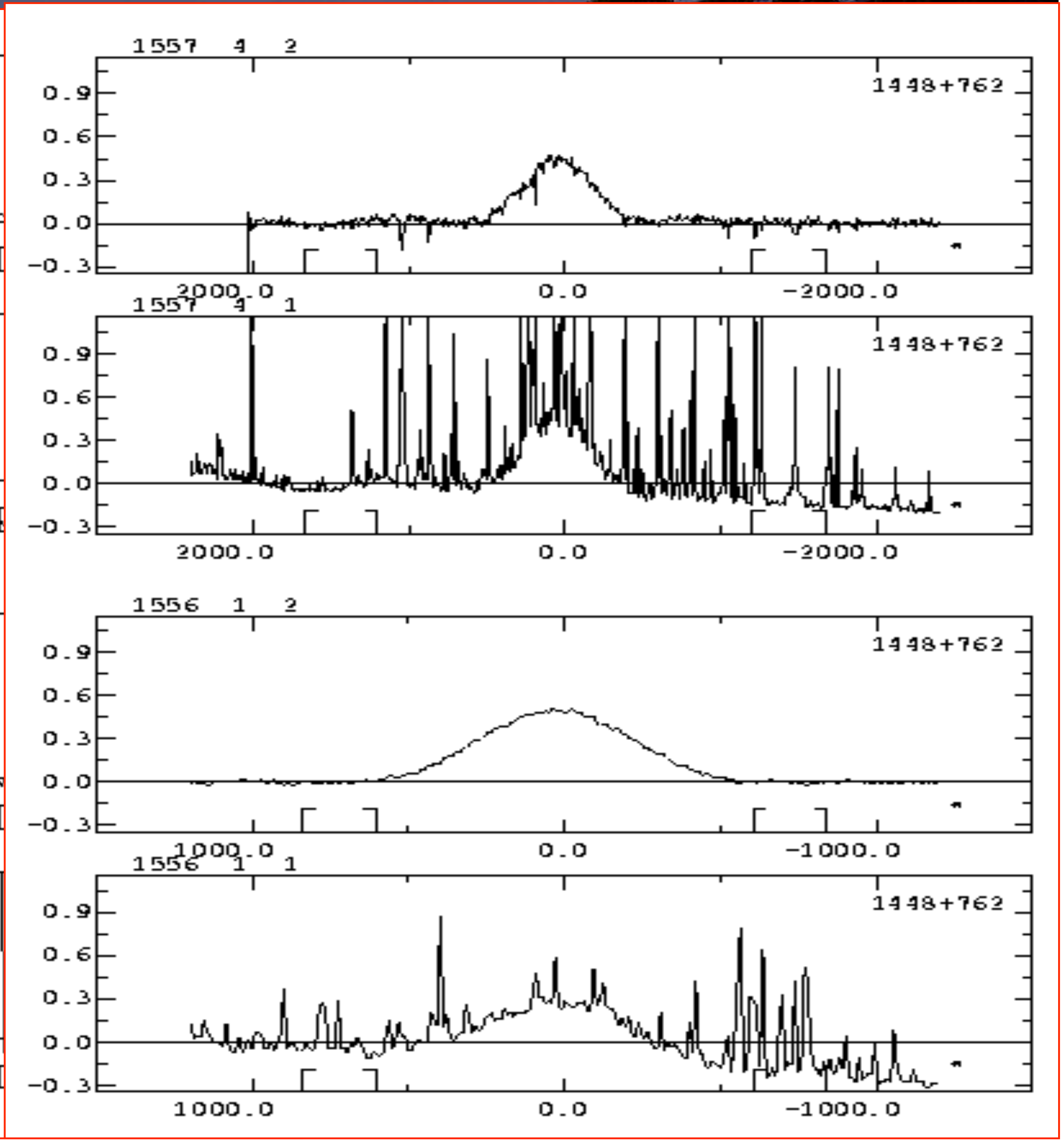




Results Effelsberg 100m with WSRT FPGA system

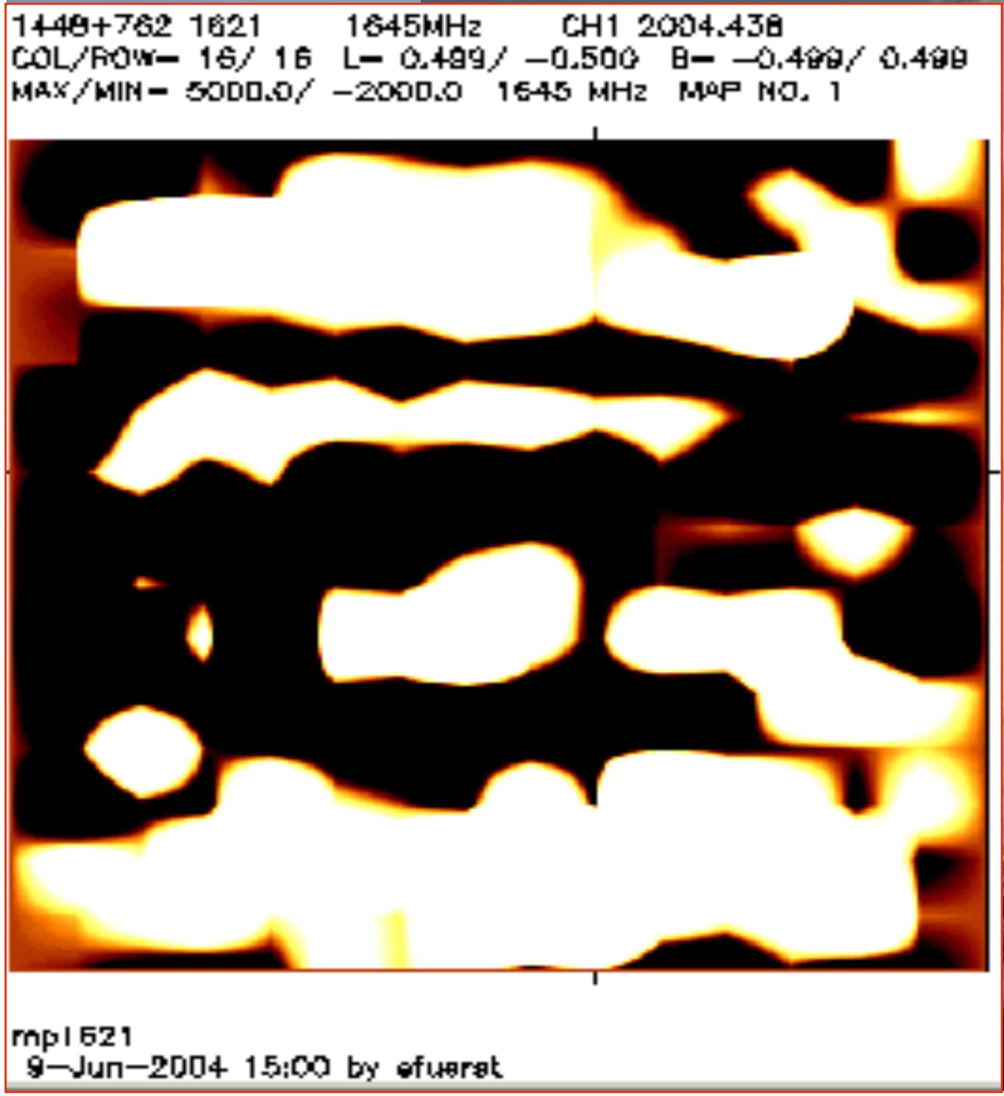
Results Effelsberg 100m with WSRT FPGA system

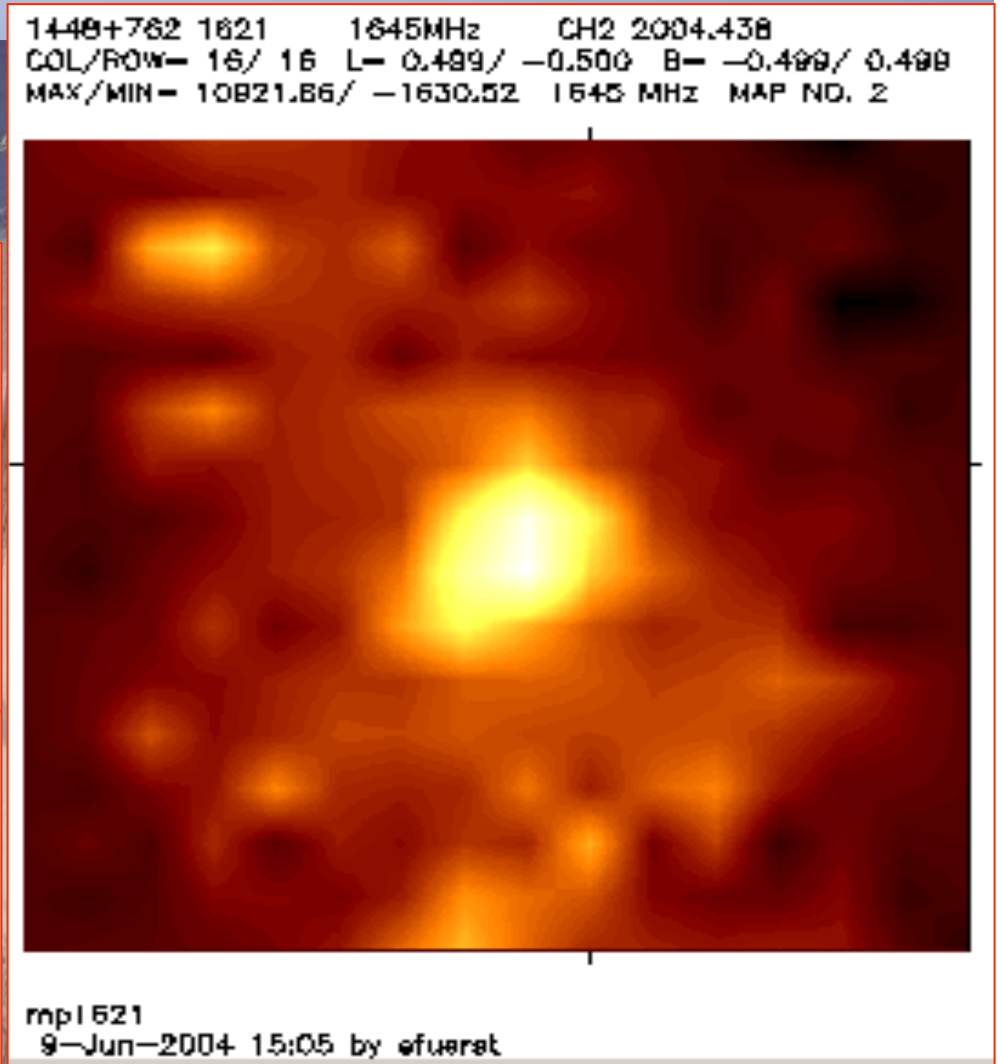


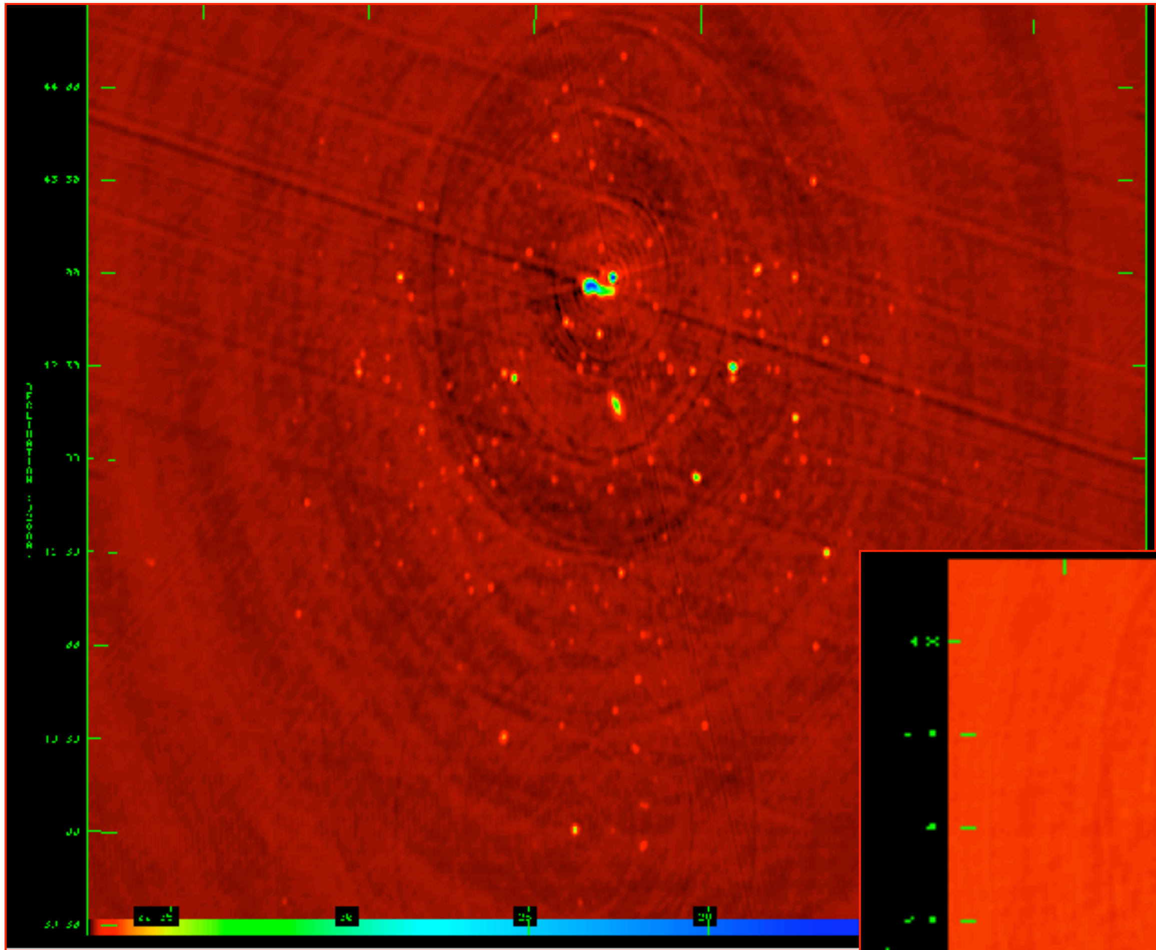


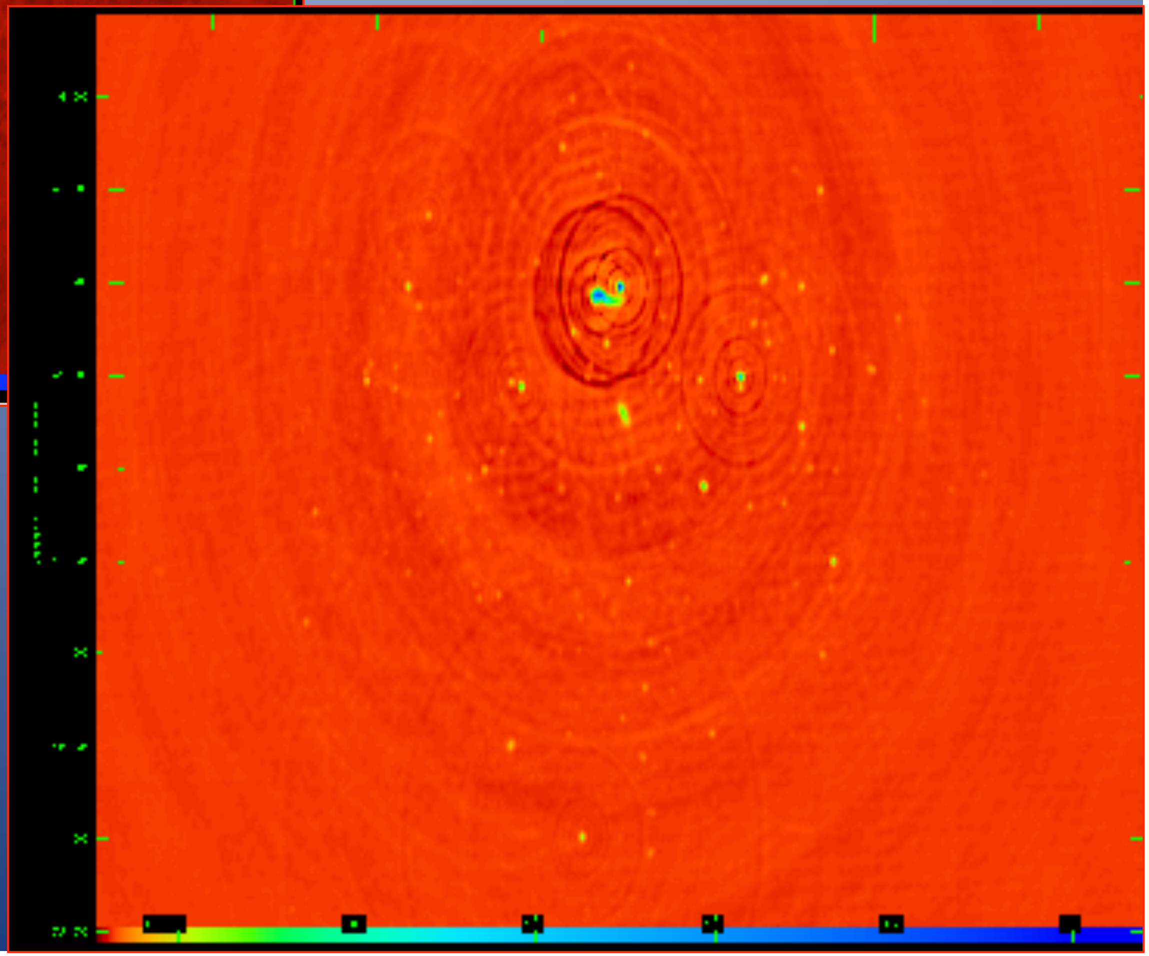
Effelsberg 100m - using WSRT system

16 x 16 Drift maps
without mitigation and
with mitigation





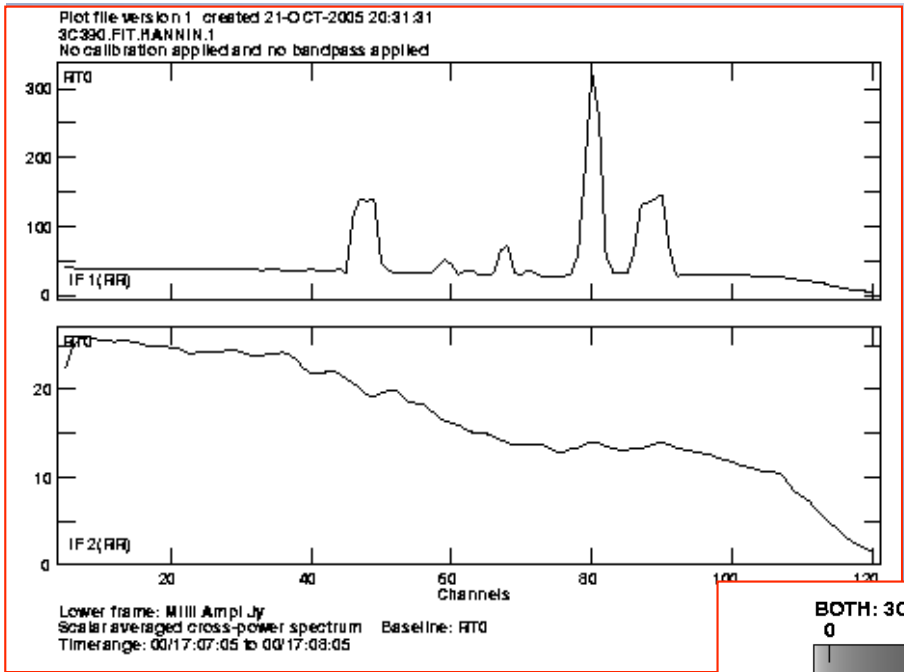


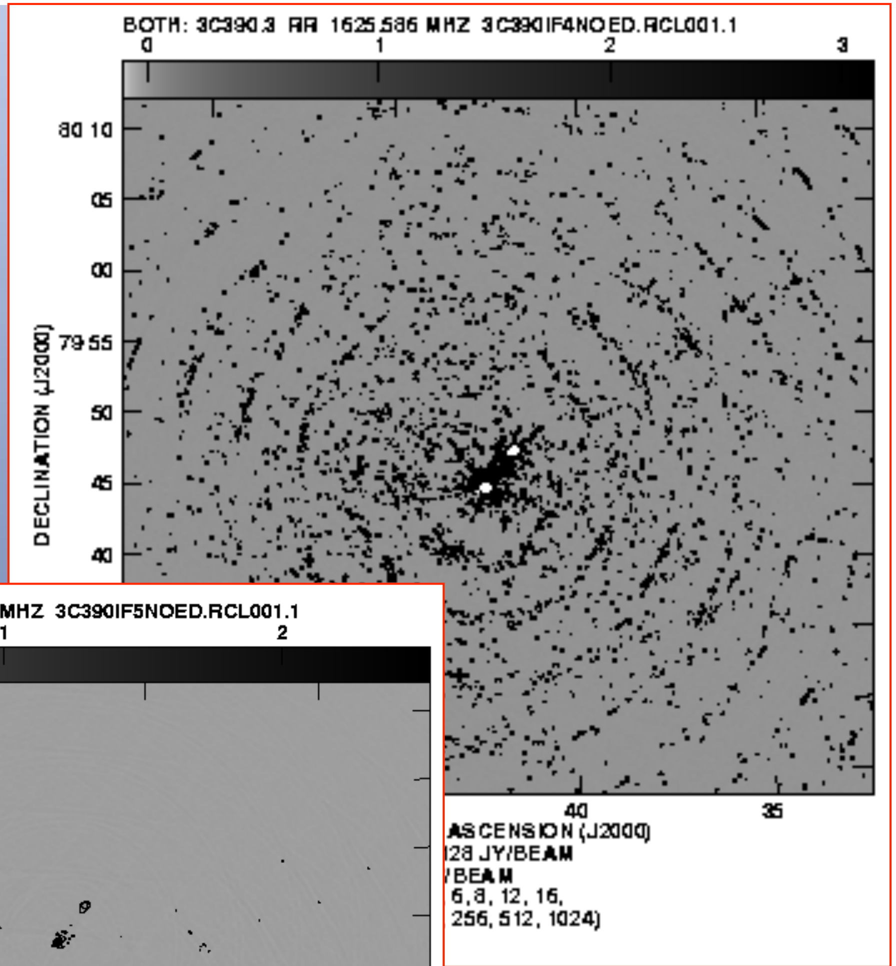


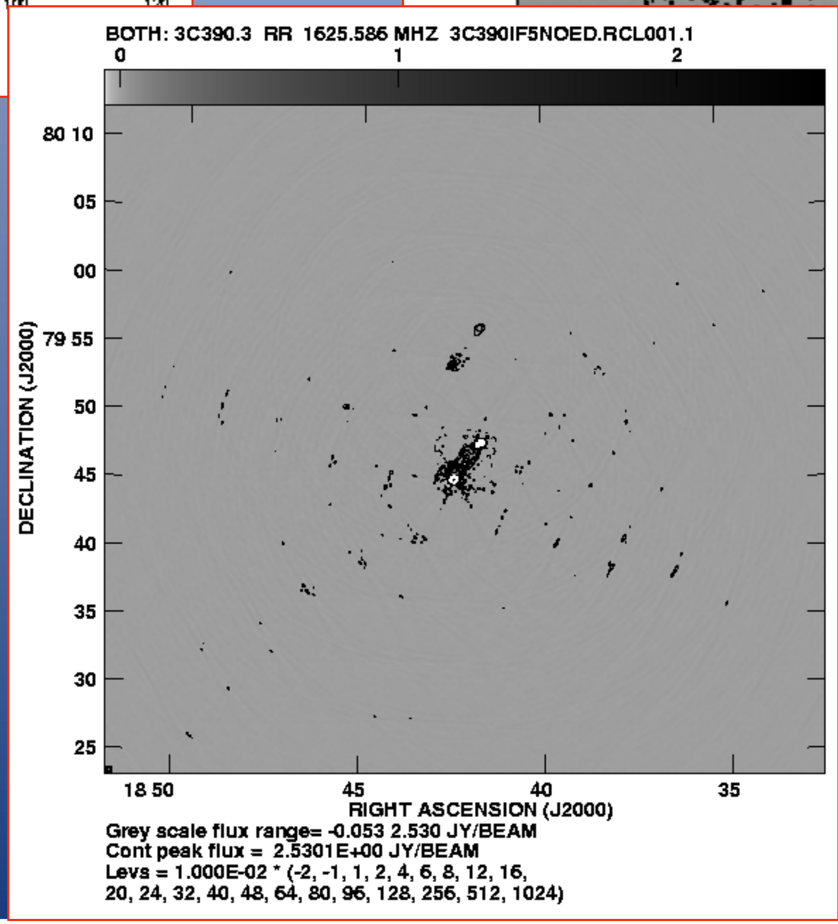
WSRT NGC891 field

at 370 MHz

without and with



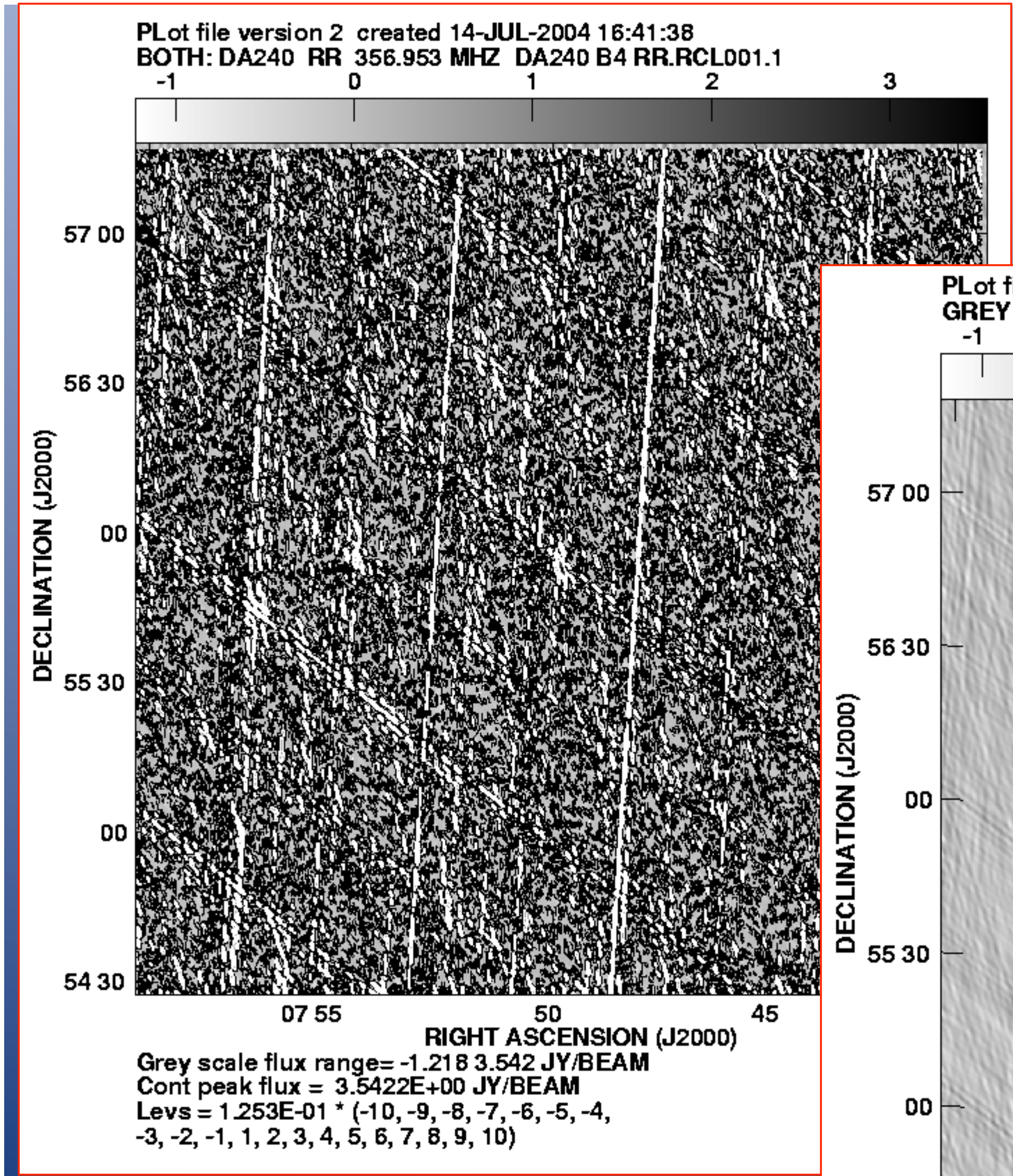


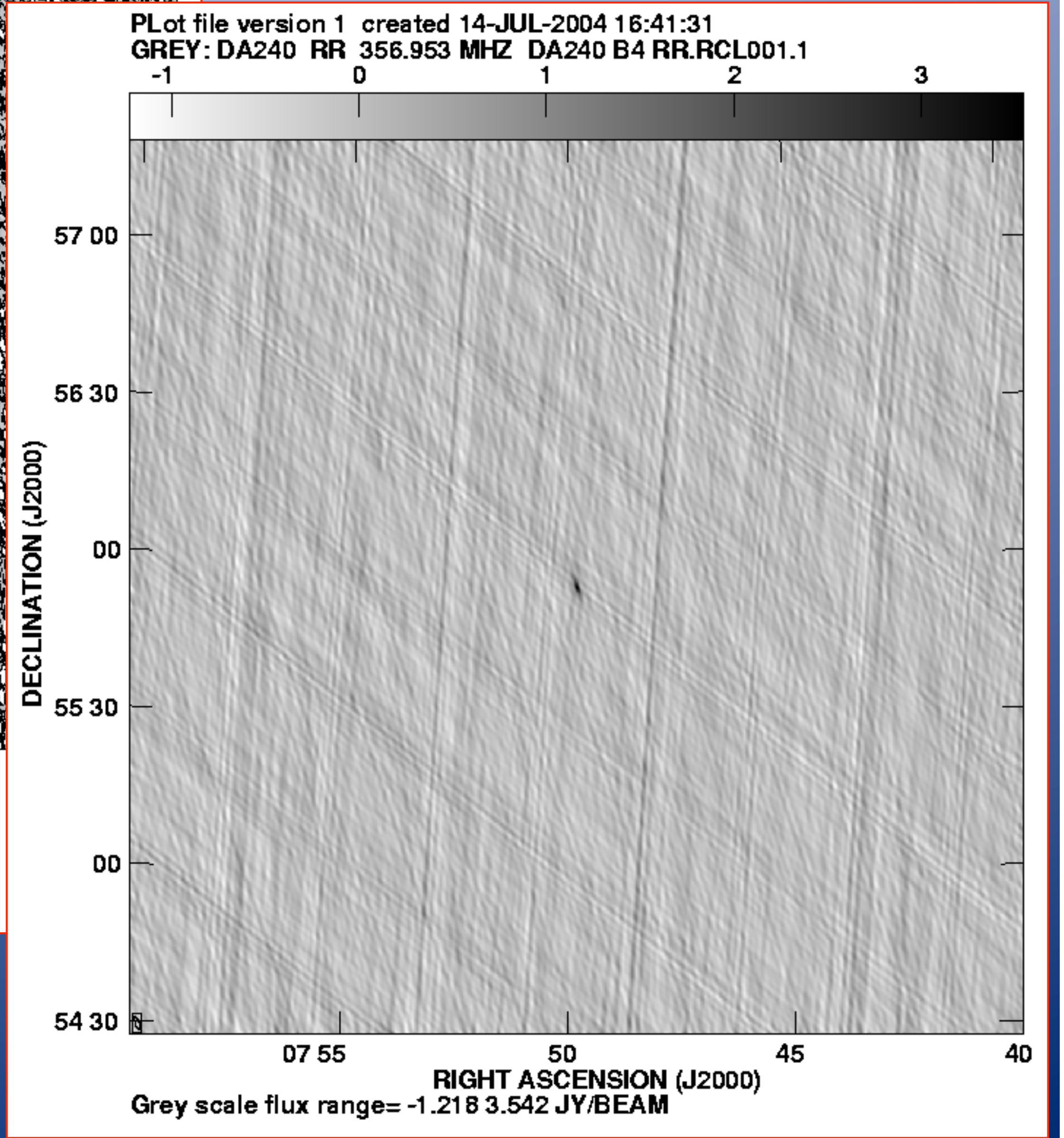


Strong Continuum Source
in Iridium Band

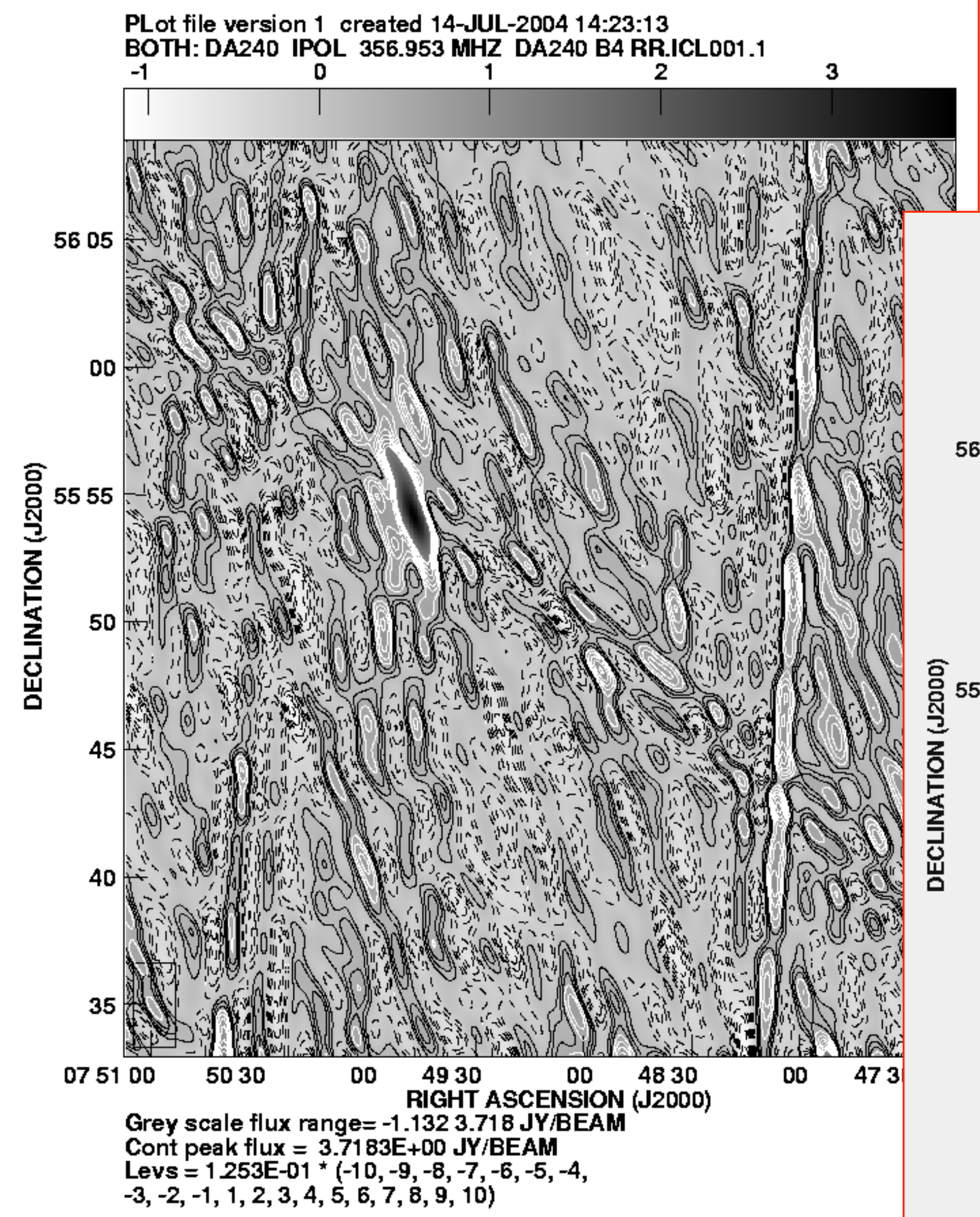
spectrum and maps without and with mitigation

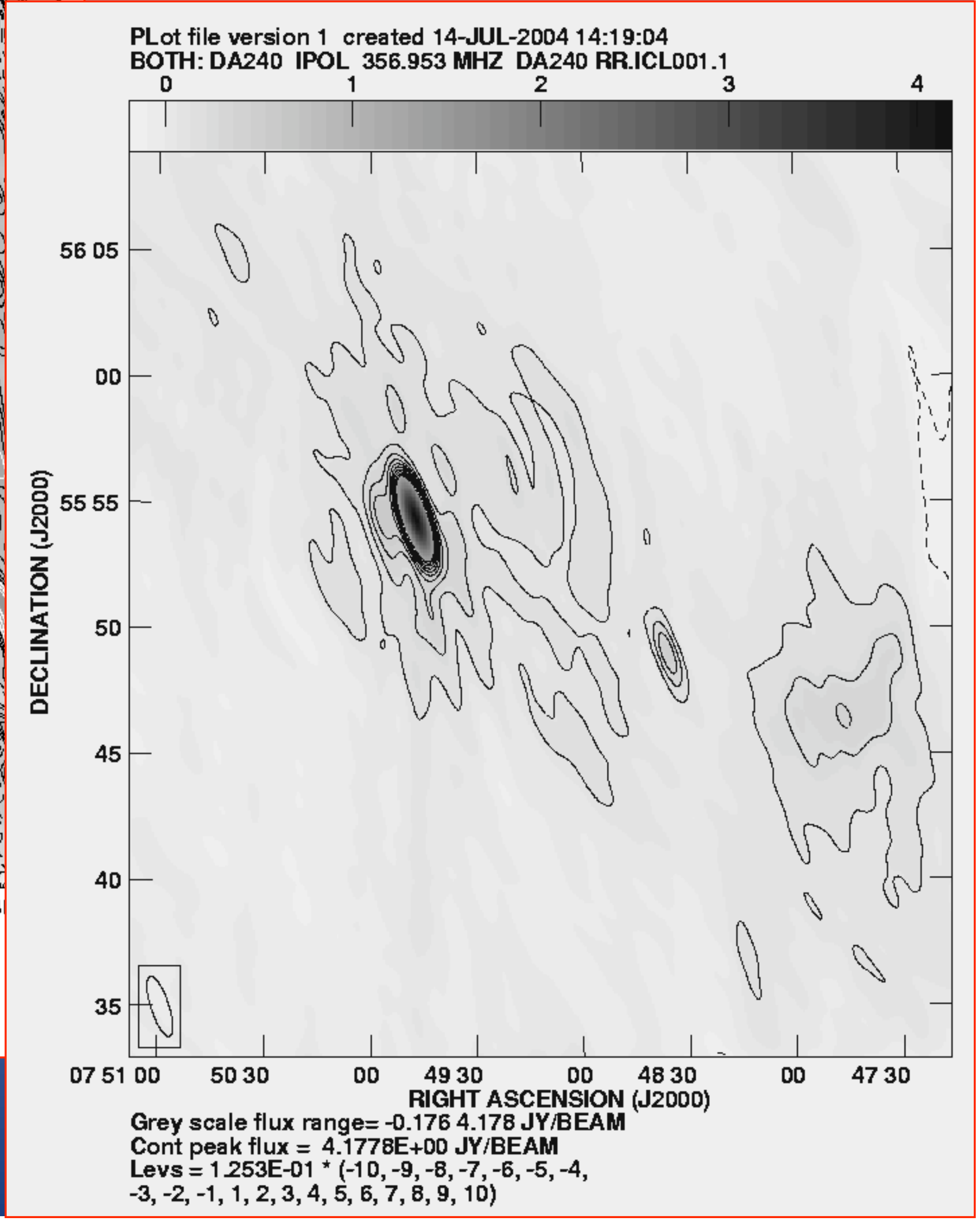
Before & After



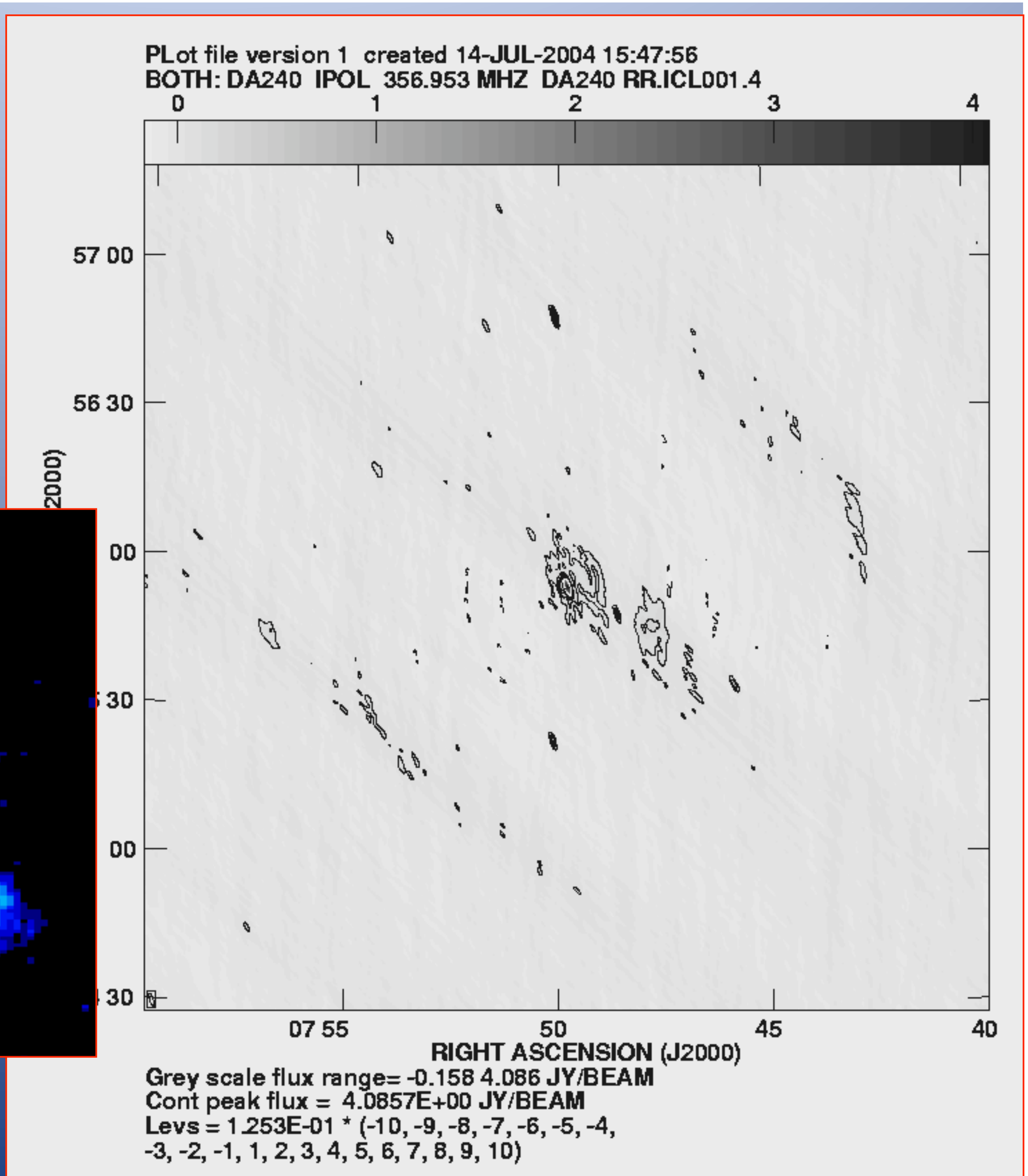


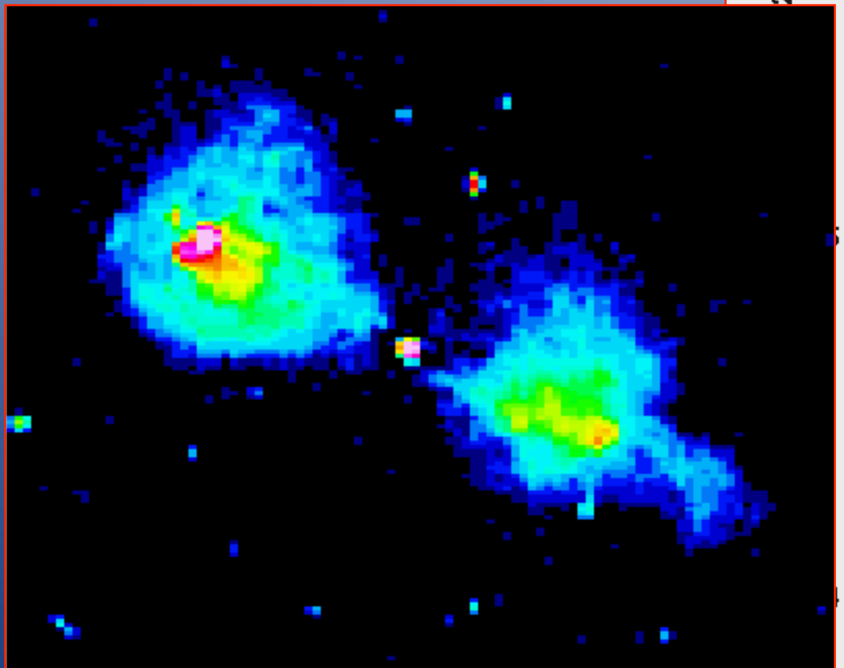
Before & After





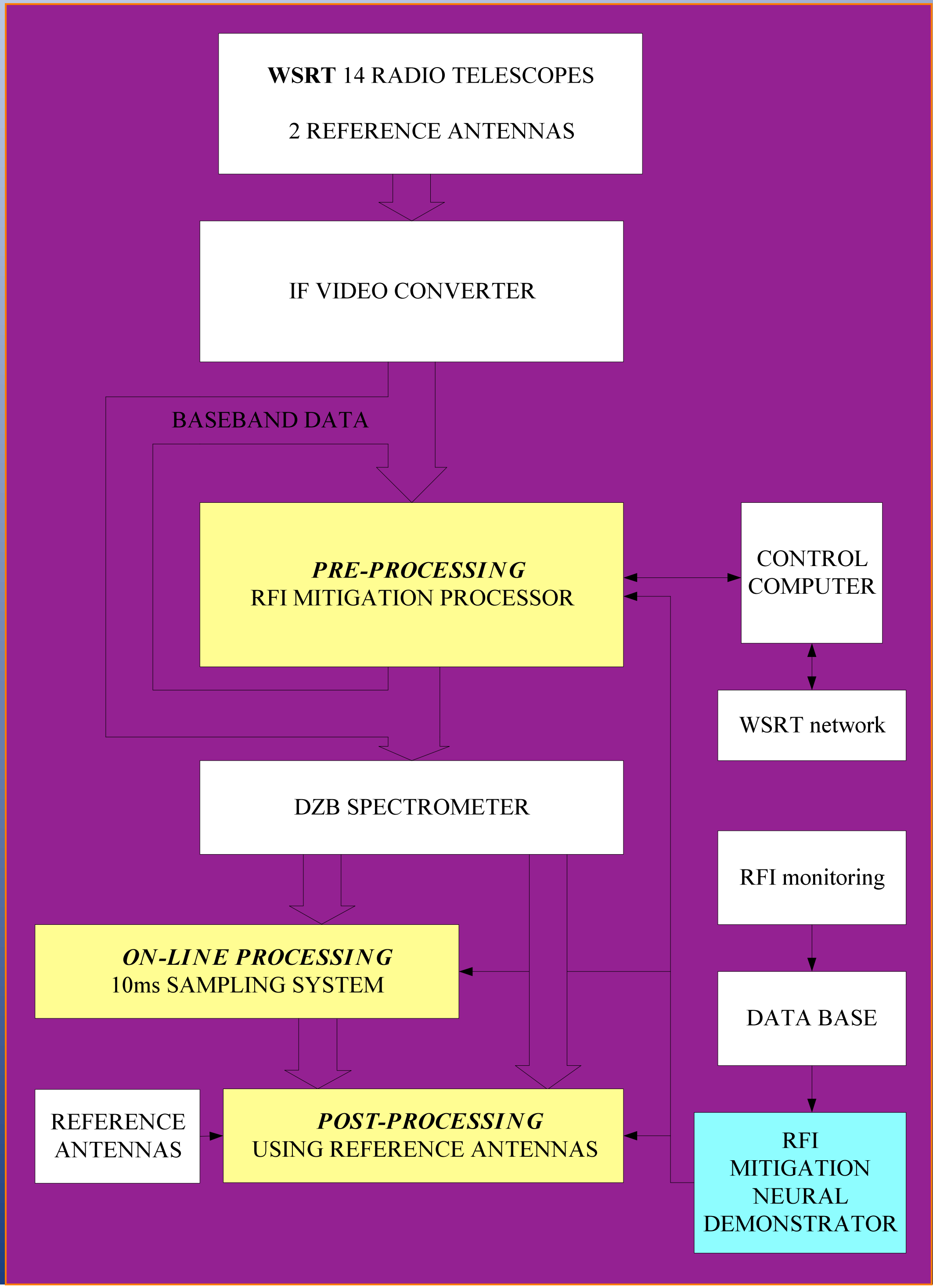
DA240 field dirty map with applied mitigation



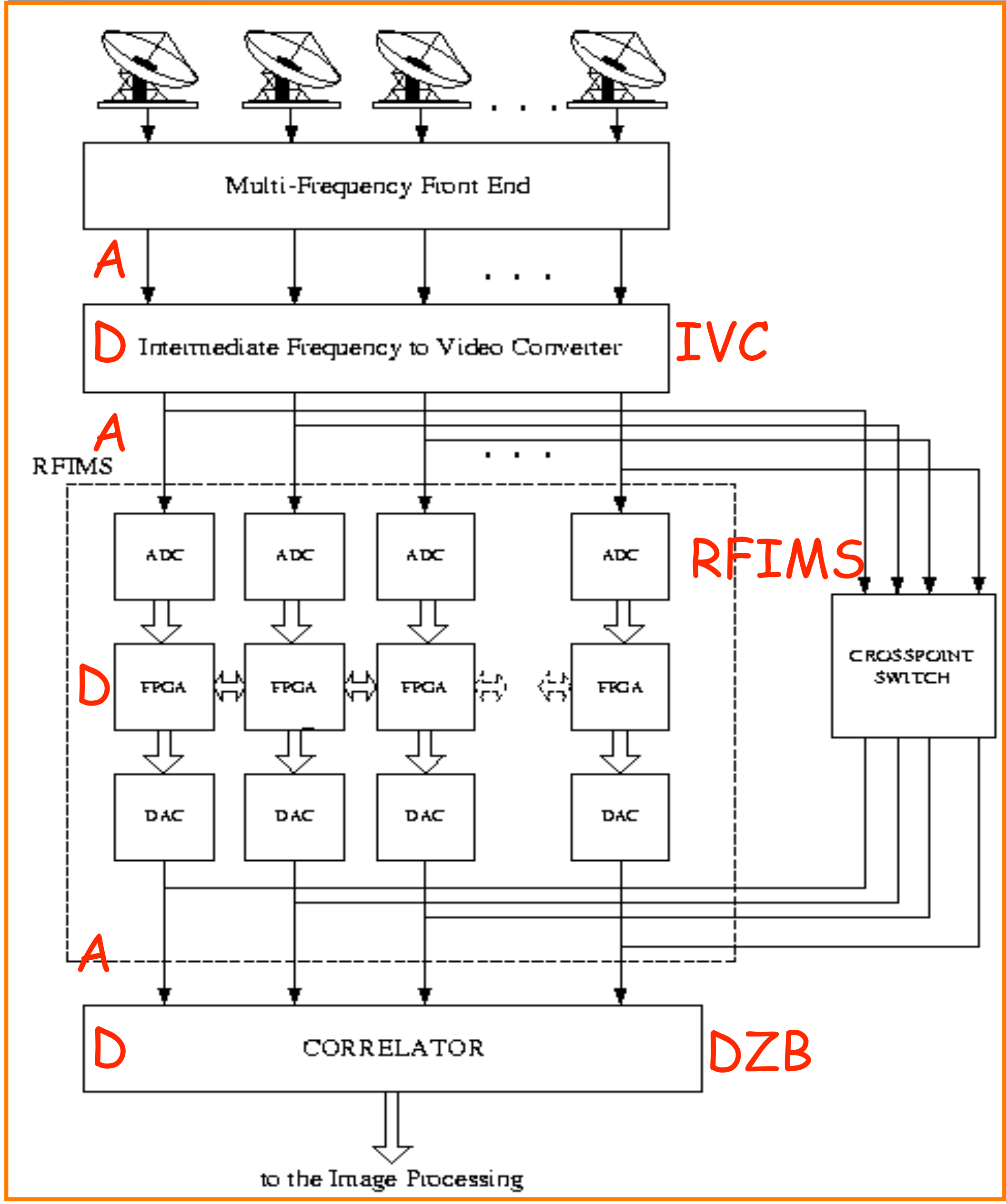


Planned Implementation Mitigation Hardware in the WSRT system

- *3 locations in data flow of system*
- *different algorithms at different stages*
- *stapling of methods*
- *AI decision-making subsystem for control*



RFIMS project evaluation



- Pro
- RFIMS worked as expected
- Rms of cleaned channels better or equal to hand-cleaned results
- Few/no remnants of RFI signatures
- Con
- Digital components designed and added with analog connections
- RFIMS bookkeeping not used for later gain calibration
- No astronomer acceptance

Evaluation

- Quantitative evaluation not always possible
  - RFI algorithms generally non-linear process
  - suppression of RFI depends on INR and RFI characteristics
  - RFI removal raises noise level and affects gain calibration

- Practical achievable limit of methods depends on INR
  - often not possible to remove RFI below noise floor
- Cumulative effect of RFI mitigation at subsequent stages
  - RFI characteristics change after each mitigation step
  - cumulative effect is not a linear sum
  - sum of what is practically possible at each step

- Cost of hardware capabilities and software development ?
  - rapidly changing parameter

Conclusions

- There is no universal method for RFI mitigation
- Choice of method depends on RFI characteristics and RT and type of observation
- Great variety of successful mitigation options
- Encouraging results with both on-line and off-line data processing
- Continue with implementing RFI mitigation in single-dish and array instruments
- Looking forward to next generation instruments

- Acceptance of RFI mitigation by the users

- Spectrum management and RFI mitigation efforts need recognition