Shanghai Astronomical Observatory
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LAYERS OF RFI MITIGATION

An Overview

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SHAO, Linnaeus U, ASTRON

The Objectives

- Mitigation means any method aimed at avoiding RFI signals in the data, removing RFI from the RAS data, and reducing/eliminating the impact of RFI on the data

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

- Prevention is best form of mitigation
- Removing RFI => the earlier - the better
  => Less downstream system costs and complexity
- Mitigation only possible for significant INR
- Mitigating weak RFI requires integration (further downstream)

- Fridman & Baan (2001)
- Briggs & Kocz (2005)
- Ellingson 2005
- Kesteven (2010)
- Baan (2010)
- ITU-R RA.2126 - rewrite

- RFI2004 - presentations www.ece.vt.edu/swe/RFI2004/
- RFI2010 – presentations & articles on POS
  www.astron.nl/rfi/presentations.php

A first Reality Check

- Existing ITU & ETSI Standards for spurious and out-of-band (unwanted) emissions insufficient for protection passive services

  => protection of RAS operations is very limited
- Prevailing philosophy: Rather than doing RFI prevention it is better to fill the spectrum with users and afterwards solve any conflict issues

  => RAS generally first victim

  => called 'spectrum efficiency'
- Increased RAS bandwidth use

  => 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

  => creative solutions required to protect RAS

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
- spectral line damage depends on location of RFI in spectrum

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

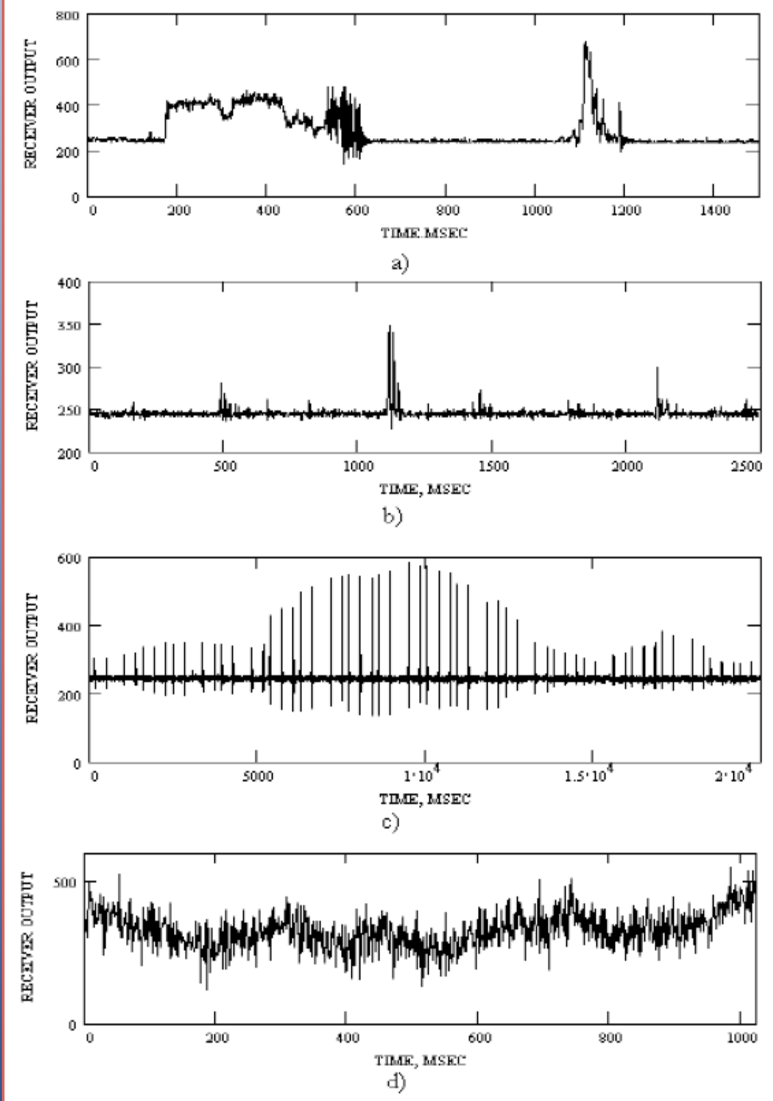


Fig. 1. Examples of *RFI* waveforms in the receiver output versus time: a) and b) impulse-like *RFI*; c) radar impulses; d) narrow-band *RFI*.

Evaluation of methodologies

- Different mitigation approach for each combination of telescope, type of observation, and type of RFI
- 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 ?
  - 0. Interference to noise ratio INR

    => how much RFI dominates the noise)
  - 1. Intensity of RFI

    => ratio of system-noise variance and RFI variance
  - 2. Occupied bandwidth

    => ratio of SOI bw and RFI bw
  - 3. Processing gain of RFI suppression

    => ratio of SNR(after) and SNR(before)
  - 4. Loss resulting from RFI processing

    => ratio of SNR(after) and SNR(no RFI)

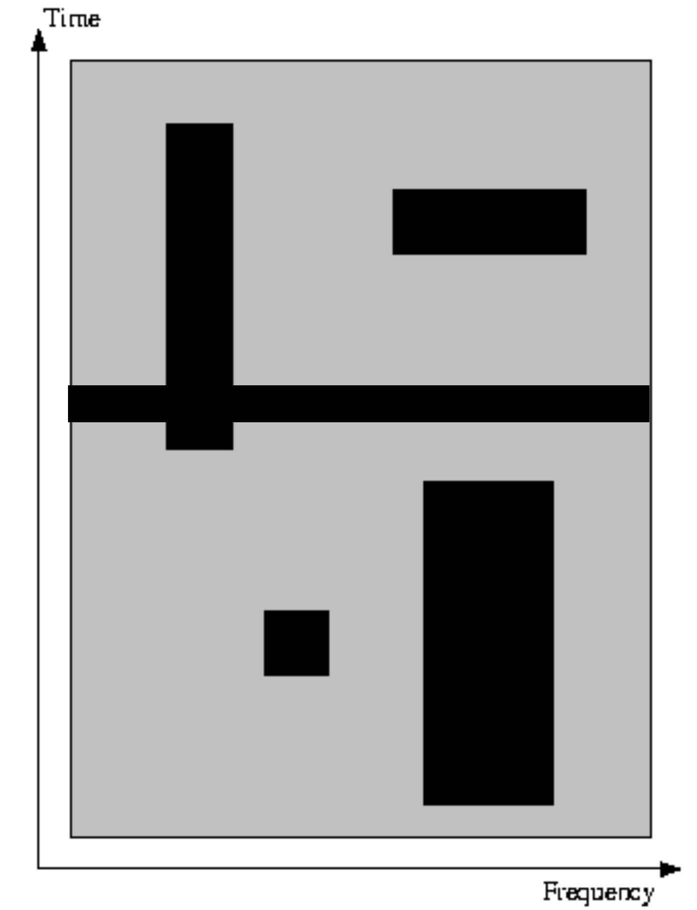
Many Steps of Mitigation

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

Pro-Active ⇔ Pre-Detection

- Establish coordination & quiet zones
  - use natural terrain
  - examples are NRQZ (Green Bank), PRCZ (Arecibo), WA Quiet Zone, SA Science Reserve, ALMA QZ
- 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 & advance coordination

- Clean up the act at your own observatory



Time-Frequency Diagrams

Excising in temporal and frequency domain

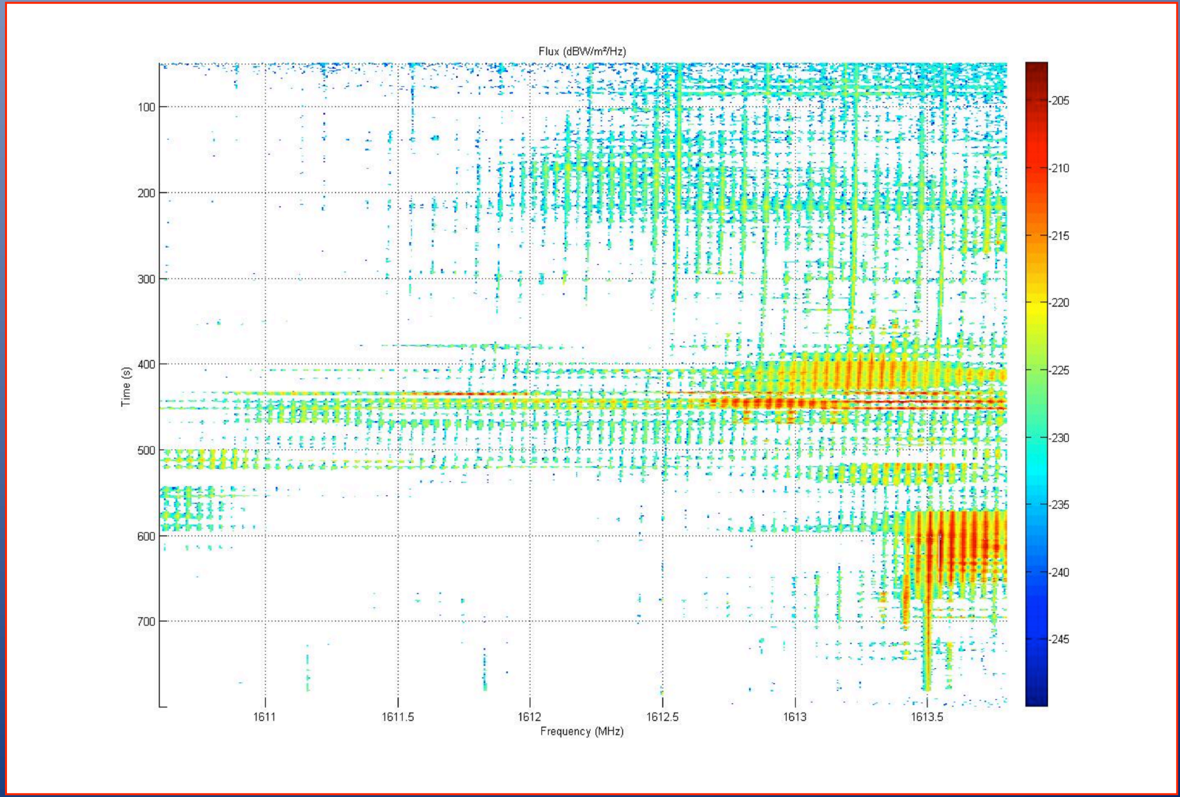
- RFI strong & short => not weak and persistent
- if intermittent & no info in rejected channels
- data loss

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 – at correlation)*, and *anti-coincidence* (array systems)
  => data loss and reduction of signal quality
- Robust receivers – receiver linearity

- Filtering results in insertion losses and raises Tsys
- Re-consider super-conducting filter technology

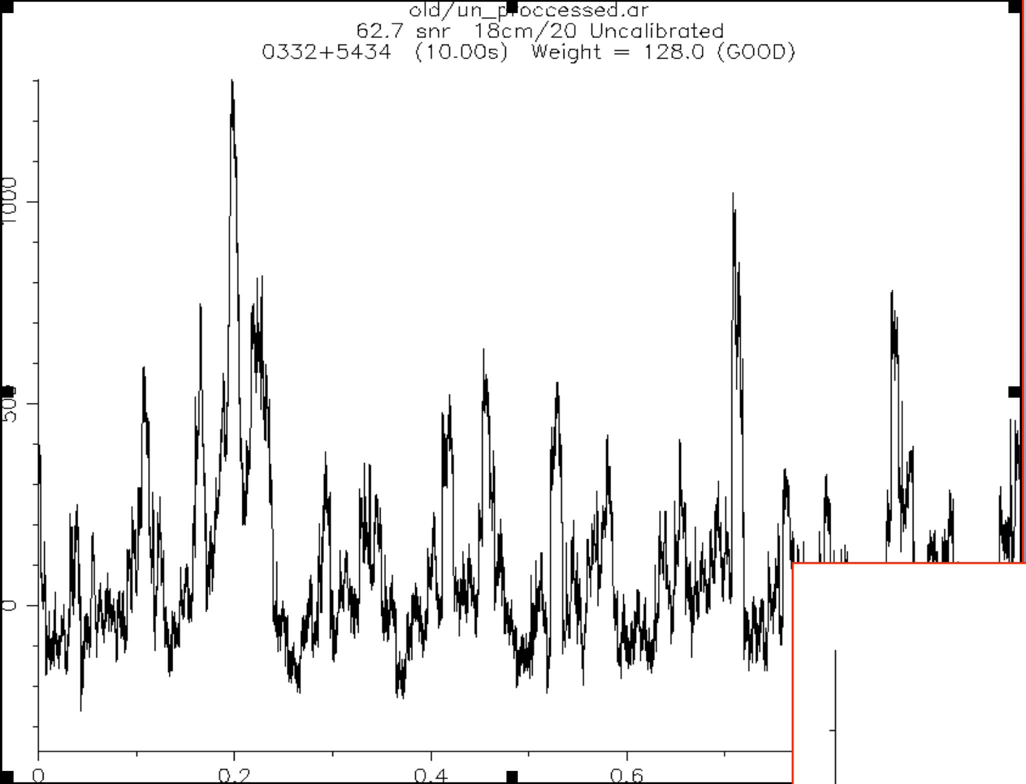
- Single RT => blanking or stopping correlator
  - example: Arecibo – SJU airport L-band radar and others
  - terrain and multi-path broadens RFI time-window
  - works well for periodic & impulsive signals
  - broad-band possible if linear system & no aliasing

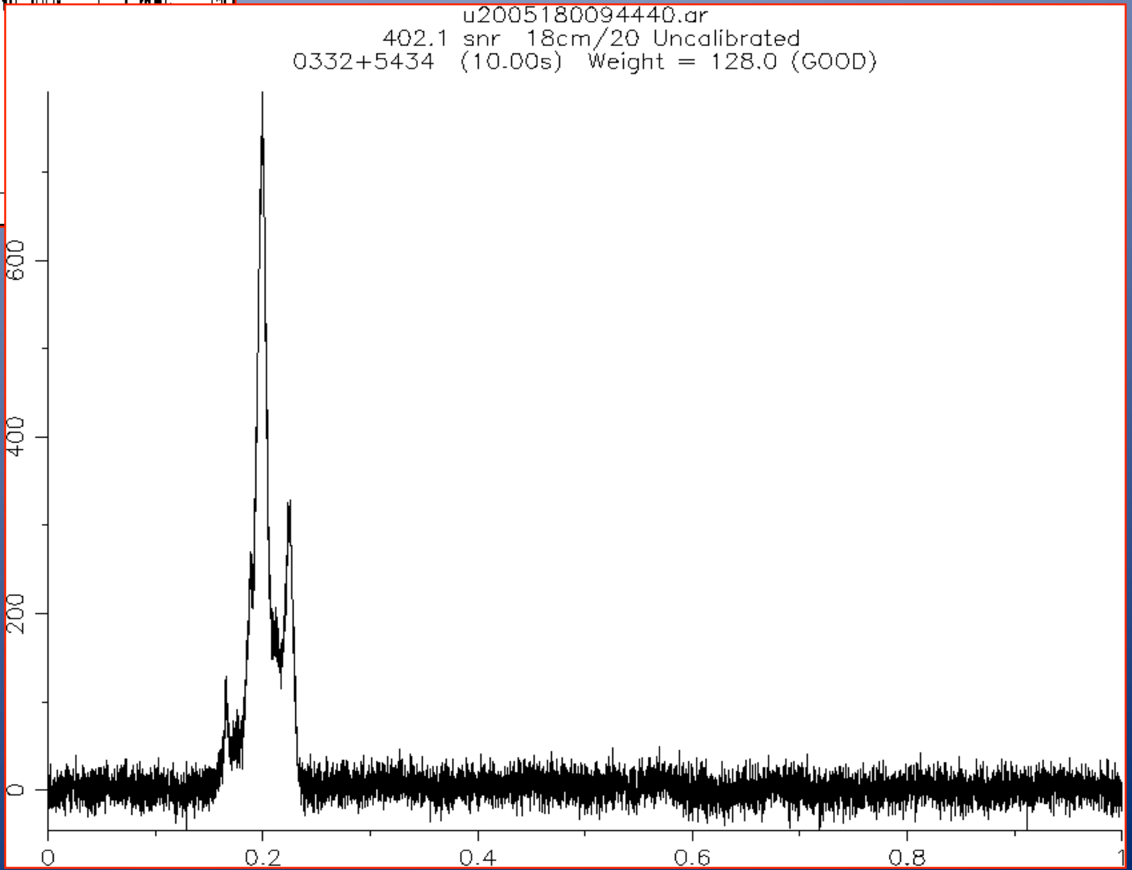
Pulsar data without and with thresholding before period folding

WSRT PUMA2 data

(Fridman & Stappers 2007

and Kesteven for Parkes)

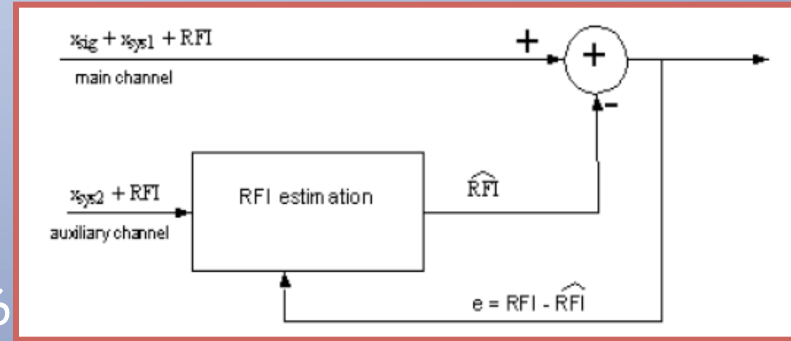


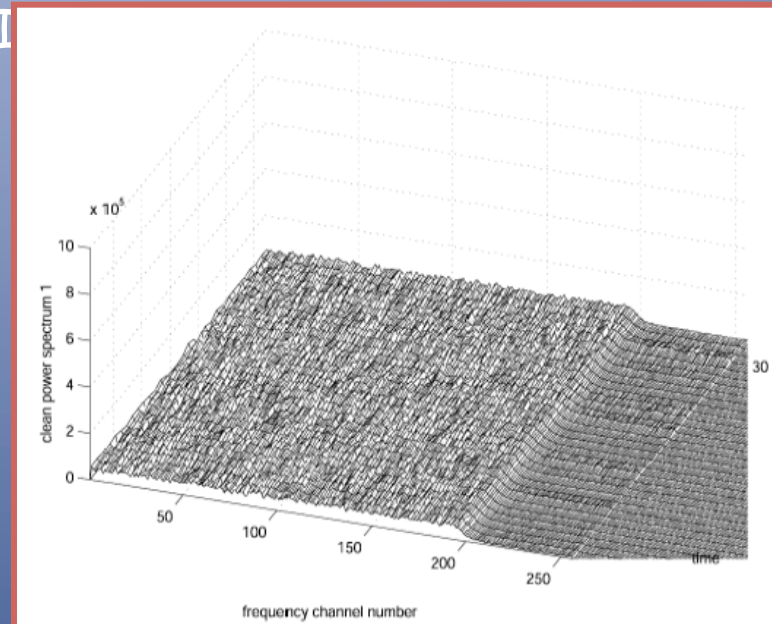


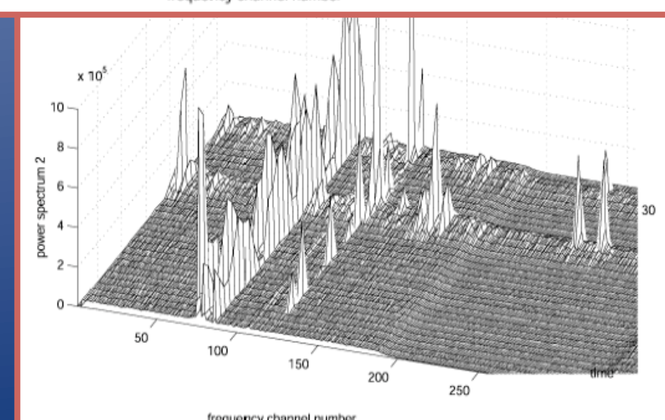
Pre-correlation - ANC

- Adaptive noise cancellation (ANC)
- Adaptive filtering w RFI copy (Haykin 1986)
  - => ON-source plus RFI & OFF plus RFI
- Temporal adaptive filtering
  - => FFT & adapting in frequency bins
  - => FFT-1 in frequency domain
- Use Reference channel & subtract

- Directed reference antenna (Barnbaum & Bradley 1998)
- Subtract RFI power spectrum estimate from PSE of main channel (Briggs et al 2000)
- Effective for multi-feed SD
- Array – use RT of WSRT as Ref antenna (Fridman & Baan 2001)







Reference Antennas

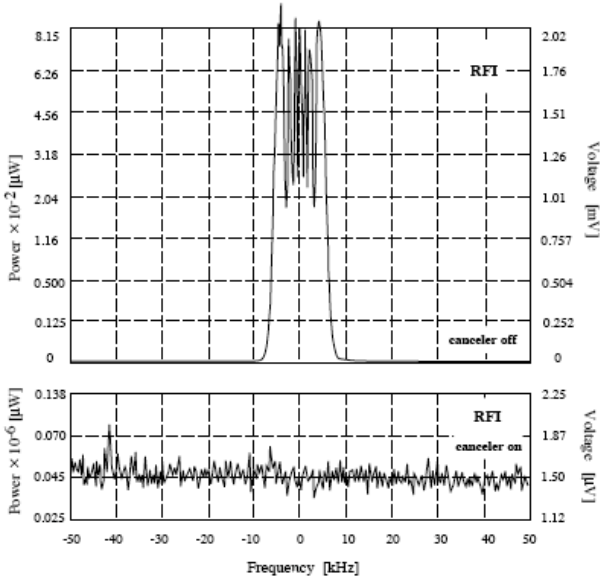
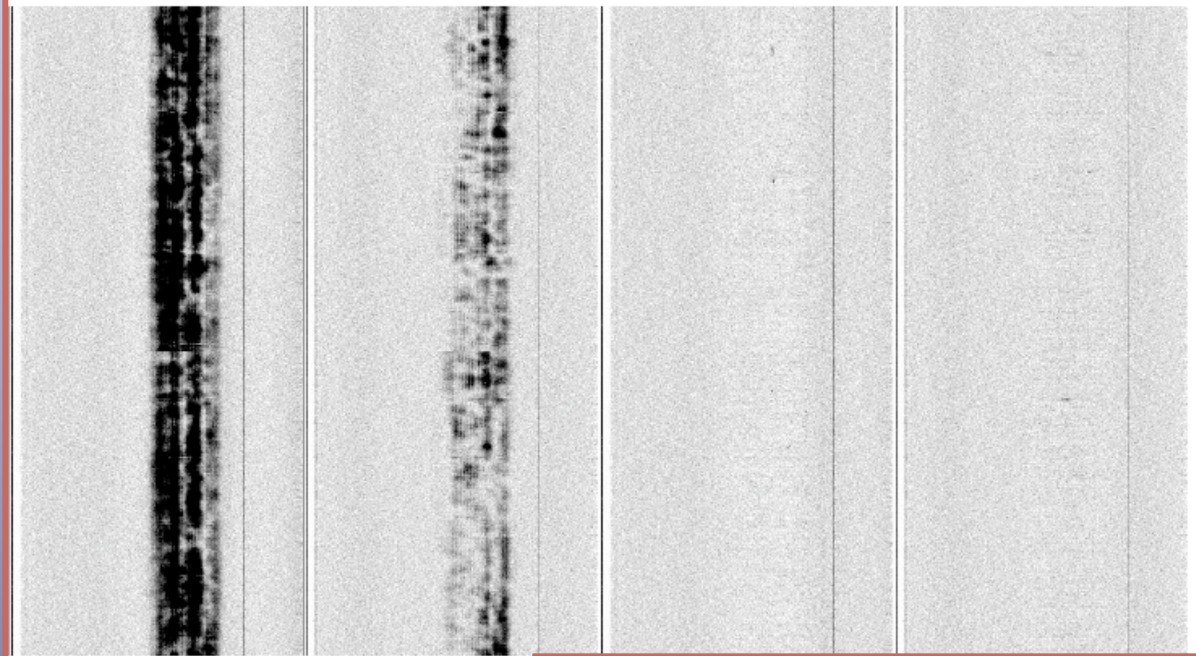
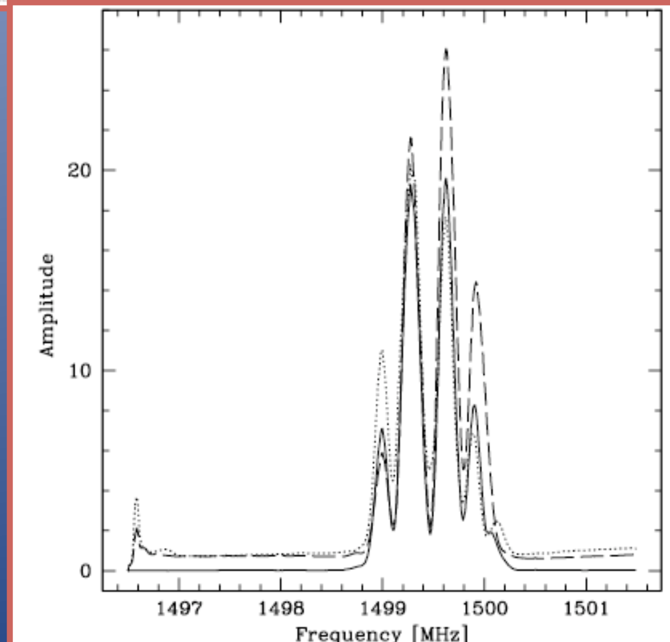


FIG. 8.—High dynamic range test of the adaptive-canceling system under stationary conditions. The data are shown in col. (2) of Table 1. The spectra in this and subsequent figures were recorded in volts. The right axis shows the linear scale in volts, and the left axis is power. Note that the left axis 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.

Barnbaum & Bradley 1998





Parkes
Briggs, Bell, Kesteven 2000

GLONASS C/A
parametric estimation/subtraction
using known modulation properties
no additional antennas
cancellation > 20 dB
(Ellingson, Bunton, Bell 2003)

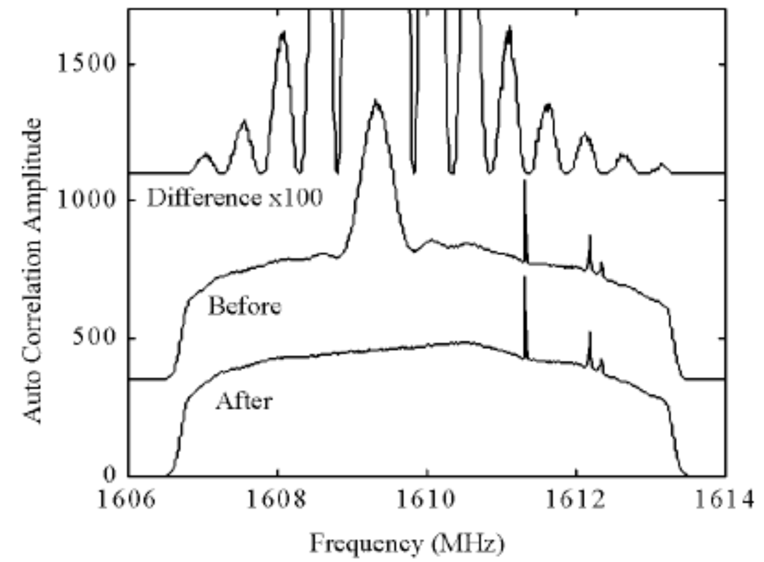
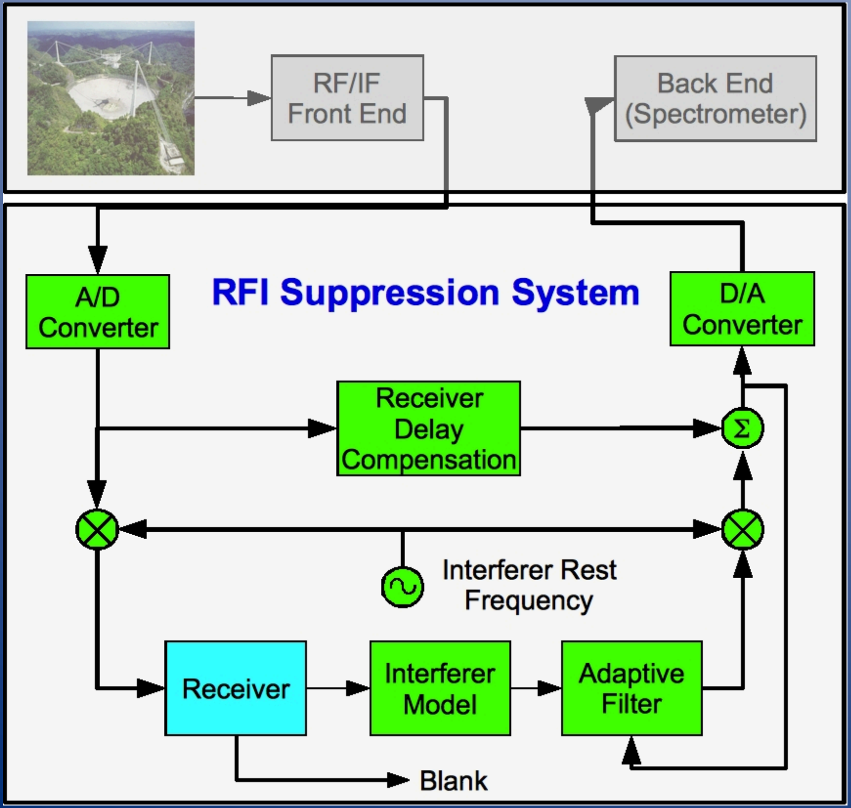


FIG. 2—*Middle curve*: Autocorrelation of raw data, including (*left to right*) *GLONASS*, test tone, and OH maser. *Bottom curve*: Same signal after processing (C/A signal removed). *Top curve*: The cancelled signal (i.e., "before"-"after") multiplied by 100, showing the spectrum of the signal that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



GPS L3 at Arecibo
no reference antenna => in IF path
apply to L1, L2C, GLONASS, ...
adaptive filtering
using simple FPGA implementation

(Nigra et al 2010)

Pre-correlation
Spatial Filtering & ANC nulling

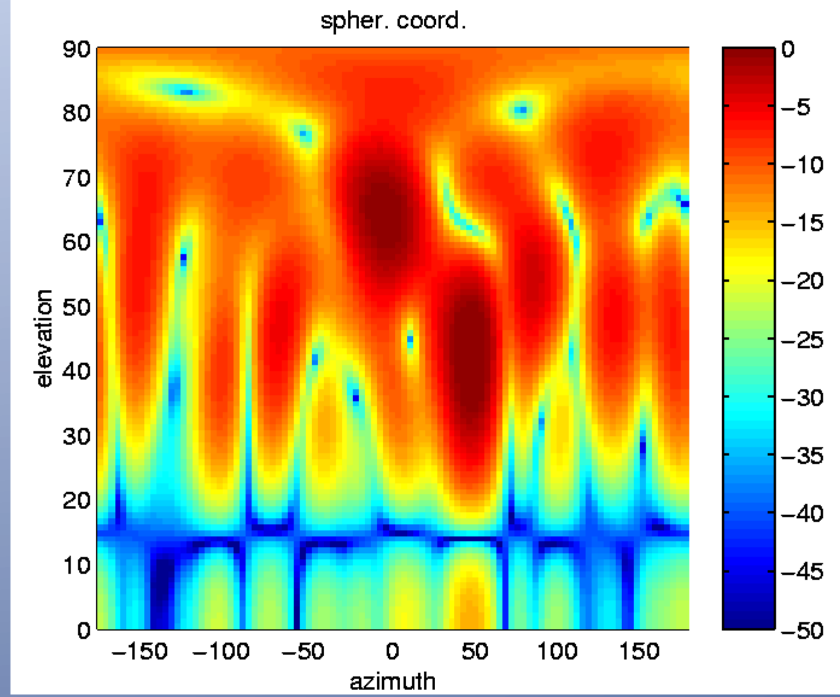
- *Smart antenna* techniques in radar and communication systems
- Multiple sensors (RTs) with view on RFI source (LOFAR, WLA, etc*)*
- Sparse Arrays => localized and stationary sources

  => correlation array & beams synthesized afterwards

  => RFI suppression afterwards using small time intervals & complex weighting during image processing (Leshem 2000)

- Sparse Arrays => WSRT spatial filtering using adaptive complex weighting (Fridman & Baan 2001)
- Adaptive filtering & Null-steering (Kesteven 2009)
- Real-time adaptive nulling in phased-arrays for new generation telescopes (van Ardenne et al 2000; Bregman 2000)

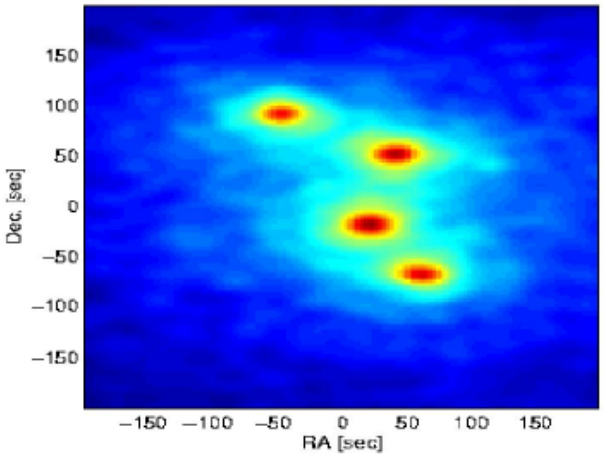
100 LOFAR stations
two beams and null at 15 deg
(Boonstra & van der Tol 2005)



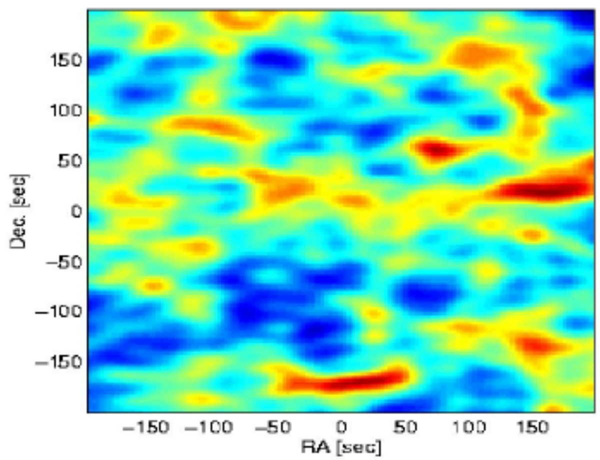
Array Spatial Filtering

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

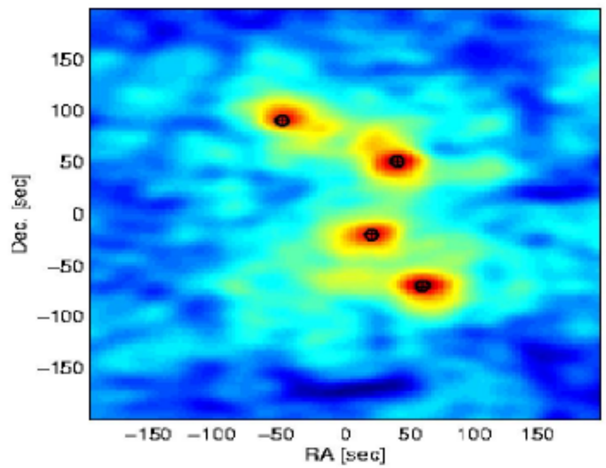
a. No interference



b. Unsuppressed interference



c. After spatial filtering



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

  => Ratan 600 (Fridman & Berlin 1996) – many more since

  => SD solar observations => thresholding using spectral kurtosis (4^{th} moment of power spectrum)(Nita & Gary et al. 2007, 2010)

  => WSRT RFI Mitigation System (Baan, Fridman, Millenaar 2004)

Data loss => affects gain calibration => accurate bookkeeping

- 'Sub-space' filtering => use RFI signature in data
  - cyclostationarity (Weber et al)
- Excision based on probability distribution analysis => statistics
  - RFI changes power spectrum to a non-central power distribution (Fridman 2001; Fridman & Baan 2001)

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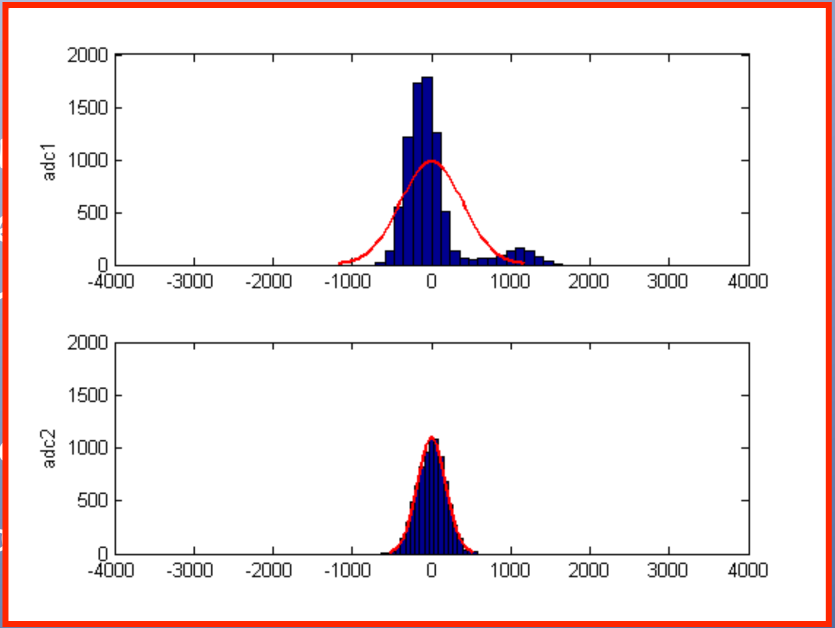

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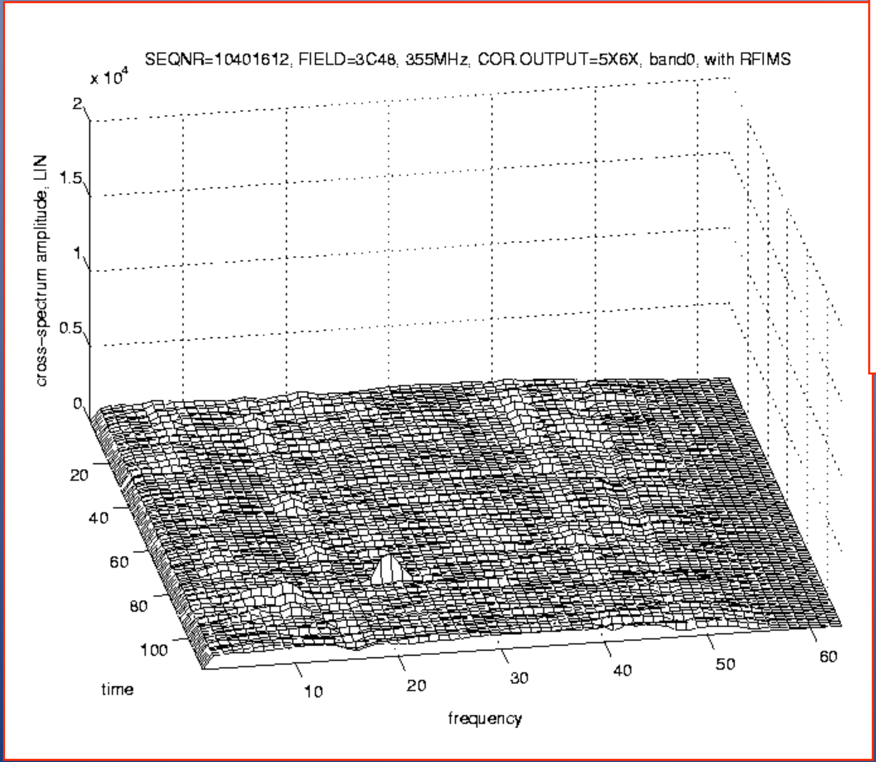
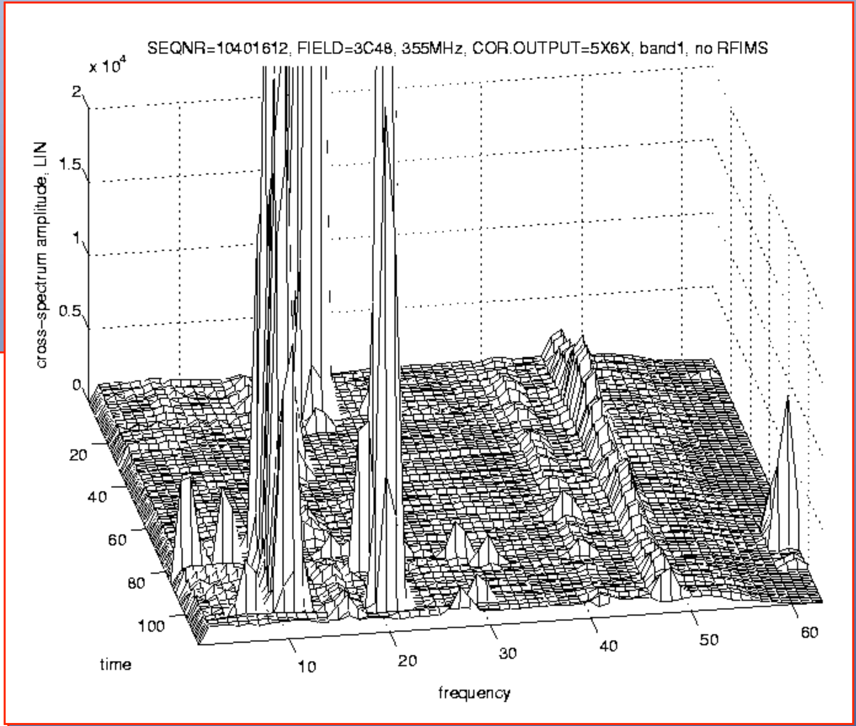
WSRT RFI-MS

Cross Corr Amp same band with and without (5X6X b0 & b1)

thresholding in temporal domain and frequency domain

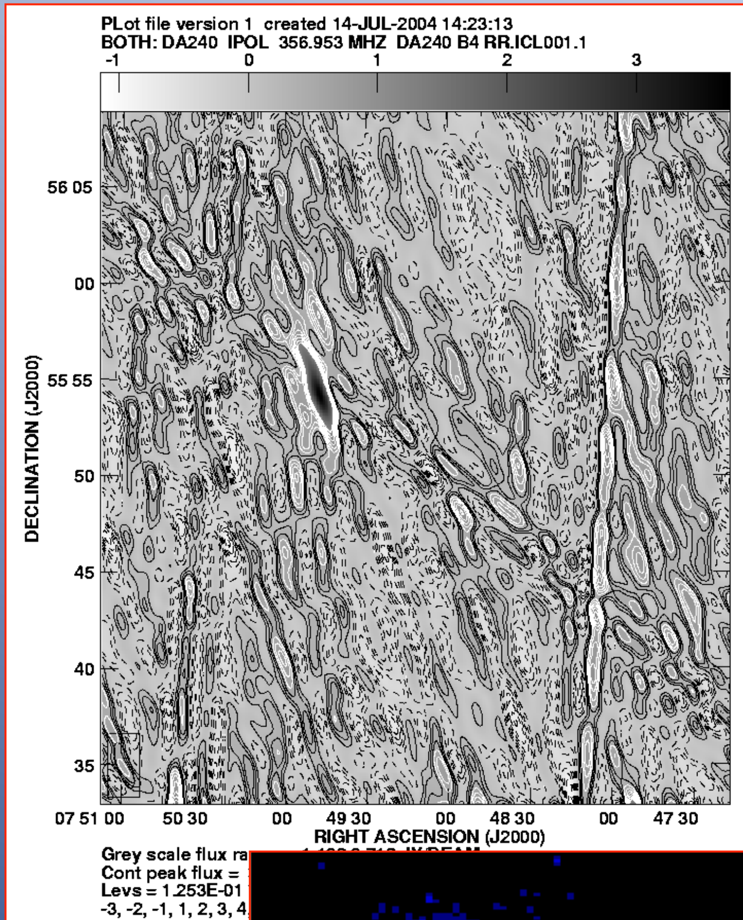


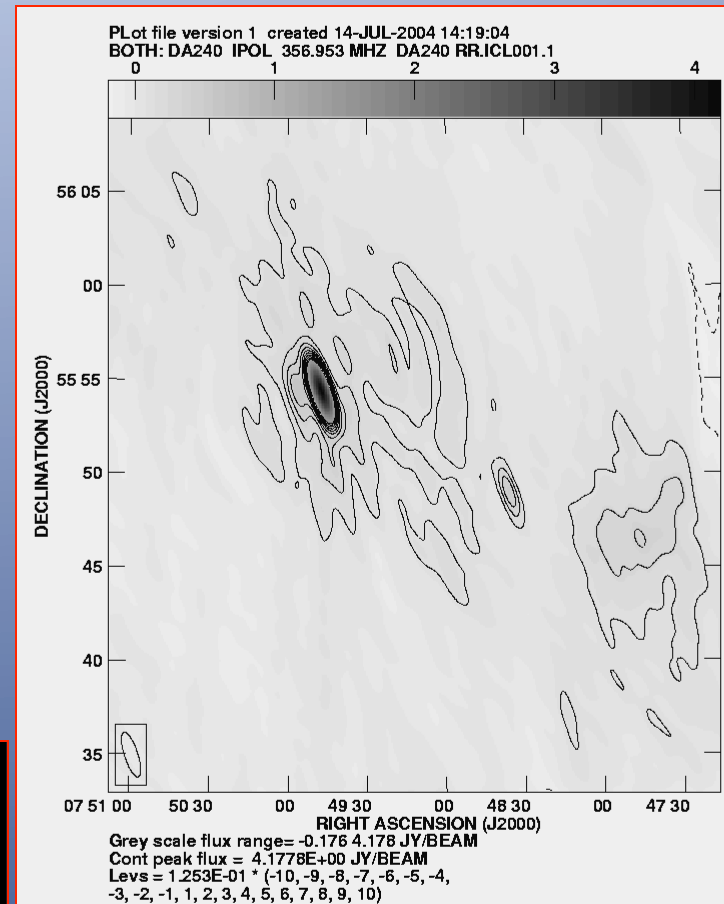


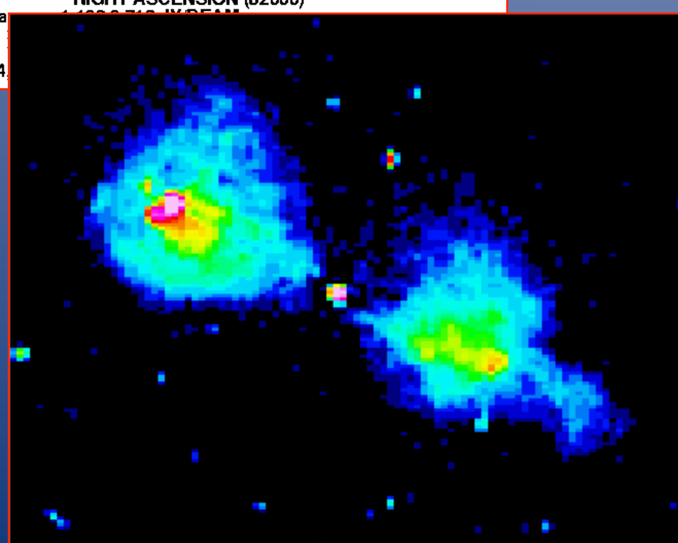
Altera Stratix FPGA system

14 RTs & 2 pol & band 20 MHz

DA240 Before & After







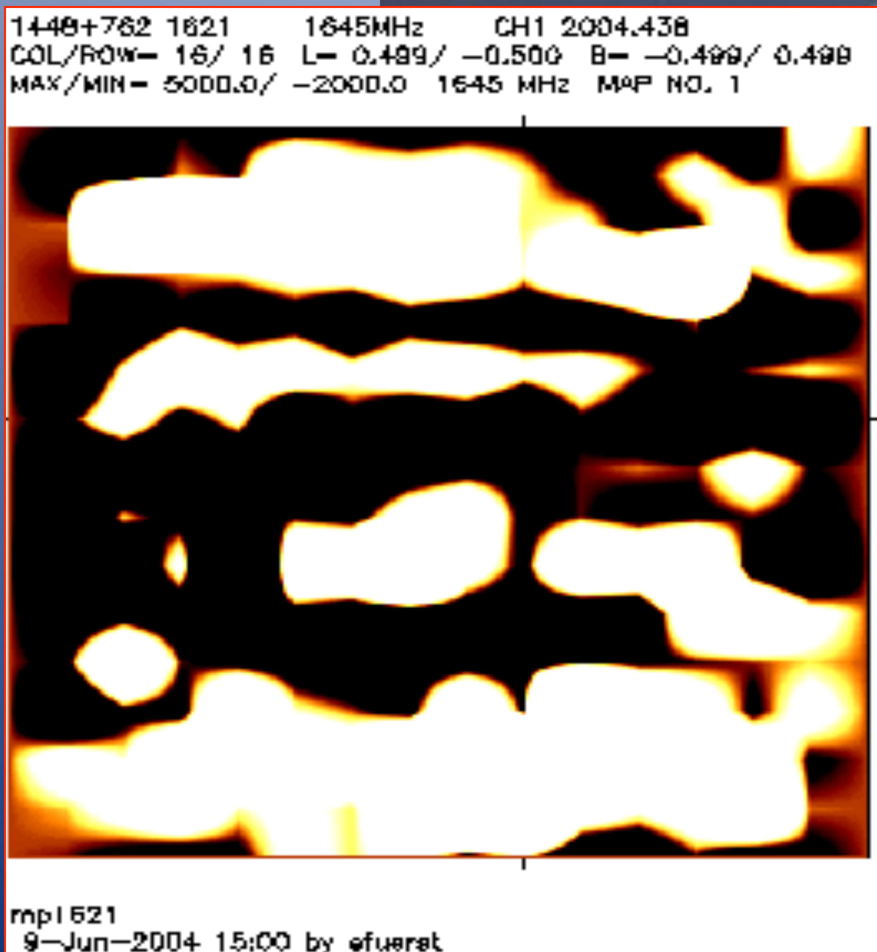
WSRT RFIMS

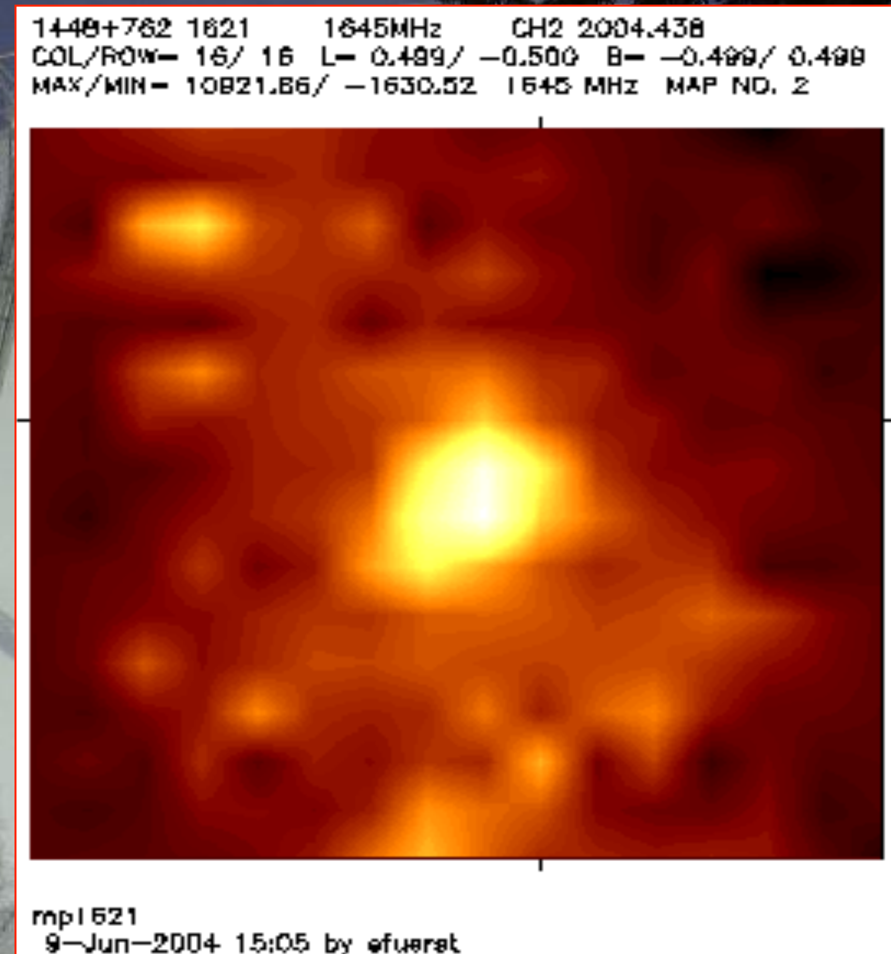
however the system was not
Accepted by astronomers

Baan, Fridman & Millenaar 2010

Effelsberg 100m - without and with WSRT RFIMS

16 x 16 Drift maps





Fridman & Baan et al. 2004

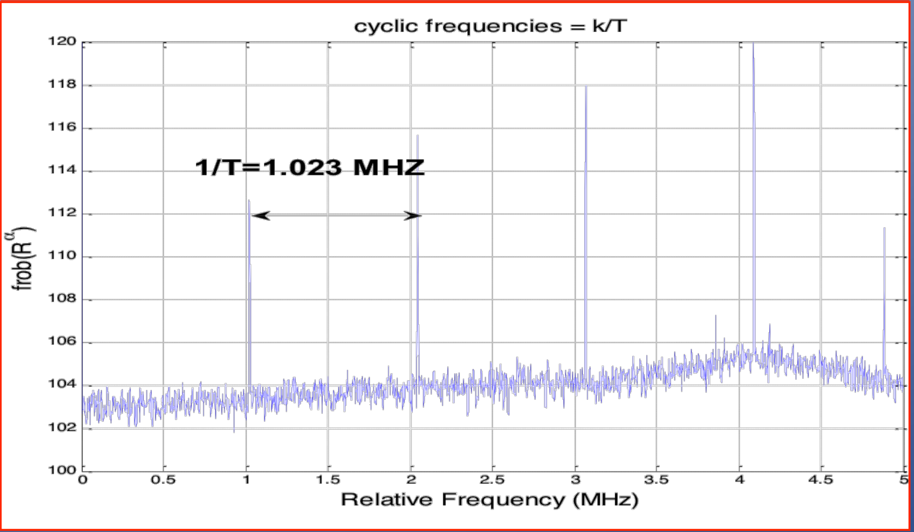
More Sub-space Filtering

- Stationary RFIprocess => statistics time independent
- Cyclostationary RFI => statistics are periodic
- FFT brings out periodic components => cyclic correlation matrix

- Sub-space methodology
- used/developed at Nançay
- & Orléans

- Applicable for spread spectrum
- with different keying schemes
- and periodic signals

Example at WSRT with GPS data



(Weber, Allal, Boonstra, et al)

At Correlation

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

- Mitigation integrated into new generation SW correlators (Deller 2010)

Post Correlation

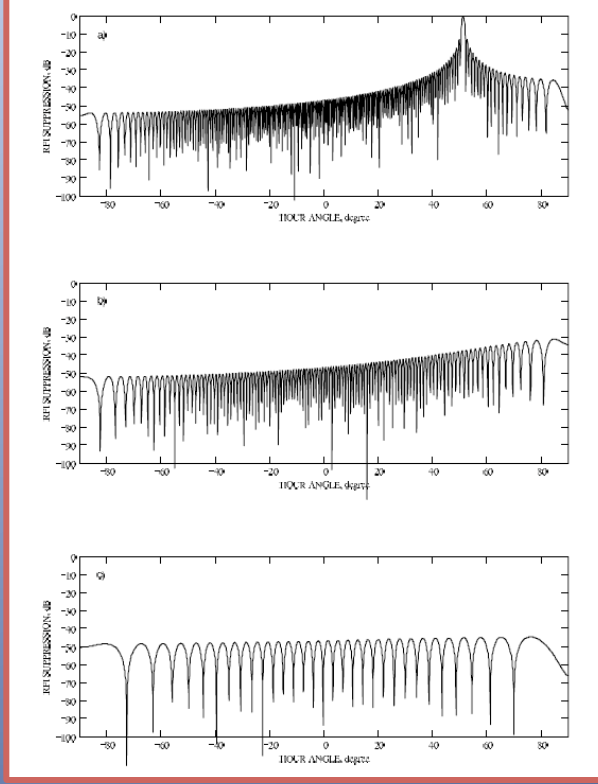
- SD – *flagging* & excising => data loss
- SD - using reference spectra
- Array – fringe tracking => spatial filtering
- Array – *flagging* => data loss & time consuming
- Array - eliminate 'stationary' RFI sources

  -- No data loss

  -- Fringe stopping => stationary (terrestrial) RFI sources fringe faster than astronomical sources, i.e at fringe stopping rate

  – UVRFI based on RfiX code for GMRT (Athreya 2009) => part of AIPS

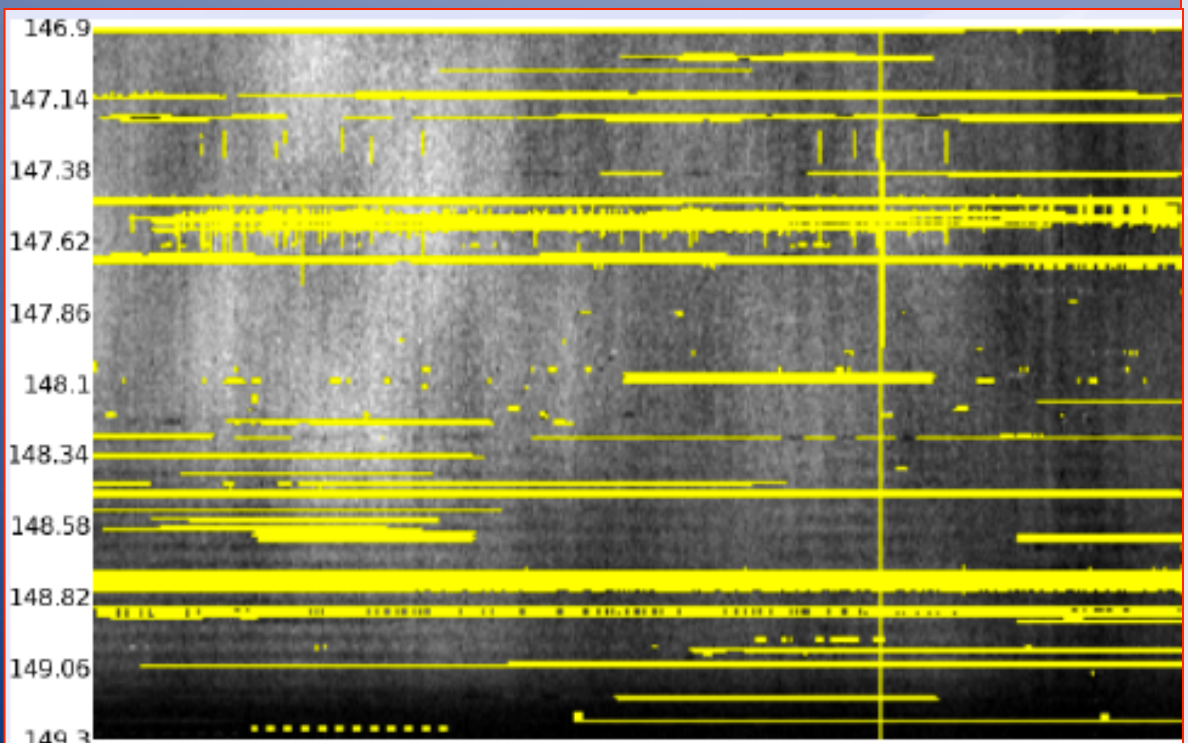
  -- Removal in image-plane using distinct motion of RFI (LOFAR - Wijnholds et al. 2004; VLA - Cornwell et al 2004)

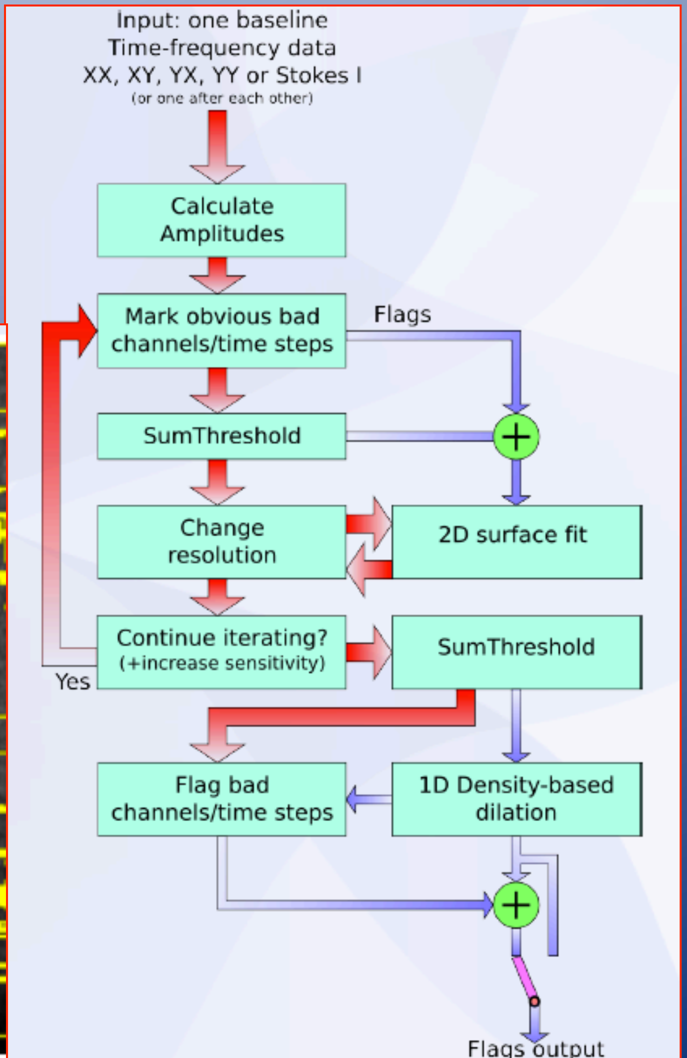


Thompson 1982
Baan et al 2004

Post-Correlation automated Flagging/Excising

- Part of pipeline processing
- Median/mean flagging in data cube or image plane (Kalberla, Flöer et al. 2010)
- Thresholding (Offringa et al. 2010,2012)
  => rfigui for LOFAR & VLA





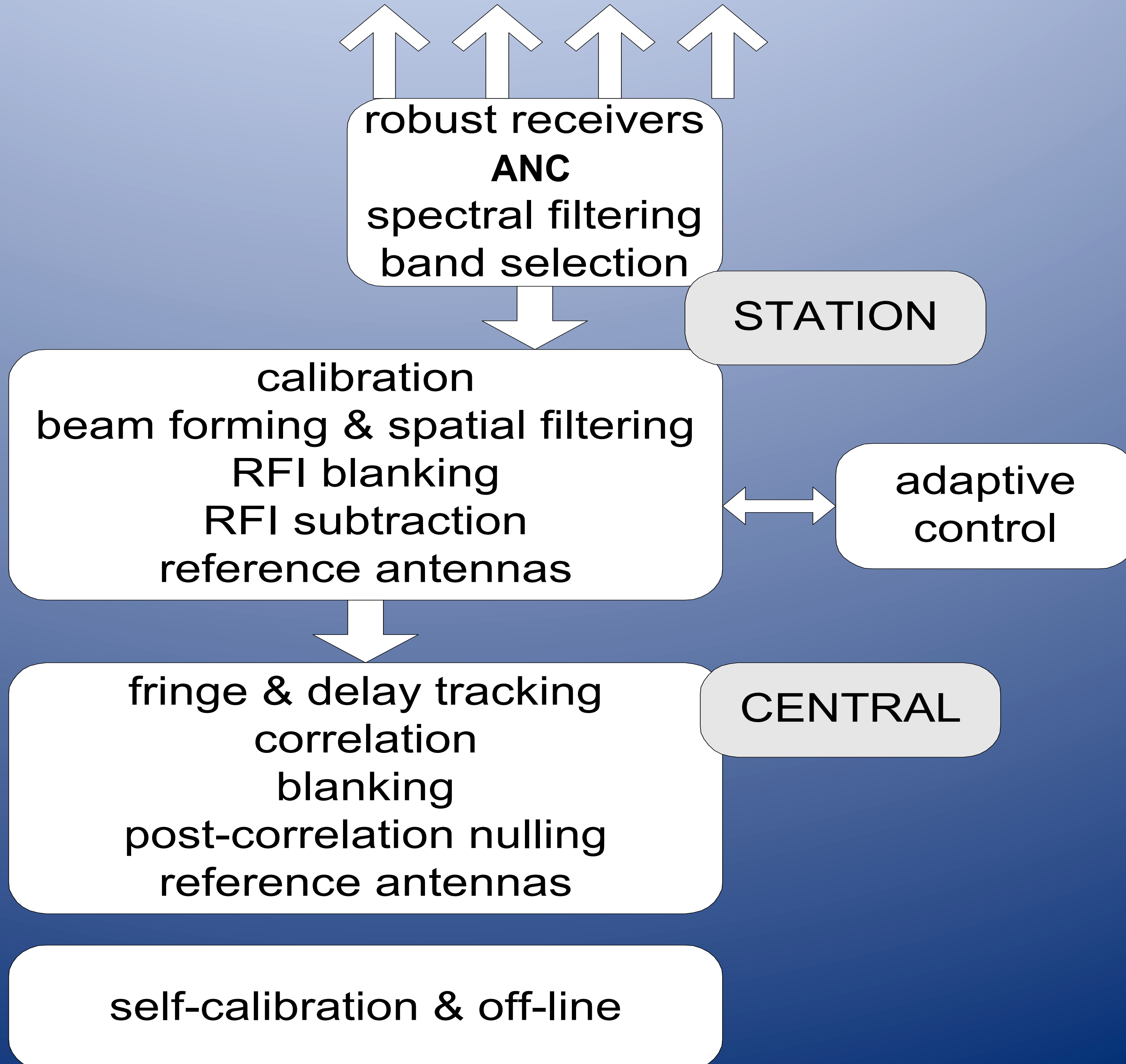
Implementation at Telescopes

- Increased processing capability => filtering (excising) with high temporal (μsec) and frequency (< 1kHz) resolution
- Reference/auxiliary antennas (for each RFI source) require (complex) system or correlator integration
- Some methods require modifications of existing spectrometers
- Future spectrometers may also determine higher stat moments

- Interferometers are less vulnerable
- Fringe-stopping and de-correlation by delay-compensation give natural suppression of weak RFI
- Strong RFI adds to system noise and affect complex visibilities
- Require accurate bookkeeping of weights for later processing

- VLBI - RFI affects calibration data at each site
- VLBI – do as required for SD telescopes

RFI mitigation strategy



Evaluation

- Quantitative evaluation of performance not always possible
  - RFI algorithms generally non-linear processes
  - 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 of steps
  - but rather sum of what is practically possible at each step

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

Conclusions

- There is no universal method for RFI mitigation
- Choice of method depends on RFI characteristics and RT and type of observation
- Successful mitigation at different stages of data taking process both on-line and off-line
- Continued implementation RFI mitigation in new and existing single-dish and array instruments
- Looking forward to next generation instruments (?)

  => LOFAR & SKA & pathfinders & LWA & MWA
- Observatories & astronomers must address RFI mitigation issues
  - In-house and external RFI
  - Flagging is not enough anymore

- Increase acceptance of RFI mitigation by the users
- Spectrum management and RFI mitigation need more recognition