RFI Mitigation Strategies for LOFAR and SKA

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Implementing Mitigation Hardware

- various locations in data flow of system
- results are limited by INR in data or by strongest source in the field
- different algorithms at different stages of the data flow after integration
- eliminate RFI as early as possible
- stacking of methods (non-linear process)
- automatic choice of algorithm or method
  - AI decision-making subsystem for control
- impact on system design and processing path
**Methodologies**

rejection in temporal domain
- strong & short bursts

rejection in frequency domain
- if no information in rejected channels

spatial filtering / nulling
- using the difference of direction-of-arrival of signal & RFI
- adaptive interference cancellation similar to adaptive noise cancellation (ANC) for SD telescopes (reference antennas)

best method depends on type of telescope, type of observations, type of RFI, and S/N of signal

there is no universal method
LOFAR RFI Mitigation Strategy

Strategy differs with strength of RFI

- robust receivers
- ADC
- spectral filtering
- band selection

STATION

- calibration
- beam forming & spatial filtering
- RFI blanking
- RFI subtraction
- reference antennas

CENTRAL

- fringe & delay tracking
- correlation
- blanking
- post-correlation nulling
- reference antennas

- adaptive control

- self-calibration & off-line
ASTRON Studies

Station & pre-correlation processing (On-line & Off-line) using real data (1998 - now)
Test systems w Signatec DSP & Altera FPGAs
(Fridman, Millenaar & Baan 2001, 2004, other papers)

1. Excision in time-frequency domain thresholding
2. Excision using filtering techniques
3. Adaptive interference cancellation using reference channels (two telescopes)
4. Spatial filtering with sparse arrays
5. Excision based on probability distribution analysis of the power spectrum HOS
ASTRON Studies

Work started mid-nineties
EU funded NoEMI project (1998 - 2003)
(Boonstra, van der Veen & Leshem & others 2001, 2002 & other papers)

Pre-correlation:
blinking algorithms of short blocks of WSRT data

Post-correlation processing:
WSRT simulation with manipulation of complex matrix
plus correction of deterioration of beam
(RFI nulling)
Use of separate reference antennas (THEA tile)
Non-real-time processing
RFI suppression due to fringe stopping,
a) $\delta = 10^\circ$, b) $\delta = 40^\circ$, c) $\delta = 80^\circ$, 
baseline=$2.7km$, $d = 25m$, $f_0 = 1420MHz$
Early results using statistics analysis

a) injection of RFI dirty & clean

b) PD histograms before & after

c) Passband clean & dirty

Fridman & Baan 2001
RFI inserted on HI absorption line Crab Nebula

Power Spectrum of signal
⇒ gaussian distrib & zero mean (chi-square w 2 deg)

PS Change due to RFI
⇒ non-central chi-square with 2 deg of freedom

Processing before averaging allows separation of RFI & signal

(Fridman & Baan 2001)
## SD Applications

<table>
<thead>
<tr>
<th></th>
<th>Continuum observations</th>
<th>Spectral observations</th>
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<tbody>
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<td><strong>Weak RFI</strong></td>
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Early SD results - Ratan 600 m

Fridman 1996
Recent SD results Effelsberg 100m with new WSRT FPGA system
Effelsberg 100m - WSRT system
16 x 16 Drift maps
## Connected Interferometer applications

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Adaptive Noise Cancellation using Reference Antennas WSRT

Fridman & Baan 2001
NoEMI Spatial Filtering

Computer simulation of post-correlation spatial filtering, adapted clean with RFI beam distortion removal

Effect of spatial filtering on an artificial sky with four sources affected by RFI


a. No interference  
b. Unsuppressed interference  
c. After spatial filtering
Spatial Filtering

- Beamforming / spatial filtering simulations ("past d", LOFAR SDP)

Spatial filter applied to WSRT data (NOEMI Boonstra)
Spatial filtering

- Spatial filtering at station level with fixed null
- Simulation of 100 antenna LOFAR station beam pattern with two beams and nulls aimed at 15 degrees above the horizon.
THEA Tile as Ref Antenna
mean of autocorrelations (noise whitened)

- dashed line: before filtering
- blue line: filter w/ ref
- green line: filter w/o ref

- N_short = 32
- N_long = 16
- N_f = 64
- p = 8, p0 = 6
LOFAR & SKA Design Studies

Integration of RFI mitigation into system and impact on signal processing & design

Online calibration & RFI mitigation

[a] Online calibration & RFI Mitigation strategy (station, central).

[b] Optimal signal processing algorithms (calibration accuracy, amount of RFI rejection, RFI distortion correction)

[c] Pre-correlation beamforming and spatial filtering

Post-correlation and image formation

[a] Blanking/thresholding/algorithms

[b] Post-correlation spatial filtering, relation to varying beamshapes, distortion corrections.

Lessons from current studies

1) Encouraging results for on-line & off-line data processing & theoretical & computer simulations

2) RFI mitigation algorithms often non-linear procs

3) Suppression of RFI signal with certain method depends strongly on INR and spatial, temporal, & spectral characteristics ⇒ characteristics change after each stage of suppression

4) Gain (& loss) do not add linearly for different stages

5) Applicability depends on telescope type & backend

6) Processing gain & loss in SOI varies with methods ⇒ practical limits depend on INR & max order of 20+ dB
RFI Mitigation Strategy Layering of methods

- Robust receivers
- ADC
- Spectral filtering
- Band selection

- Calibration
- Beam forming & spatial filtering
- RFI blanking
- RFI subtraction
- Reference antennas

- Fringe & delay tracking
- Correlation
- Blanking
- Post-correlation nulling
- Reference antennas

- Self-calibration & off-line

- STATION
- CENTRAL
- Adaptive control
Conclusions

1. SD & connected interferometer tests show that the real-time RFI mitigation works successfully.
2. Algorithms effectiveness varies with situation = adjust algorithms
3. RFI MS implementation on existing RT hardware can be difficult
4. Integration of RFI mitigation subsystems in SKA & other RTs is a must. RFI mitigation post-processing (multi-bit ADC (>14)), short averaging intervals, higher-order statistics, auxiliary reference channels).
5. Complexity and effectiveness of RFI mitigation algorithms depend on high-performance number crunching components (also needed for other things)
6. Develop universal computing platform for processing & RFI mitigation