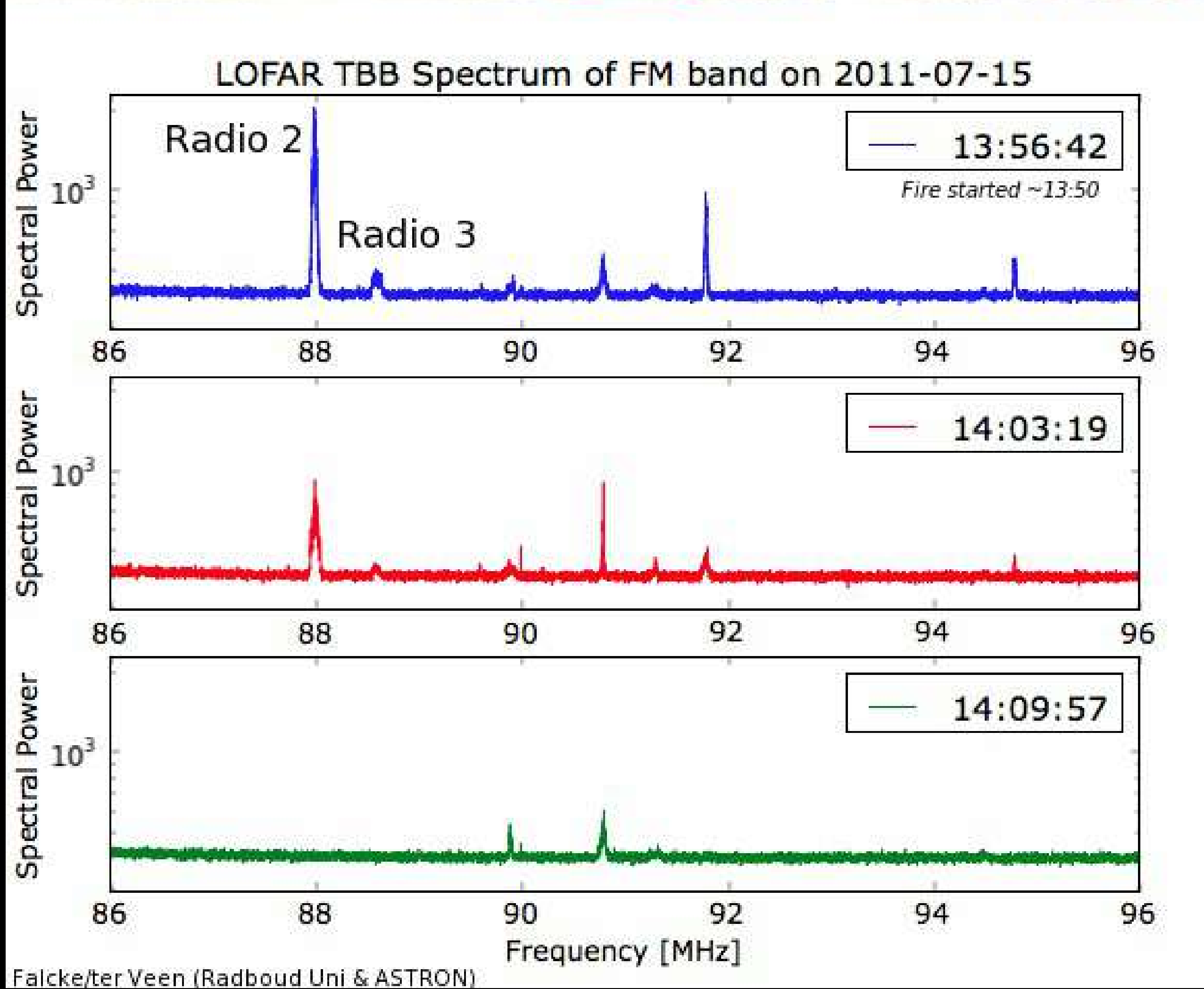
Active RFI mitigation



Resources

RFI 2001 — Bonn, Germany
http://www.iucaf.org/MitigationWorkshop01/RFI_new.htm

RFI 2004 — Penticton, Canada
https://www.faculty.ece.vt.edu/swe/RFI2004/

RFI 2010 — Groningen, The Netherlands
https://www.astron.nl/rfi/

RFI 2016 — Socorro, NM, USA
go.nrao.edu/rfi2016

RFI 2019 — Toulouse, France
https://rfi2019.sciencesconf.org/

RFI 2021 — London, UK
TBA

RFI in radio astronomy – impacts

RFI can have various impacts on astronomical data:

- Mask signal of interest (up to 10^9 stronger than astronomical sources)
  - Spectral lines / polarization
  - Non–repeatable transient experiments
- Mislead observation interpretation or false positives (transients, SETI…)
- Loss of data
  - Increases operational cost
  - Reduces instrument sensitivity / availability
- Calibration solution unsolvable
  - Mimics artificial additional sources
  - Time–critical calibration (pulsar timing)
- System deterioration

Goals of (active) RFI mitigation

- Reduce corruption of astronomical data
- Capture useful data outside astronomy bands
- Improve instrumental calibration
- Train next–gen astronomers to advanced signal processing methods
- Prepare for future threats:
  - Broadband "spread–spectrum" transmissions
  - Dynamic Spectrum Access
  - New technology (CubeSat, 5G…)
- Enable low–SNR science at any INR

It is NOT

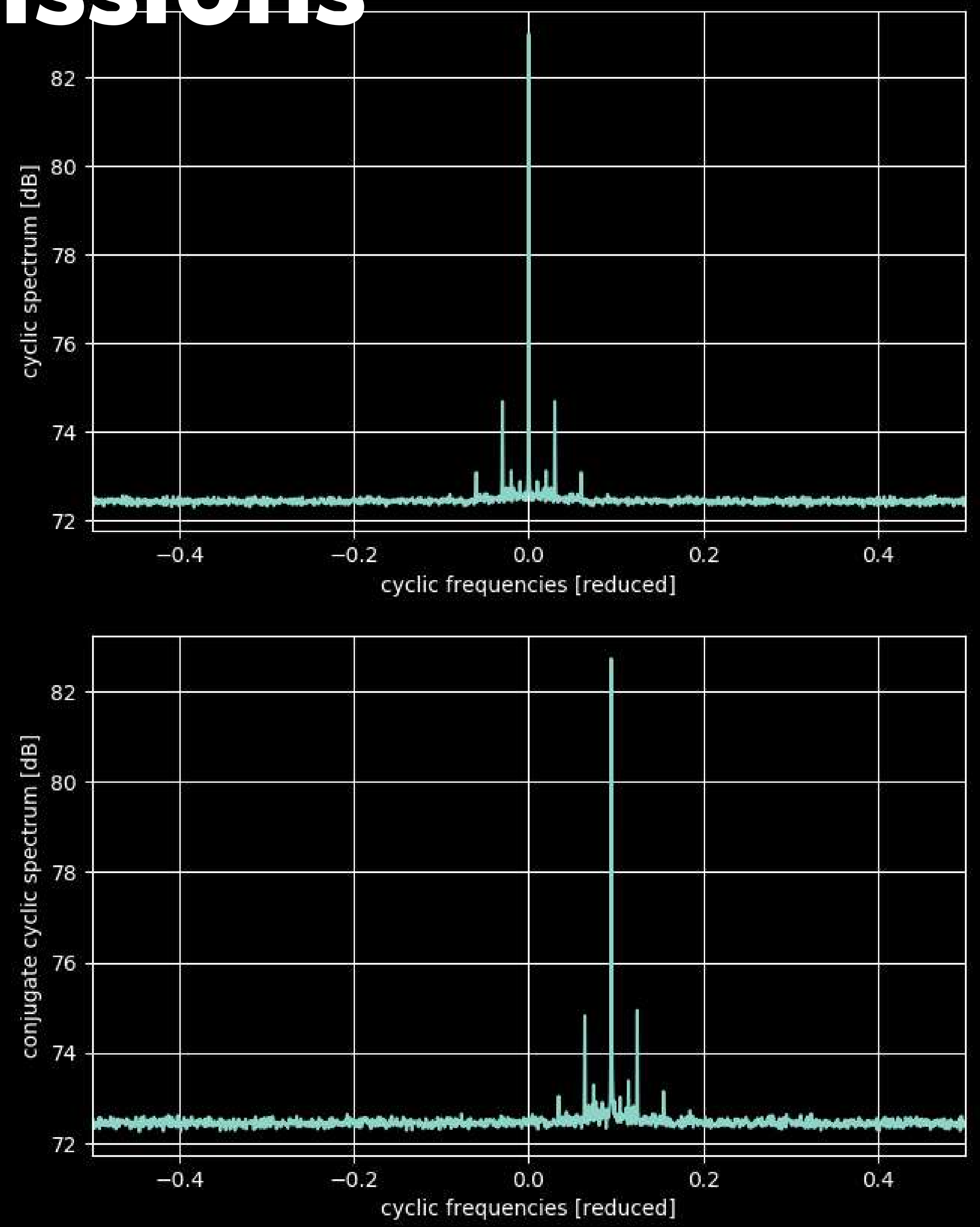
- Easy!!
- Satisfying
- Excuse to utilize astronomical resources

RFI vs Natural emissions

RFI is (luckily) distinguishable from natural astronomical emissions

Exploitable signal features include:

- **Interference–to–Noise Ratio**
- **Higher–order statistics**
- **Polarization**
- **Non– / cyclo–stationarity**
- **Non–circularity**
- **Signal bandwidth**
- **Sparsity**
- **Dispersion**
- **Near– / Far–field**
- **Spatial location**
- **…**



What do we want?

What do we want?

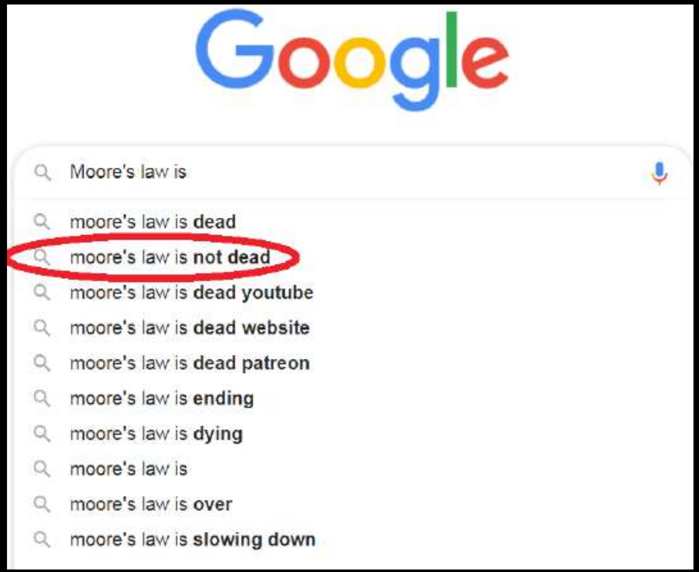
- **Ideally : trustworthy science–ready data products (incl. RFI mitigation and calibration) produced on–the–fly (RFI mitigation–enabled radio telescope)**
- **OR : Accurate offline blind cleaning (if storage allows)**
- **OR : Supervised offline blind cleaning (if storage allows and expert eye available)**
- **...**
- **OR, worst case : everything that's possible to address science case**

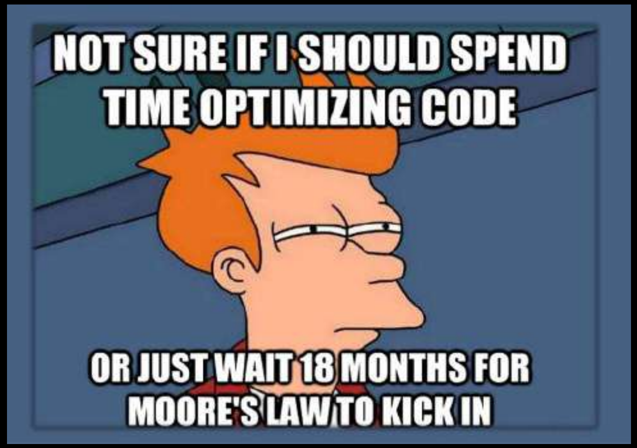
RFI mitigation is instrument–dependent:

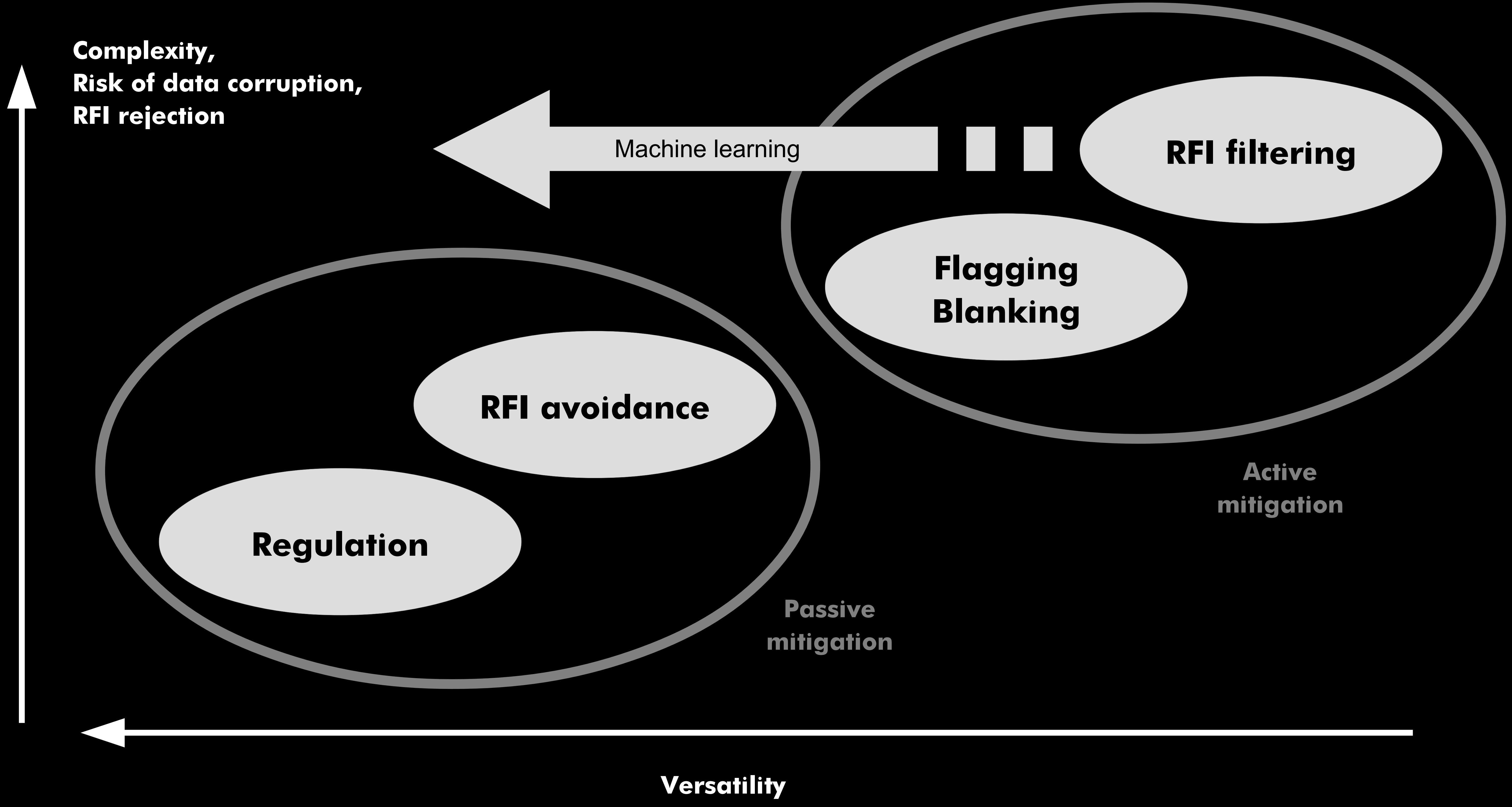
- **Infrastructure? (single dish / array, reference antenna / RFI monitor, data center / fast signal processing platforms...)**
- **What recurring RFI? Pulsing? Continuous? Narrow–/Wide–band?...**
- **What are the risks? (receiver saturation? Calibration issues? False positive on rare events?)**
- **Demographic prediction? Future threats?**
- **What are the science goals?**
- **RFI mitigation requirements is science case–dependent?**

Research in RFI mitigation

- **Active field of research (radio astronomy, Earth remote sensing, telecommunication…)**
- **Many papers, conferences, proceedings….**
- **Computational complexity is limiting factor**



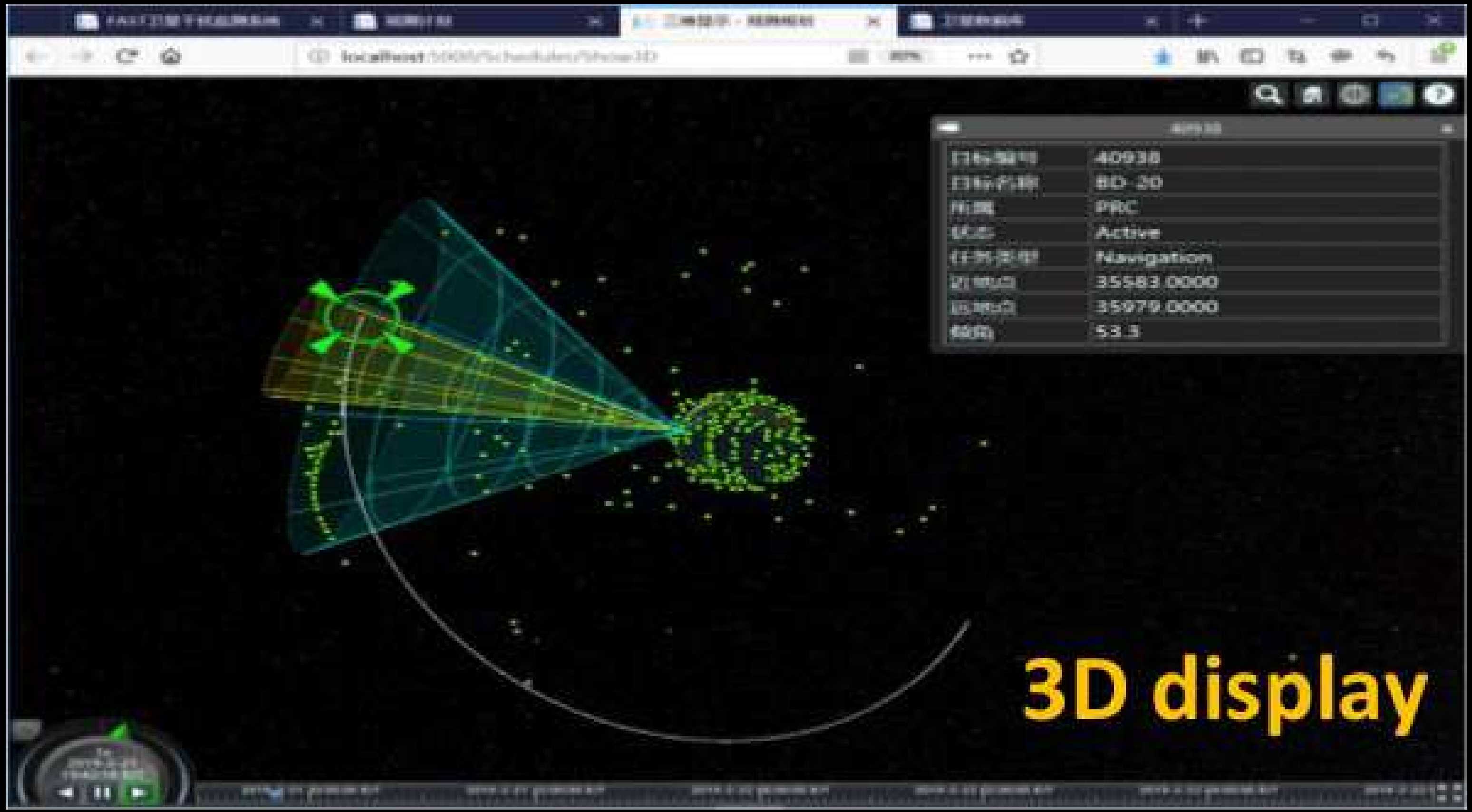


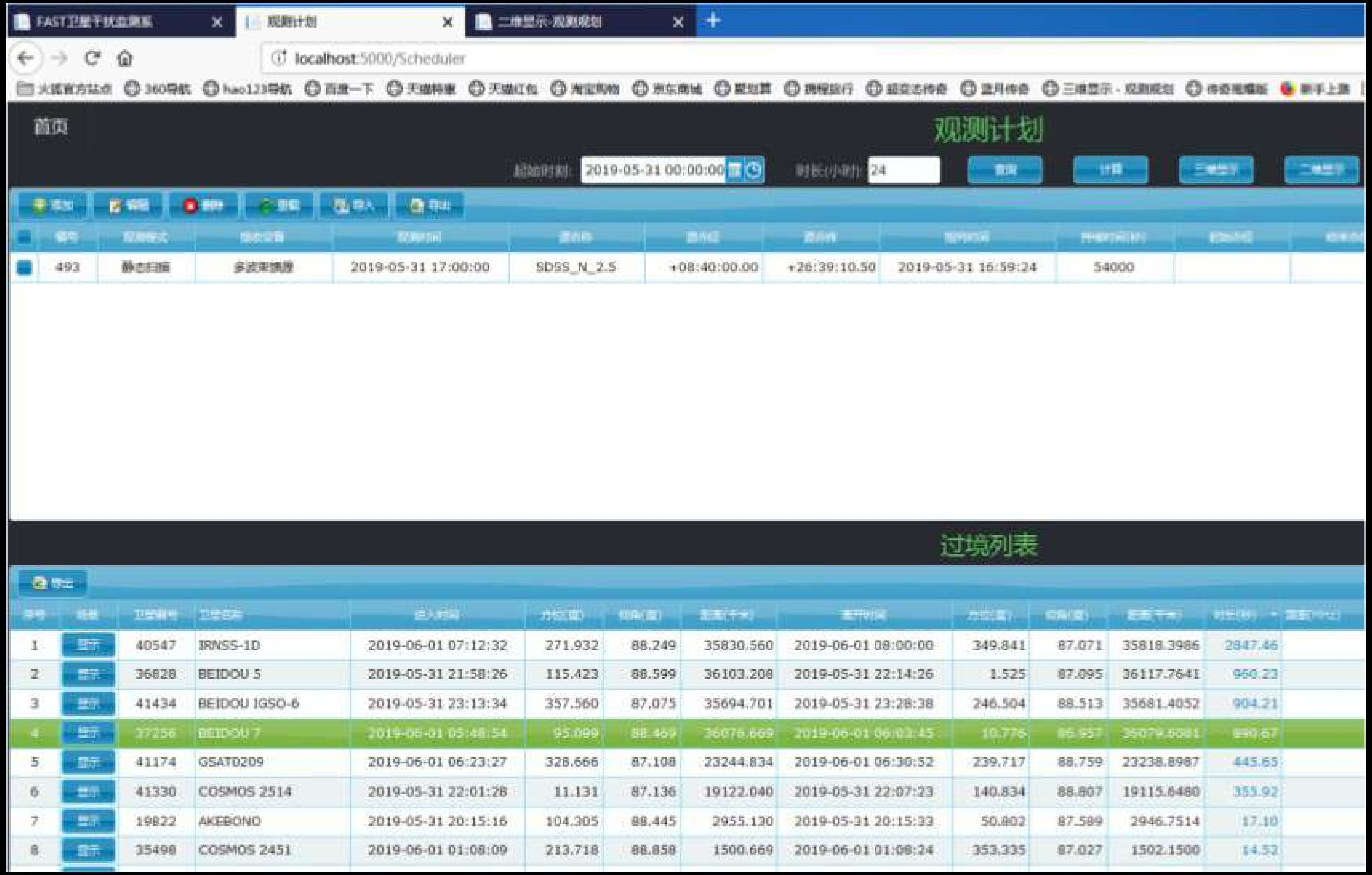

Complexity,
Risk of data corruption,
RFI rejection
Machine learning
RFI filtering
Flagging
Blanking
RFI avoidance
Regulation
Active mitigation
Passive mitigation
Versatility

RFI avoidance

Zhang et al. 2019 – unpublished

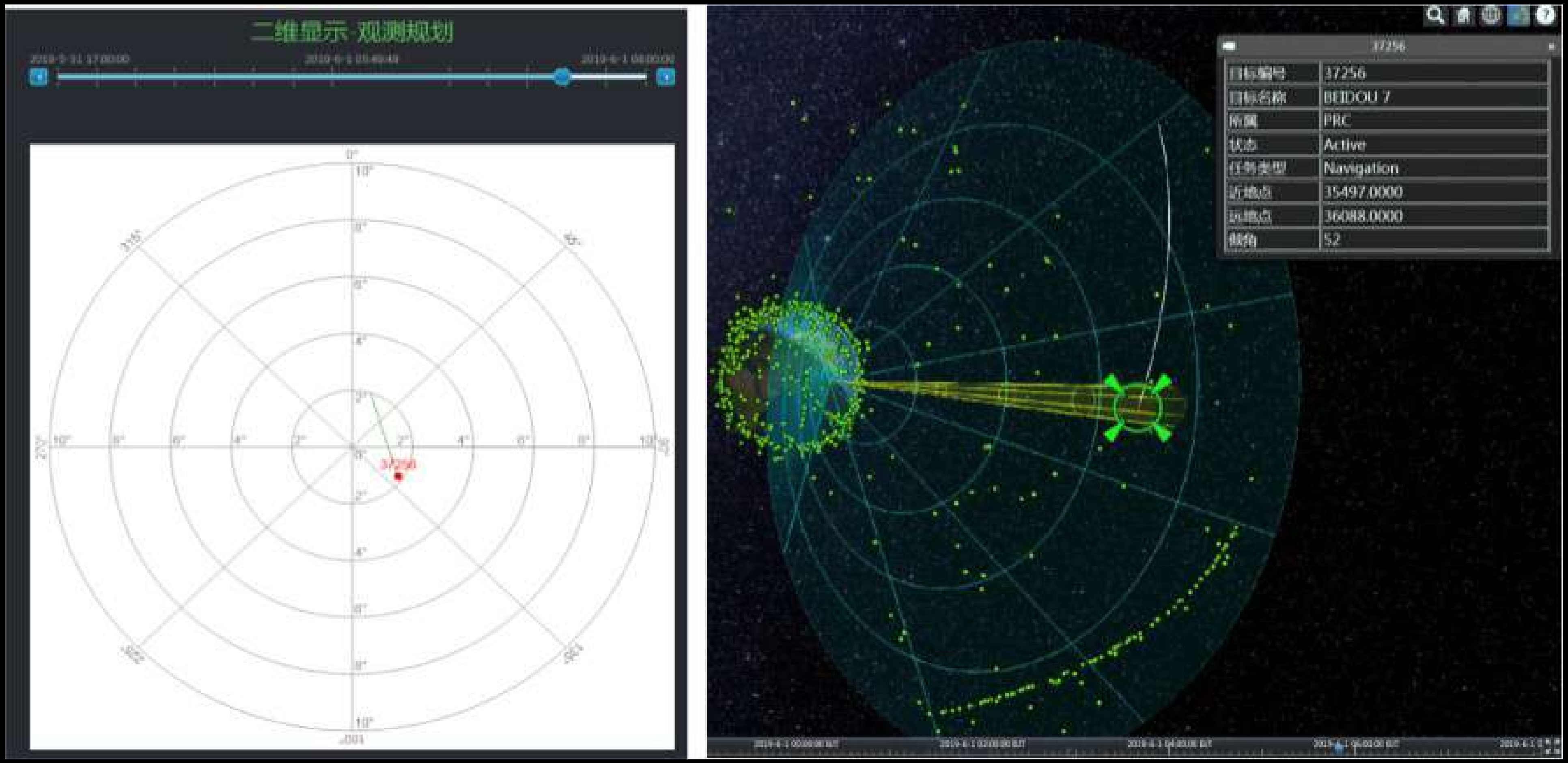
FAST NGSO satellite prediction engine allows warnings emissions within observation scheduler





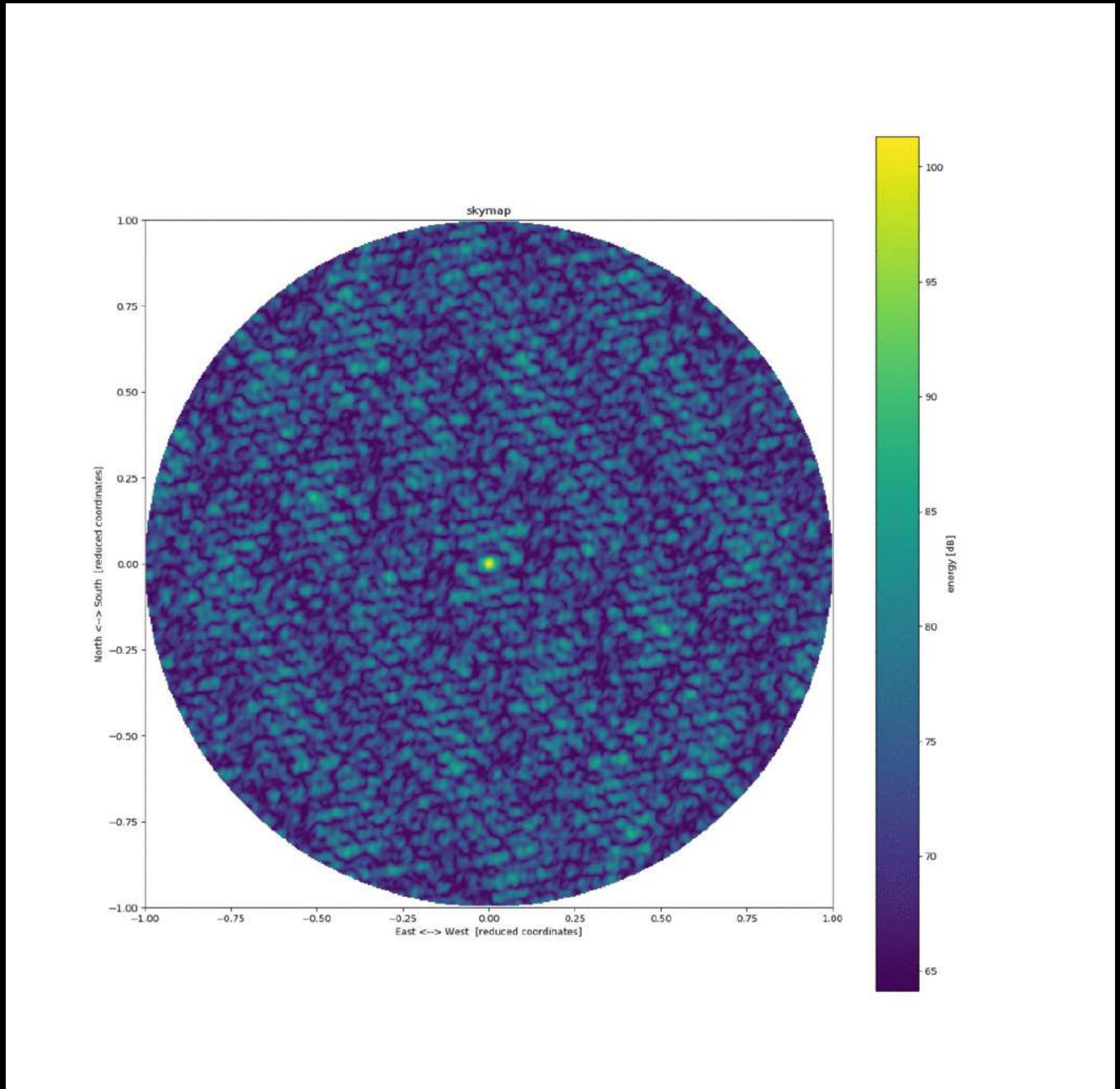
RFI avoidance

Danger: angular distance <1 degree
Attention: angular distance <2 degree



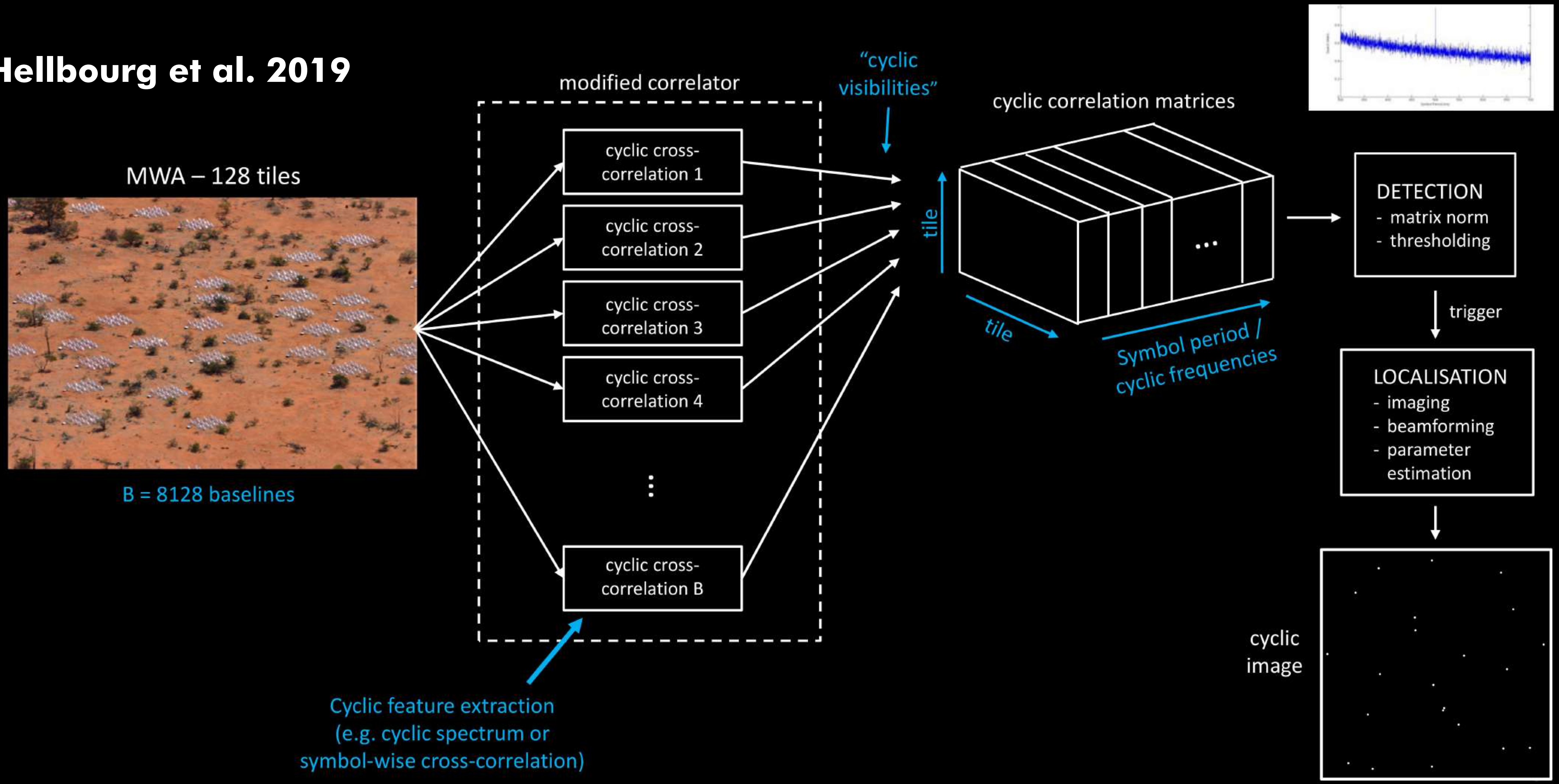
RFI avoidance – Cyclic imager

- **Cyclostationarity : temporal periodicity of statistical moments of a signal**
- **Property exhibited by most telecommunication signals**
- **Astronomical sources are stationary or non-stationary**
- **Cyclic imaging removes the contribution of all natural transmissions**
- **Allows RFI environment forecasting**



RFI avoidance – Cyclic imager

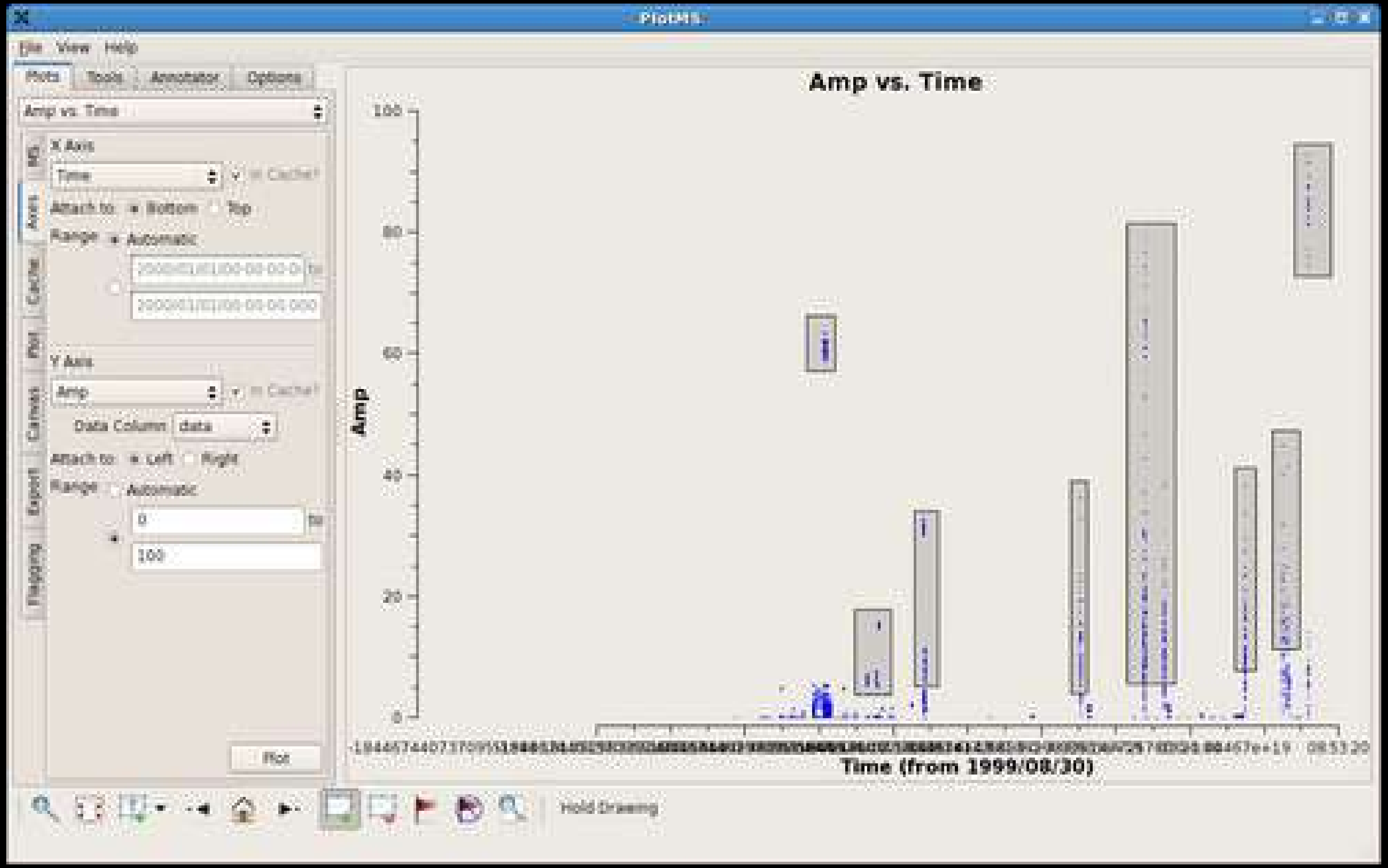
Hellbourg et al. 2019



RFI avoidance

- Rely on detection / estimation / prediction
- Informs on probability of RFI corruption
- Possibly generates “preventive flags”
- Could be associated with fully reconfigurable instrument to produce dynamic radio astronomy

RFI flagging



- Astronomer expert eye is powerful
- Error recognition is standard syllabus for astronomers
- Most data reduction software packages include manual flagging
- Not suitable for next–generation telescopes (flagging all antennas, all cross–products etc...)

RFI blind detection

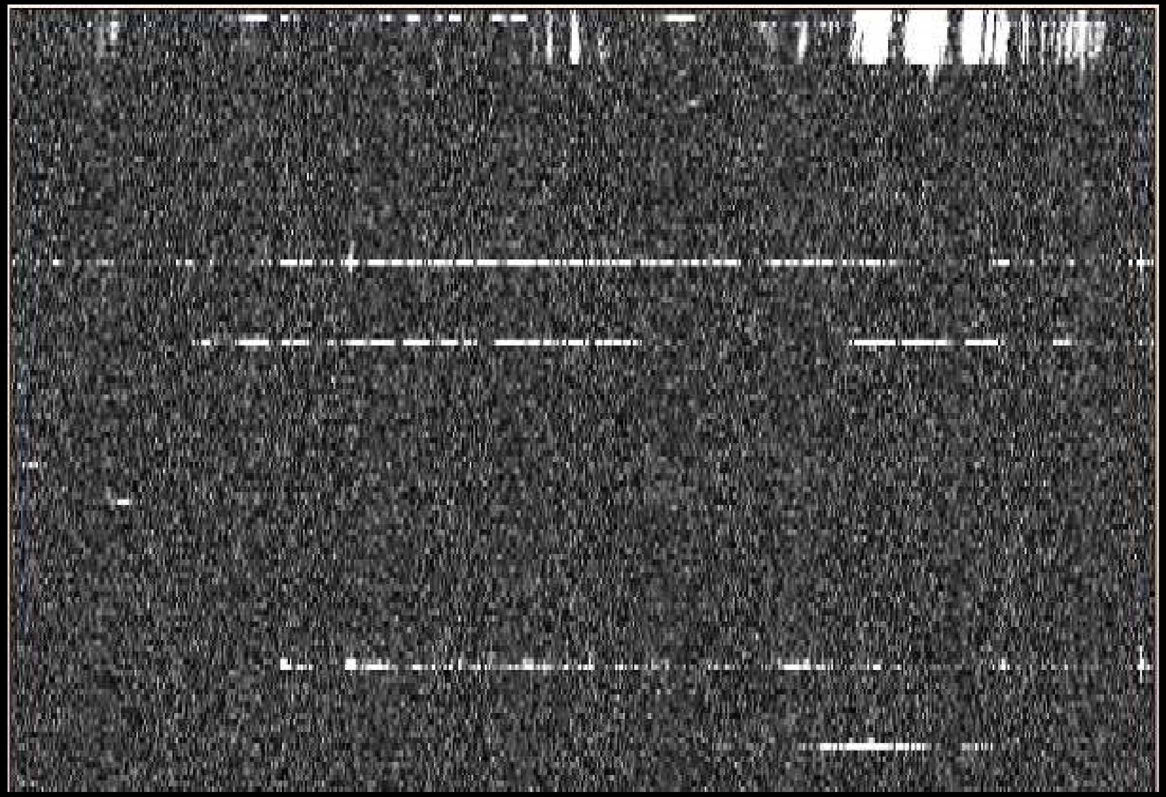
- Concept : detect statistical parameters excesses or inconsistencies
  - Corrupted data distribution deviates from normal (e.g. J. Jonas presentation) [narrow band RFI]
  - Corrupted data shows variance (~ power) excesses [wide band RFI]

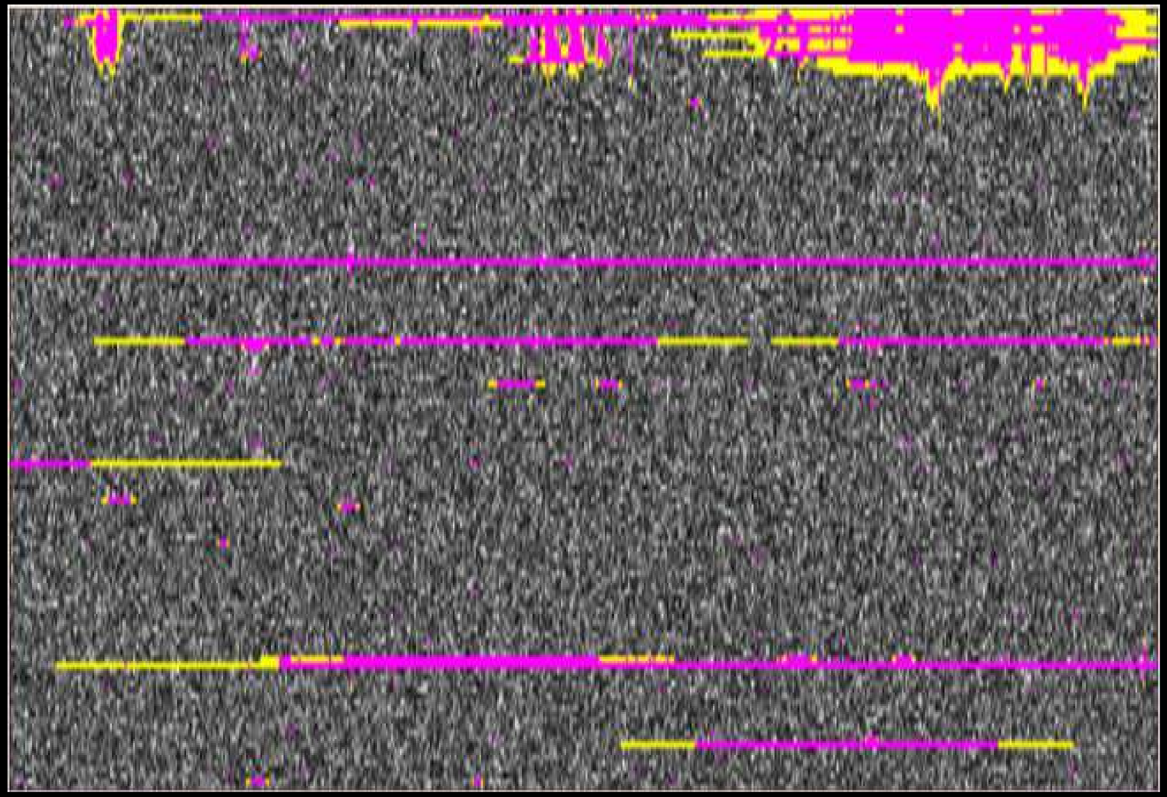
- Variance analysis:
  - easily and accurately estimated (maximum likelihood estimator = cheap implementation)
  - hard to calibrate => SNR wall

- Distribution deviation analysis
  - Higher accuracy (especially at low INR)
  - Higher computational cost (clustering or regression analysis)

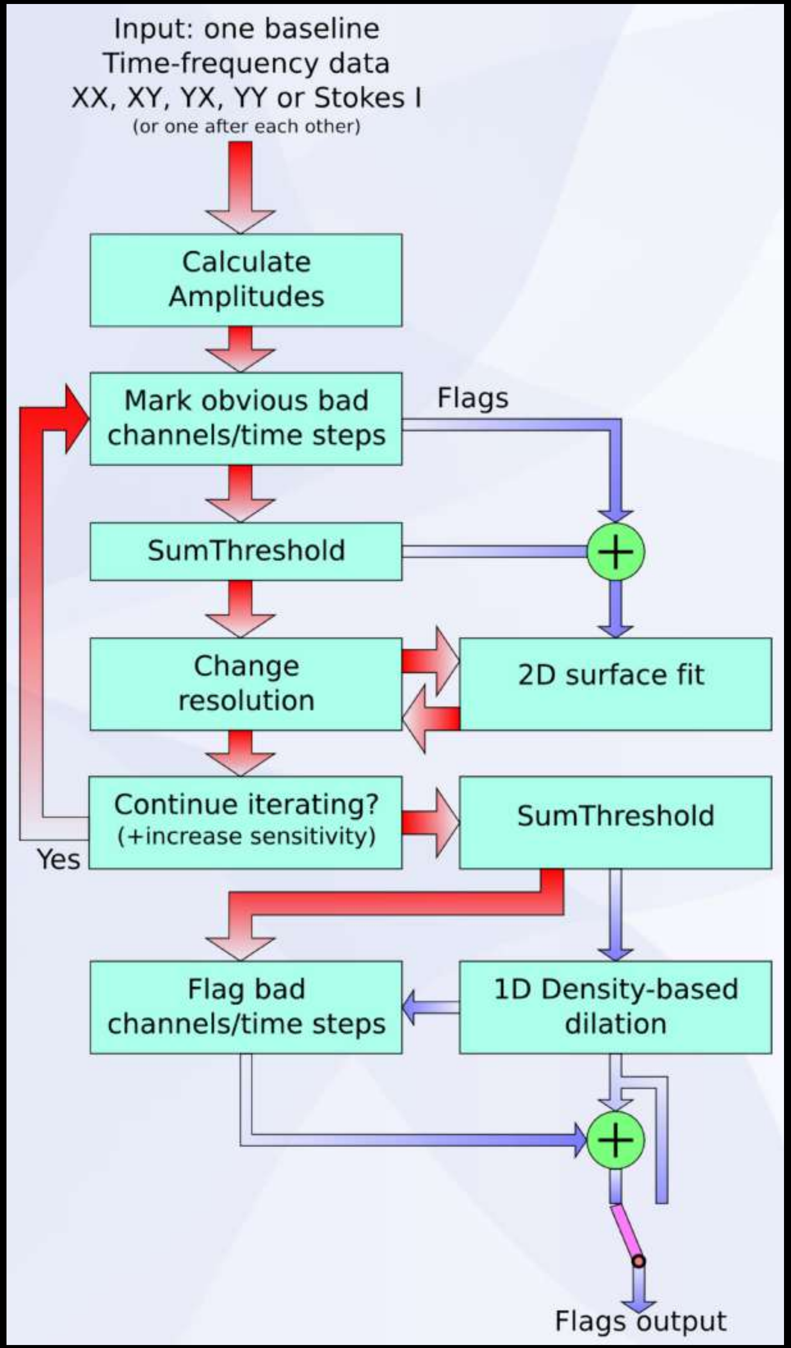
RFI flagging

- Interactive (casaplotms), semi–automatic, automatic (AOFlagger, TFCrop, RFlag)
- Applied at the antenna level, raw correlations, or UV domain
- Discard corrupted time–frequency data
- Flagging method performance = RFI detection accuracy and false detection rate
- Flagging methods based on local or global data statistics





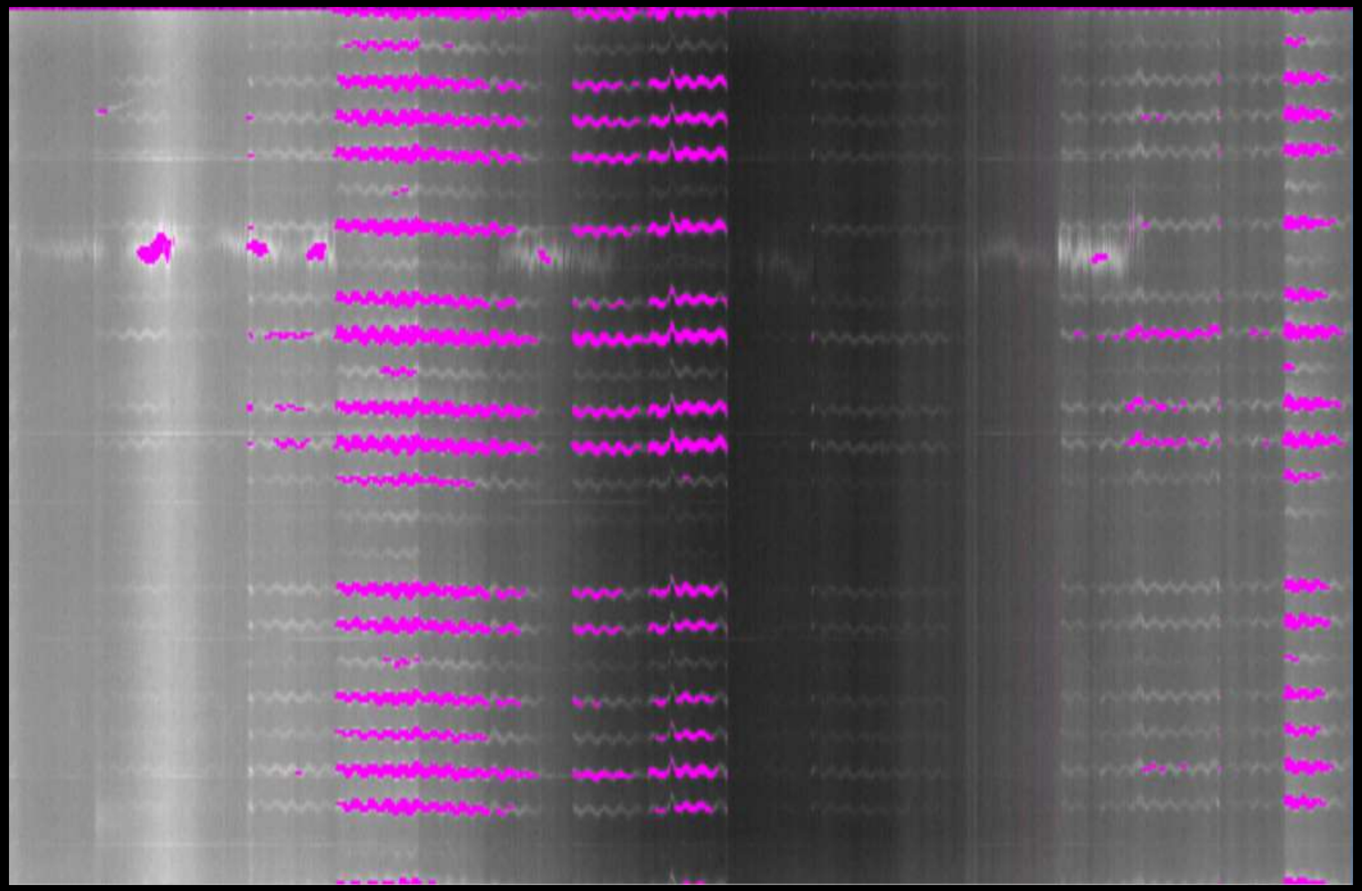
RFI flagging



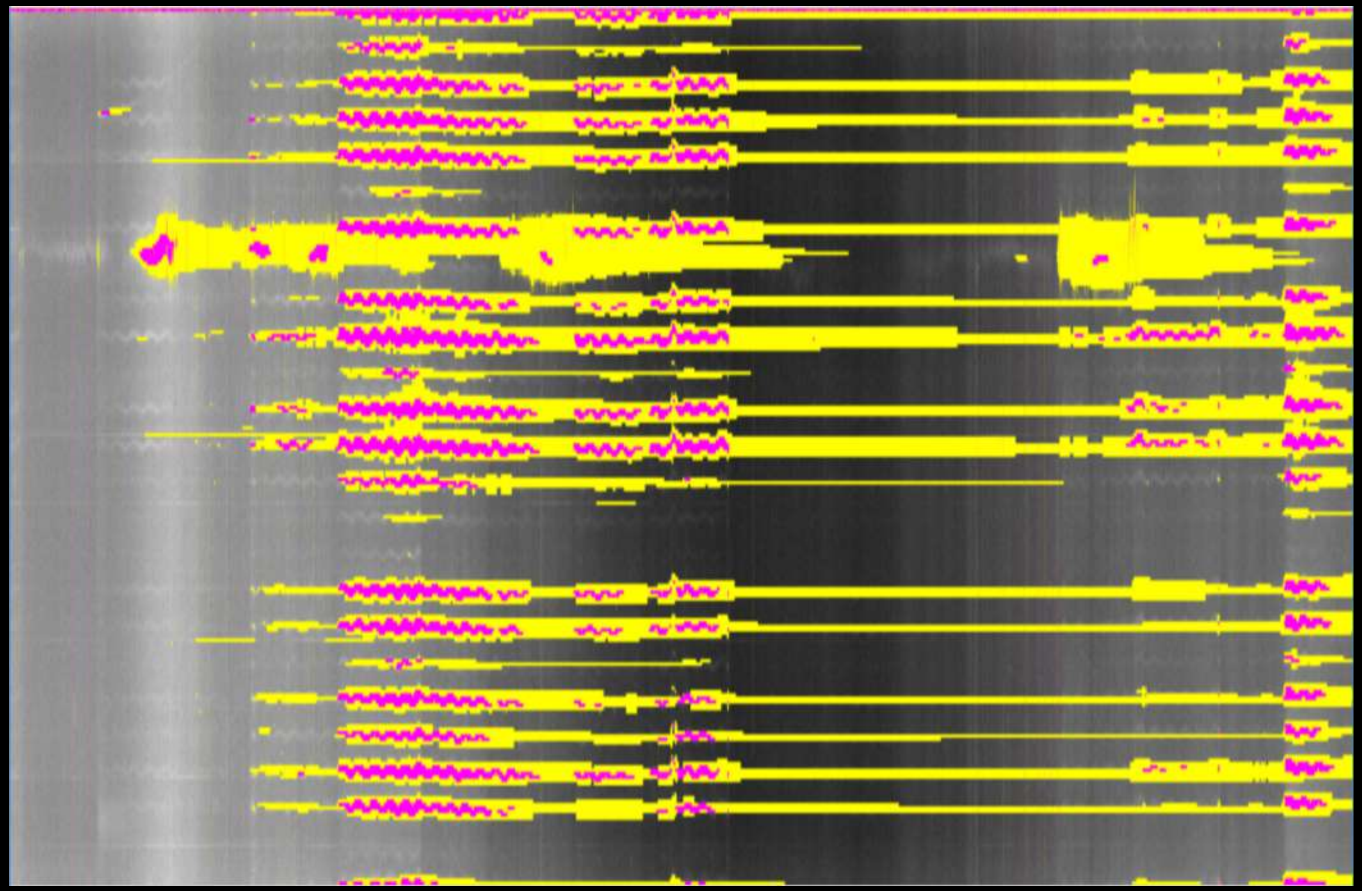
Offringa et al 2012

- **One of most offline popular flagging methods**
- **LOFAR, MWA, WSRT, JVLA, GMRT, ATCA, Parkes, Arecibo…**
- **Available on CASA / AIPS++ / Miriad**
- **Limitations coming from rapidly varying sources (Sun, transients)**
- **Can scale linearly with # of samples**

RFI flagging



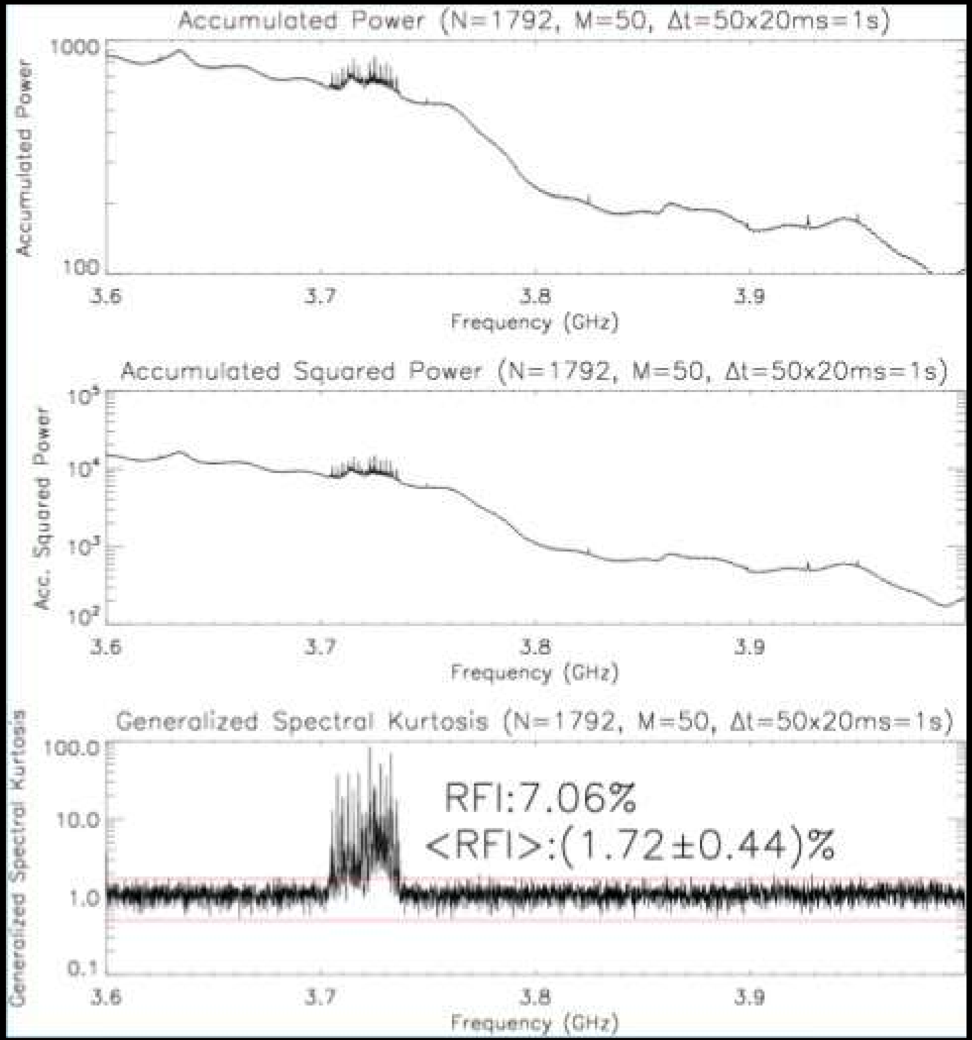
Linear complexity



Dilution
Non–linear complexity

Spectral Kurtosis

Nita et al. 2010

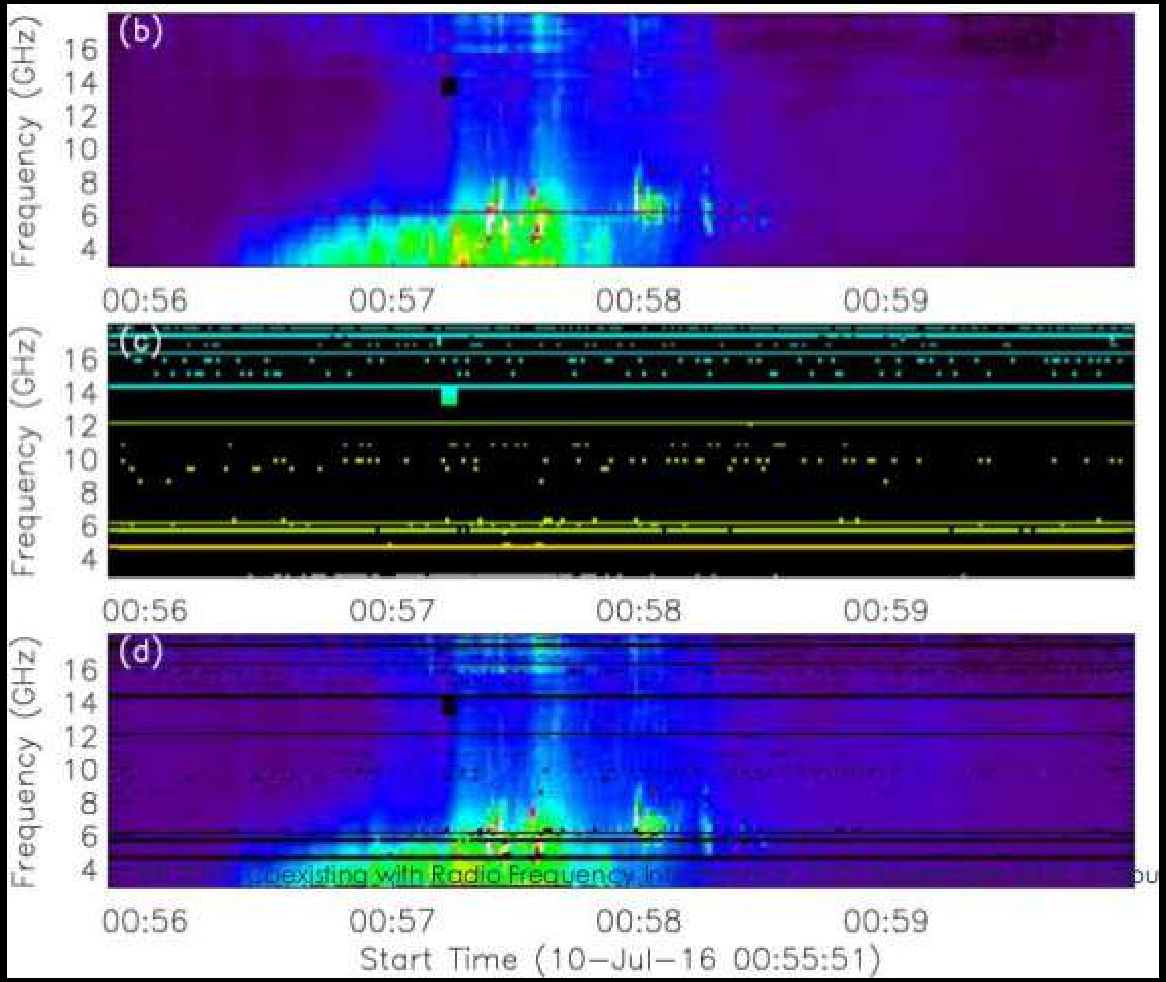


$$s_1 = \sum_{k=1}^{N} P_k$$

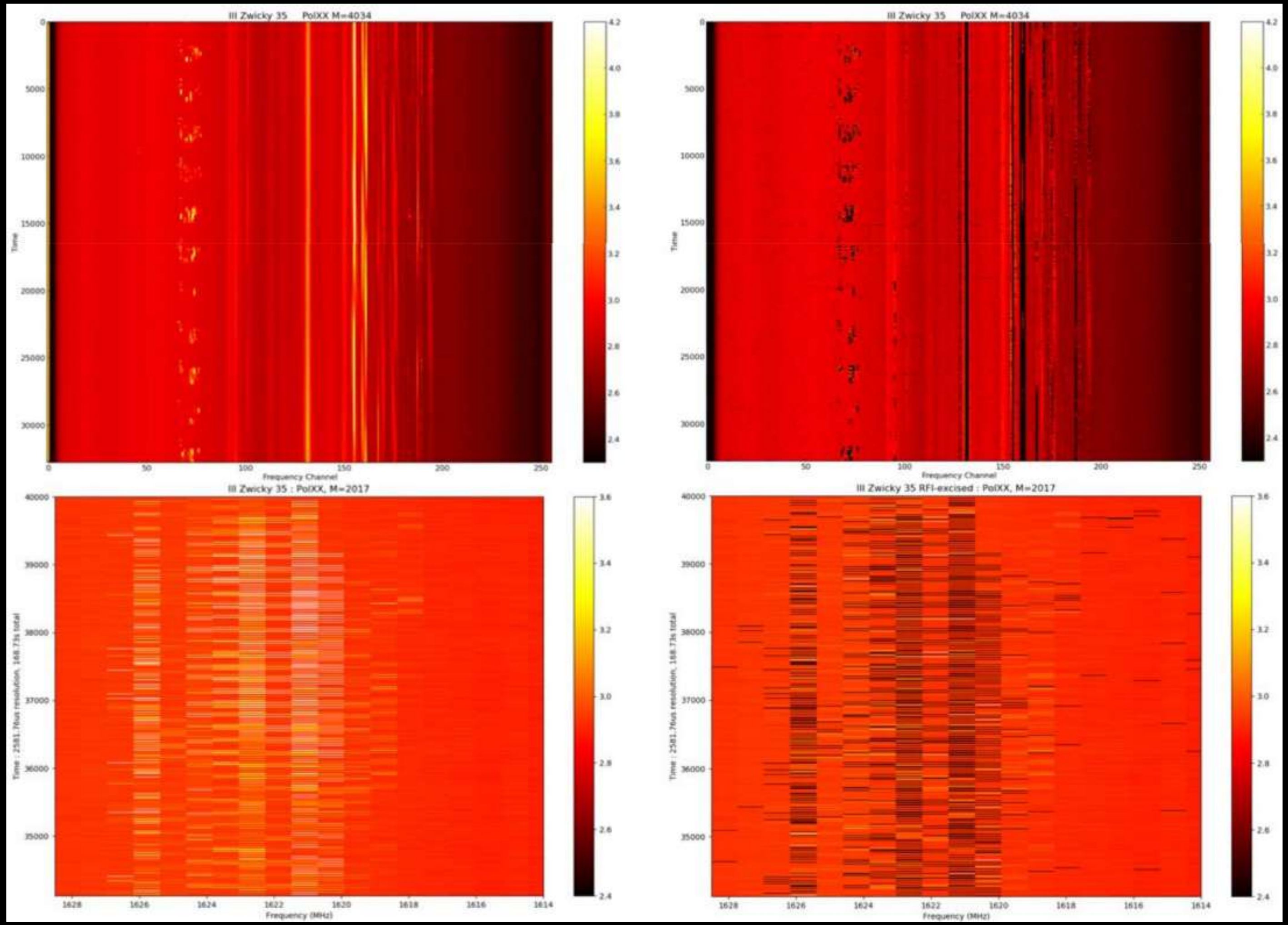
$$S_1 = \sum_{i=1}^{M} s_1$$

$$S_2 = \sum_{i=1}^{M} {s_1}^2$$

$$SK = \frac{MN+1}{M-1}\left(\frac{MS_2}{{S_1}^2} - 1\right)$$



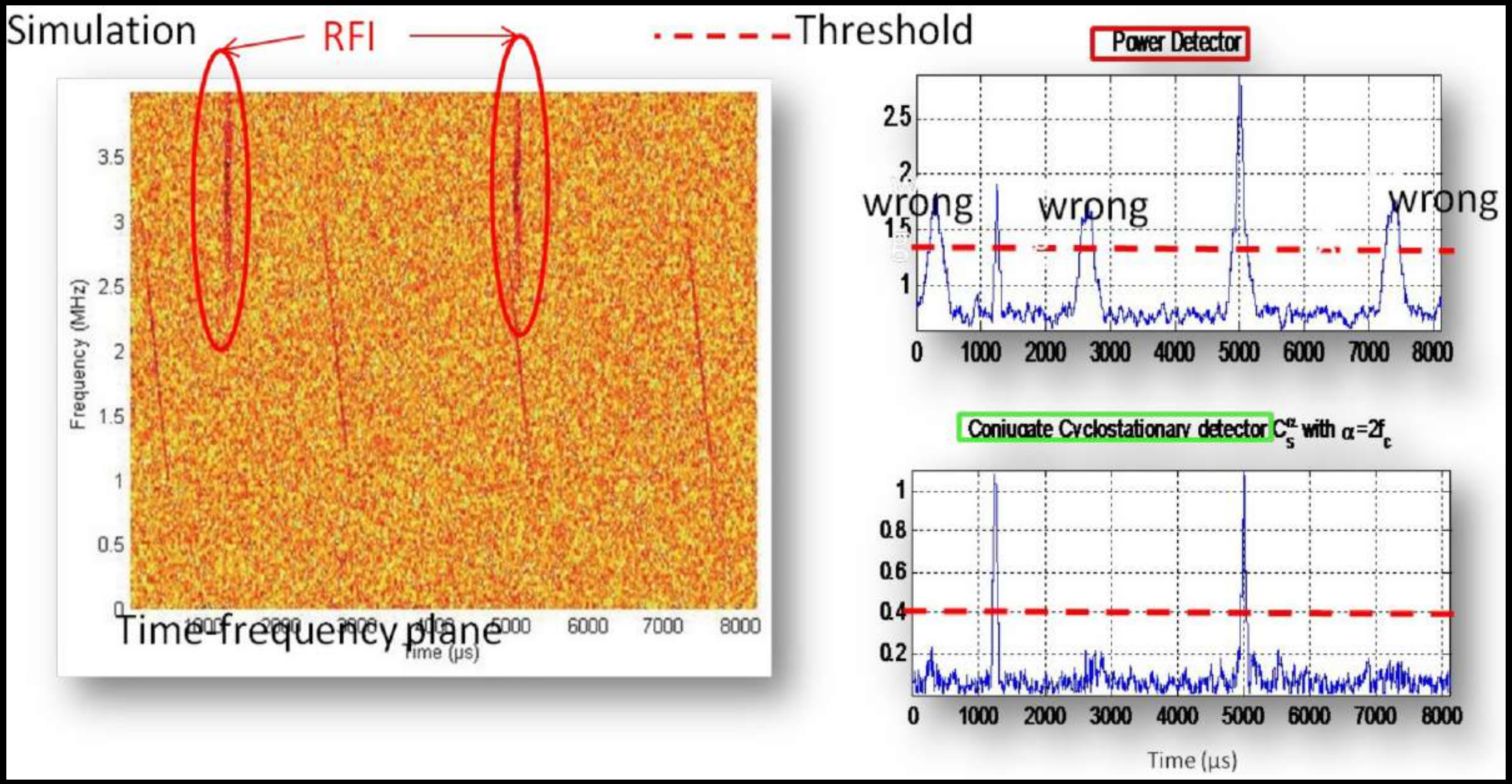
Spectral Kurtosis

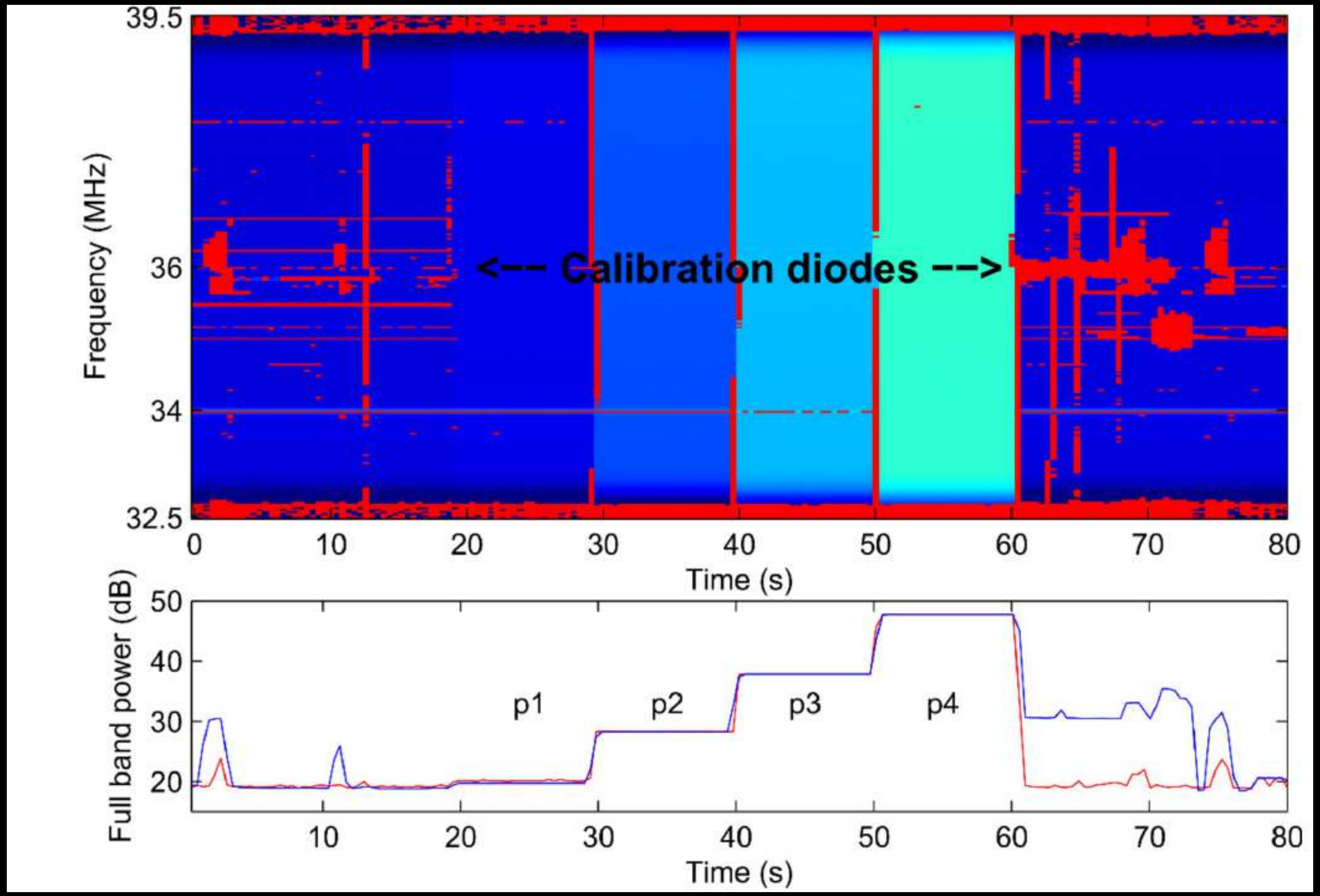


- **Good separation between astronomical and artificial emissions**
- **Multi−scale SK allows transient RFI detection**
- **Implemented at Green Bank Observatory to work on GUPPI Raw**
- **Generalized SK allows implementation on any correlation product (with loss of time resolution...)**

Cyclostationary flagger

Changuel et al. 2011
Separates cyclostationary sources (RFI) from non–cyclostationary (natural emissions)
(Nançay decametric array)

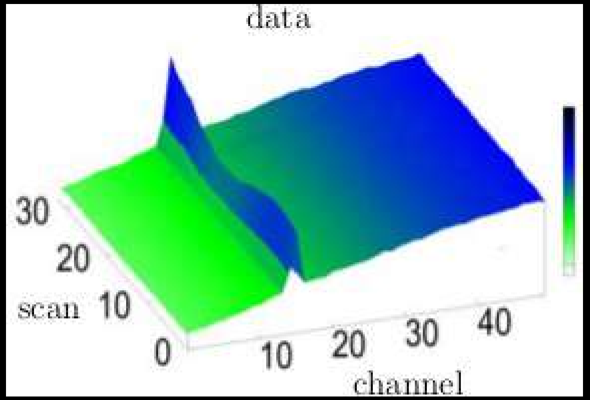


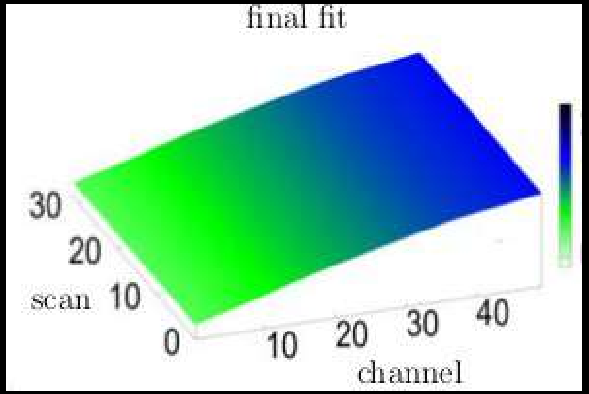


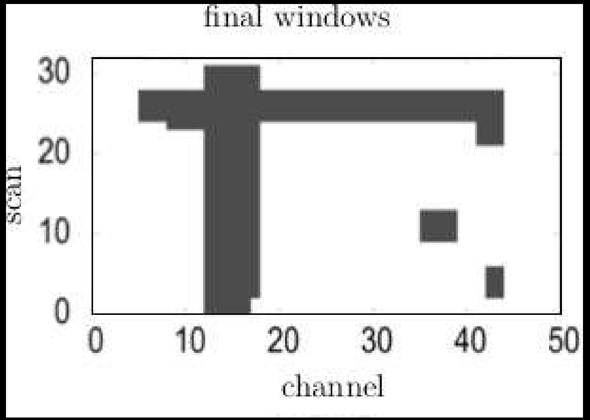
RFI excision

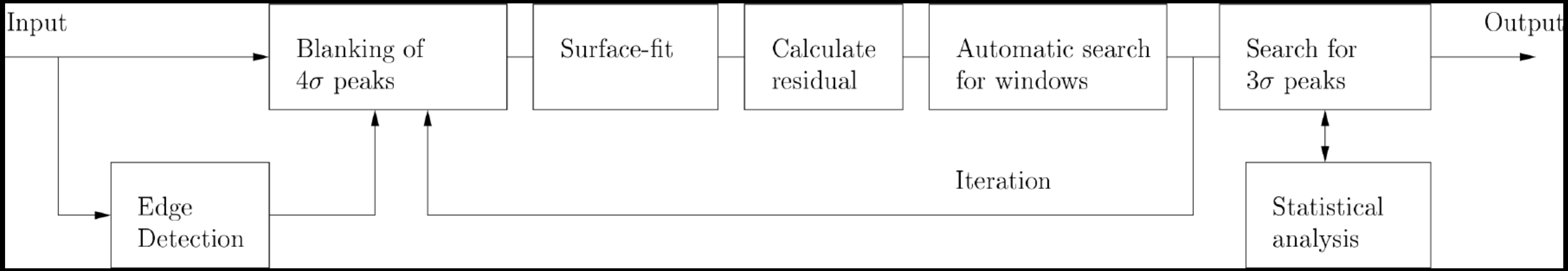
Winkel et al. 2007

- **RFI−free T−F power smoothness constraint**
- **Robust surface fitting applied to correlated data**



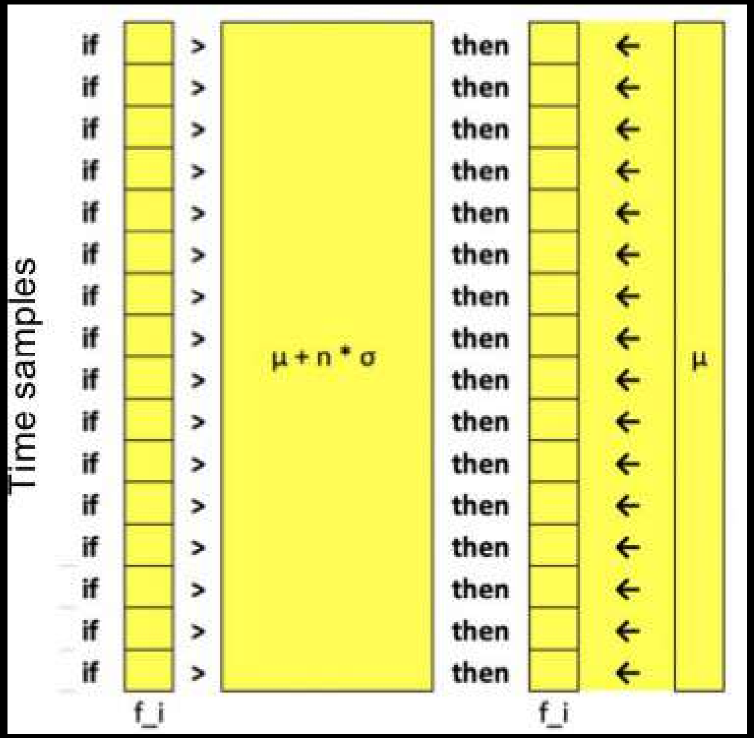


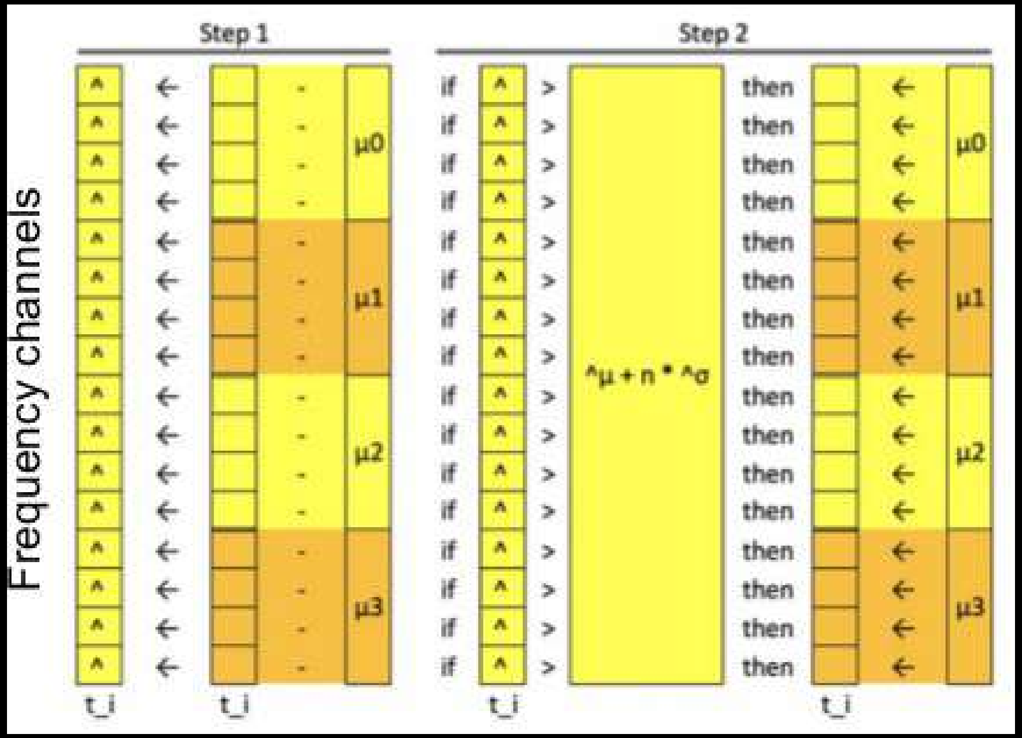


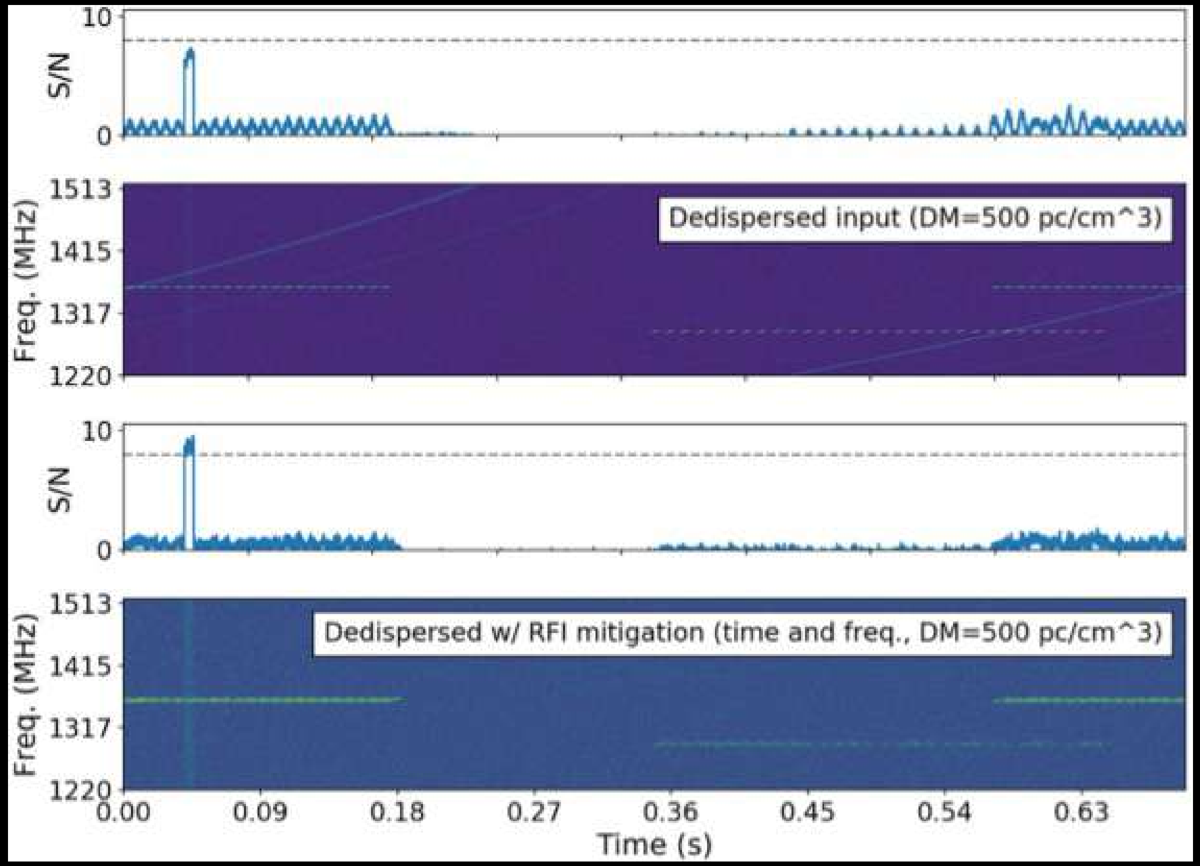


Real–Time thresholding

Sclocco et al. 2019
Developed for APERTIF FRB pipeline to reduce false positive rates

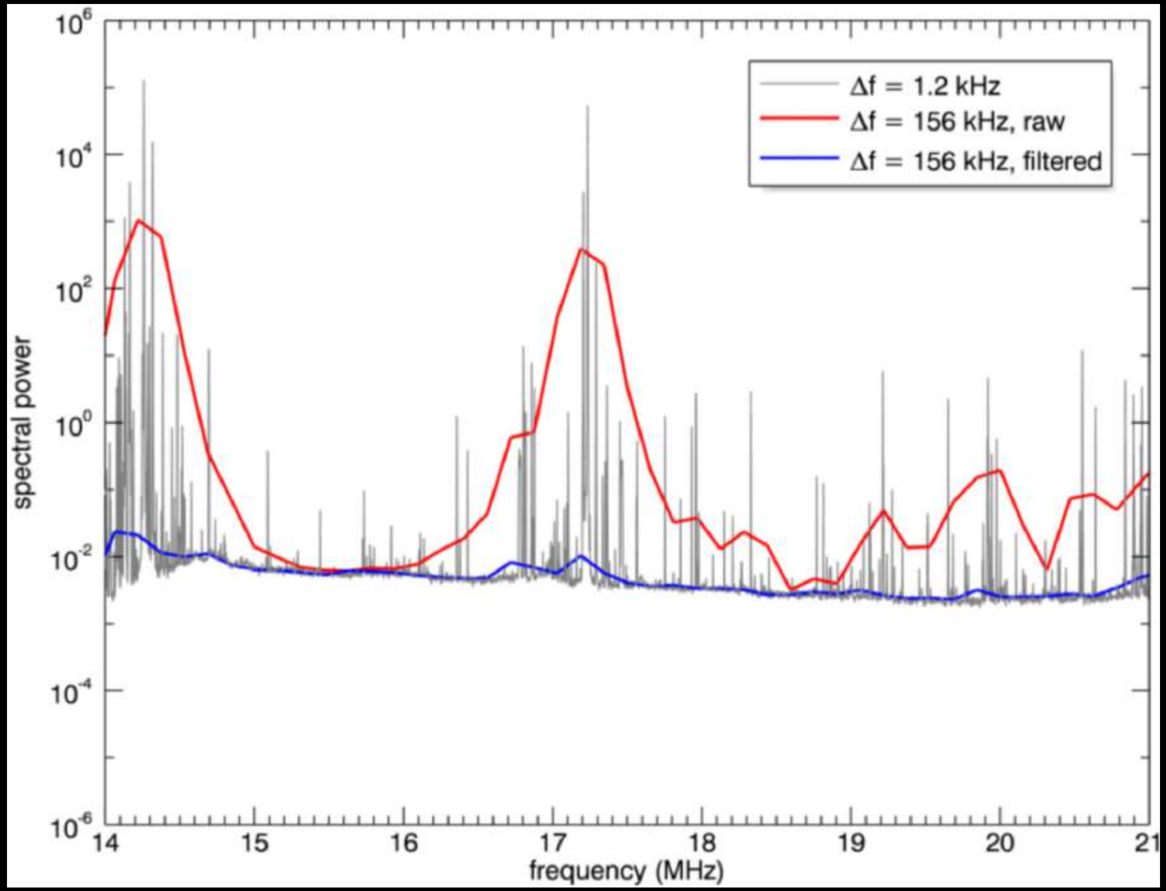






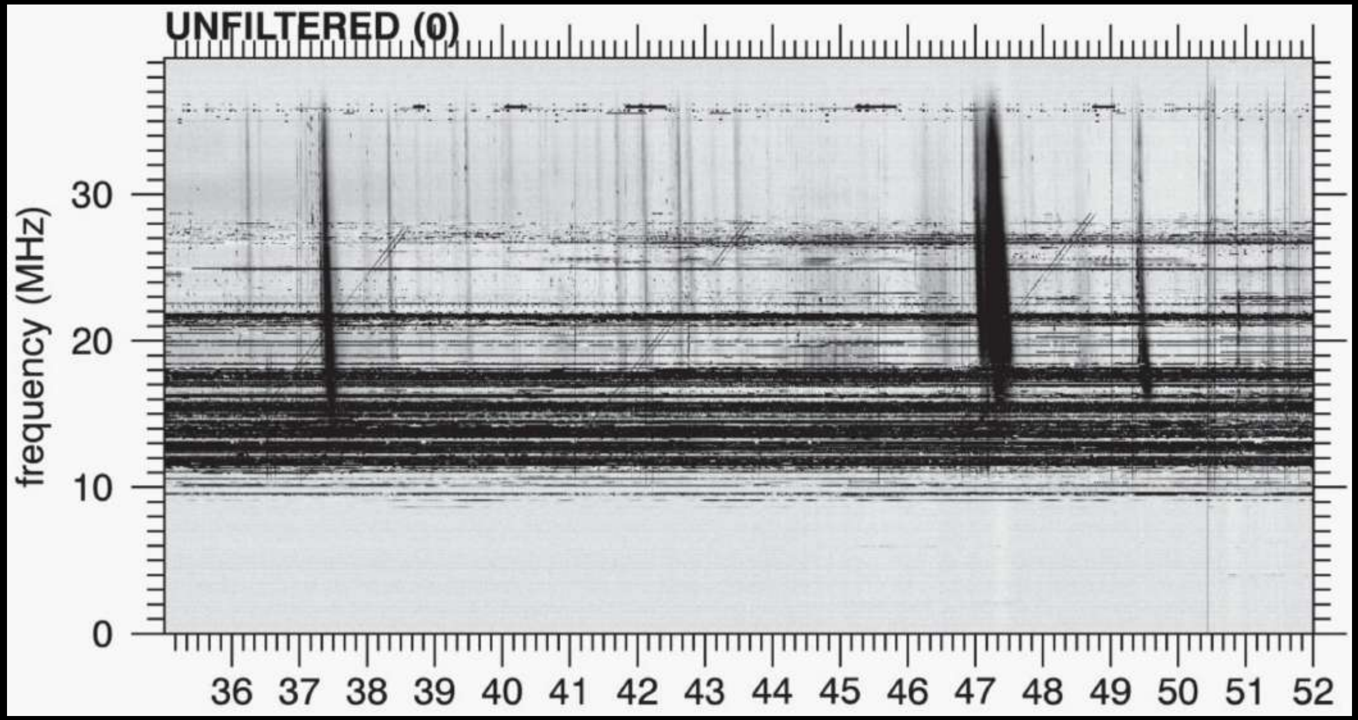
Real–time RFI flagging/blanking

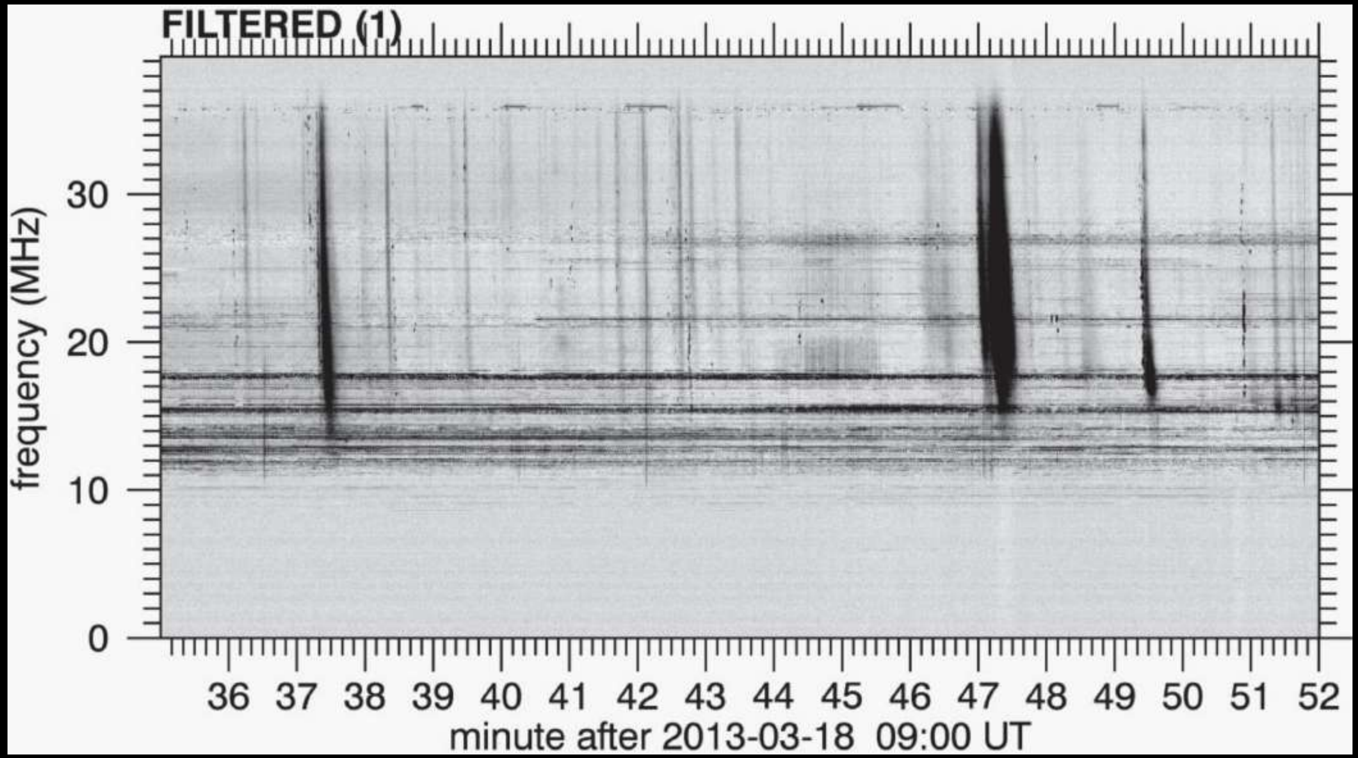
Dumez–Viou et al. 2017

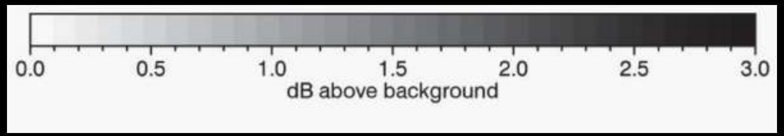


- Real–time RFI detection at “high” spectral resolution (resolutio = 1.2 kHz)
- Affected bins replaced with median value (resolution = 156 kHz)
- Produces compelling results at astronomical spectral resolution
- Real–time implementation on Nançay decameter array

Real–time RFI flagging/blanking

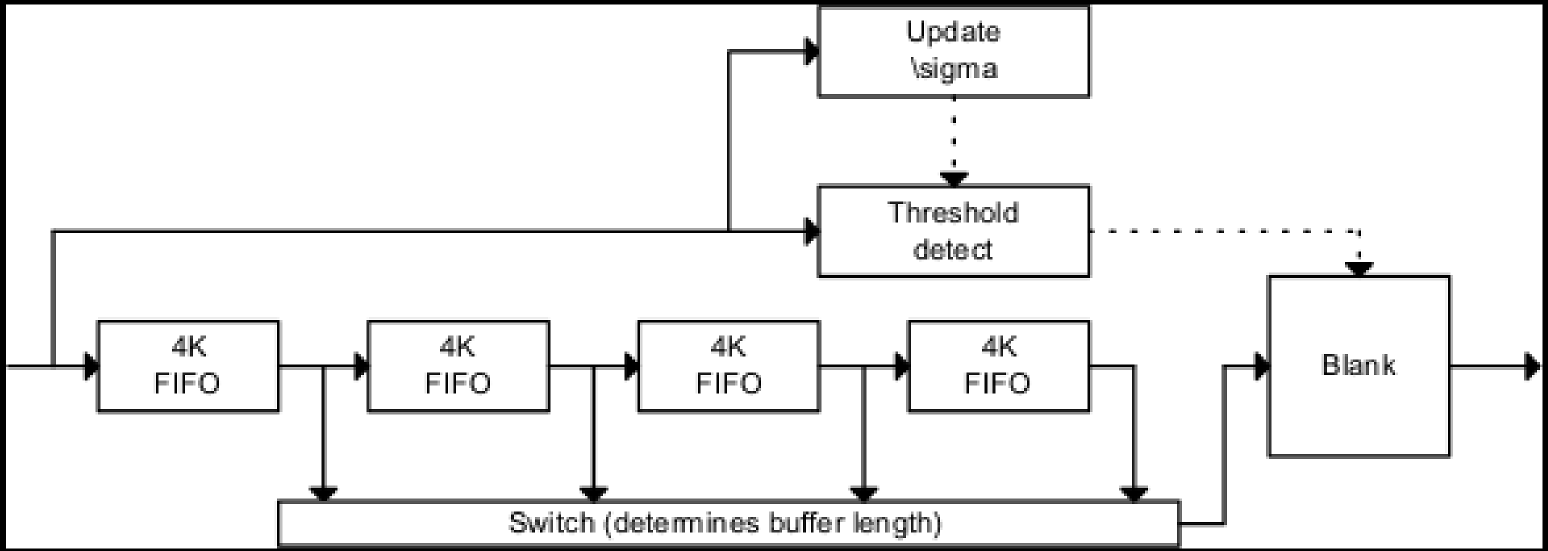


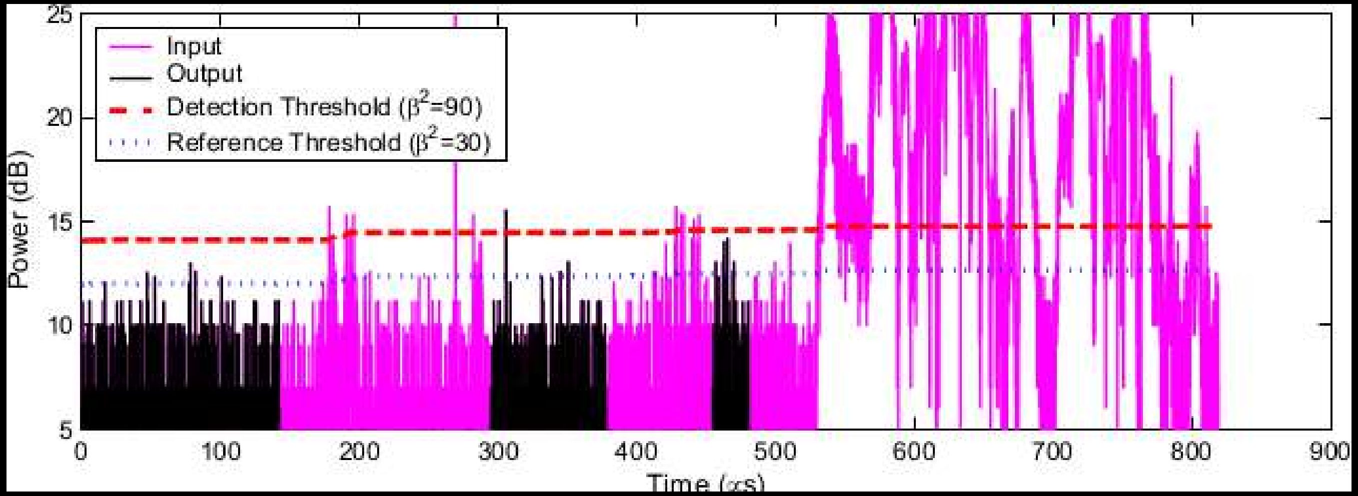


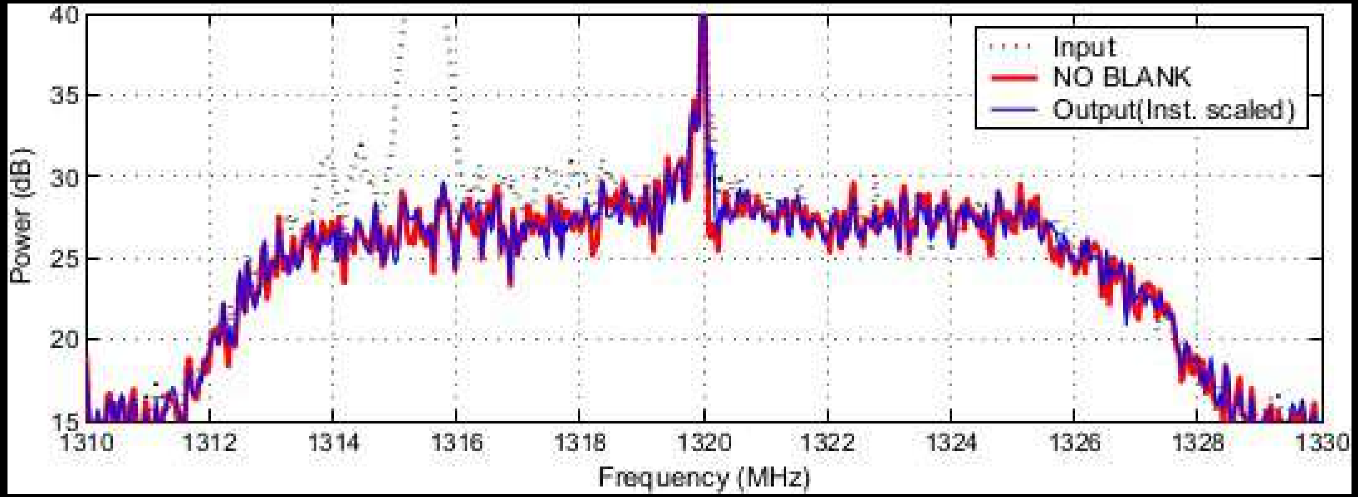


Asynchronous Pulse Blanking

Niamsuwan et al. 2004
RADAR Pulse blanker demonstrated with Arecibo data





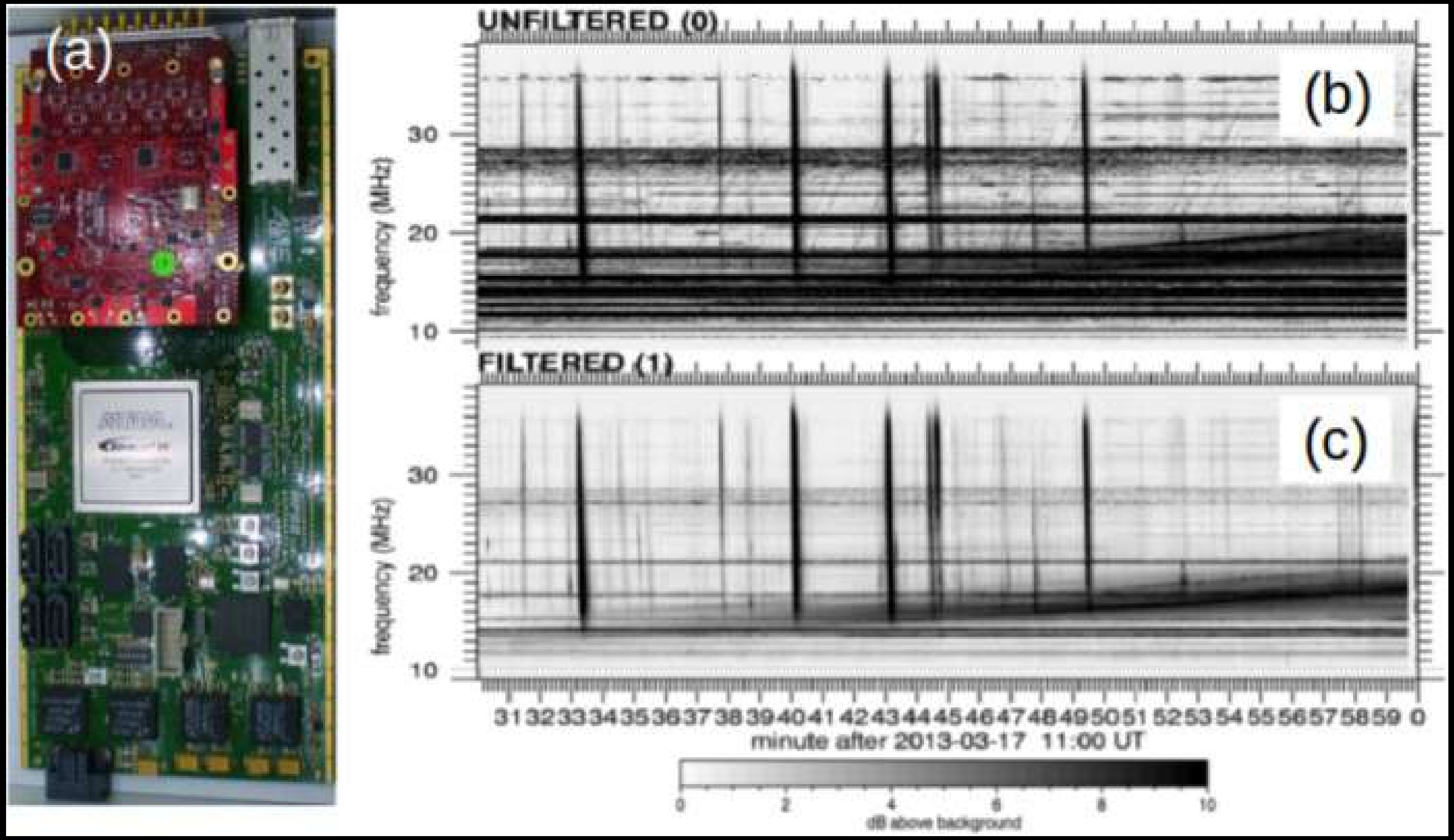


Flagging / Blanking

- Flagging methods are generally “tried and trusted”
- Higher detection sensitivity can be reached with matched detectors if a priori information is available
- Loss of data → might severely impact telescope sensitivity in the future
- Usually works best at high Interference–to–Noise Ratio regimes
- Limitation : Fast–varying astronomical sources, fast fringes, spectral lines — but usually astronomical sources are weak compared to RFI
- High–cadence signal processing or appropriate storage required
- Scattering and multipath – independent

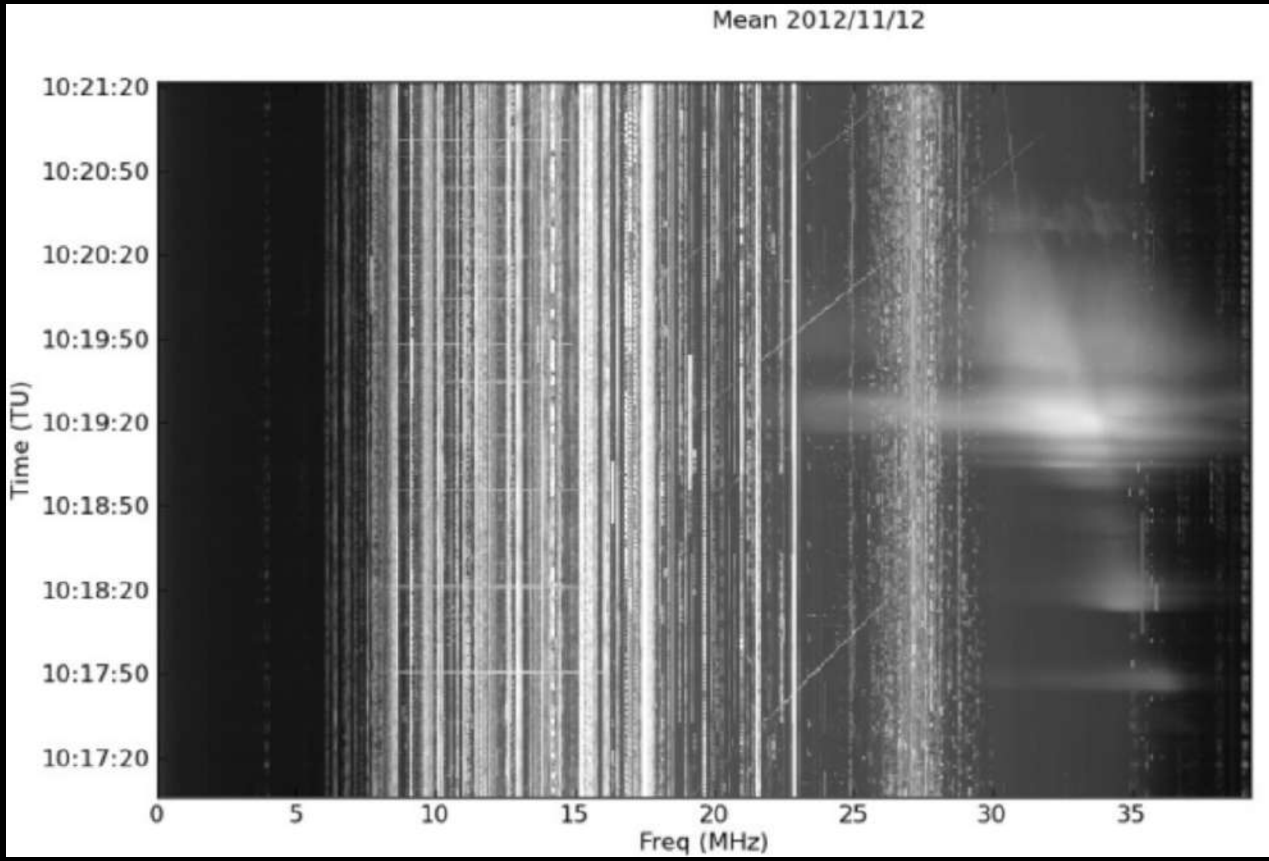
Median T–F filtering

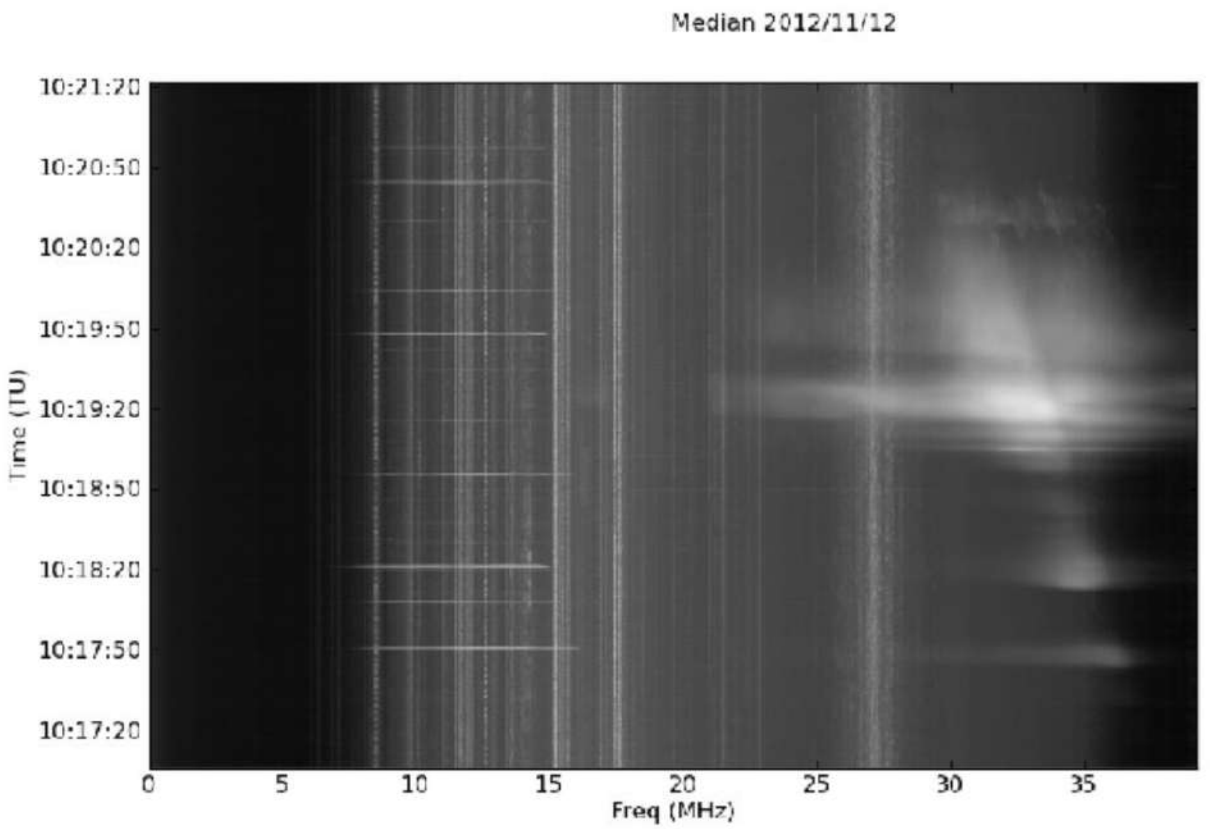
Dumez–Viou et al. 2017



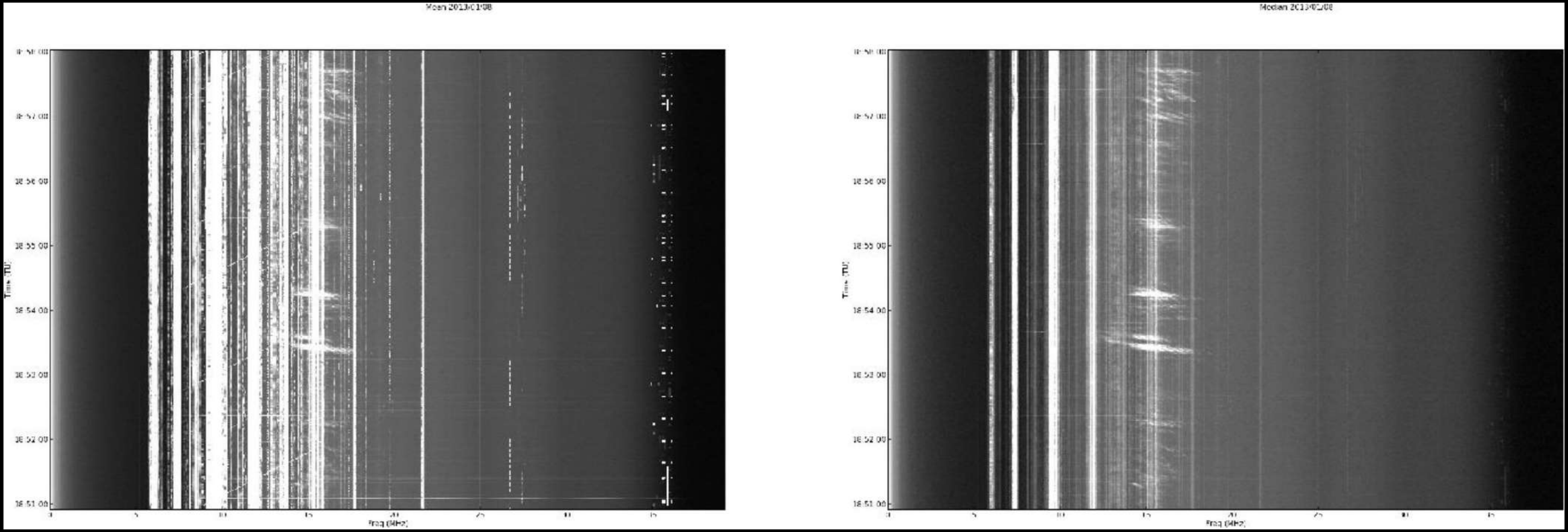
- **Dedicated board processes post–correlation data products**
- **Median filtering removes most RFI leaving astronomical signal (solar bursts) unaffected**
- **Operational since 2016 on decameter array at Nançay observatory**

Median T–F filtering



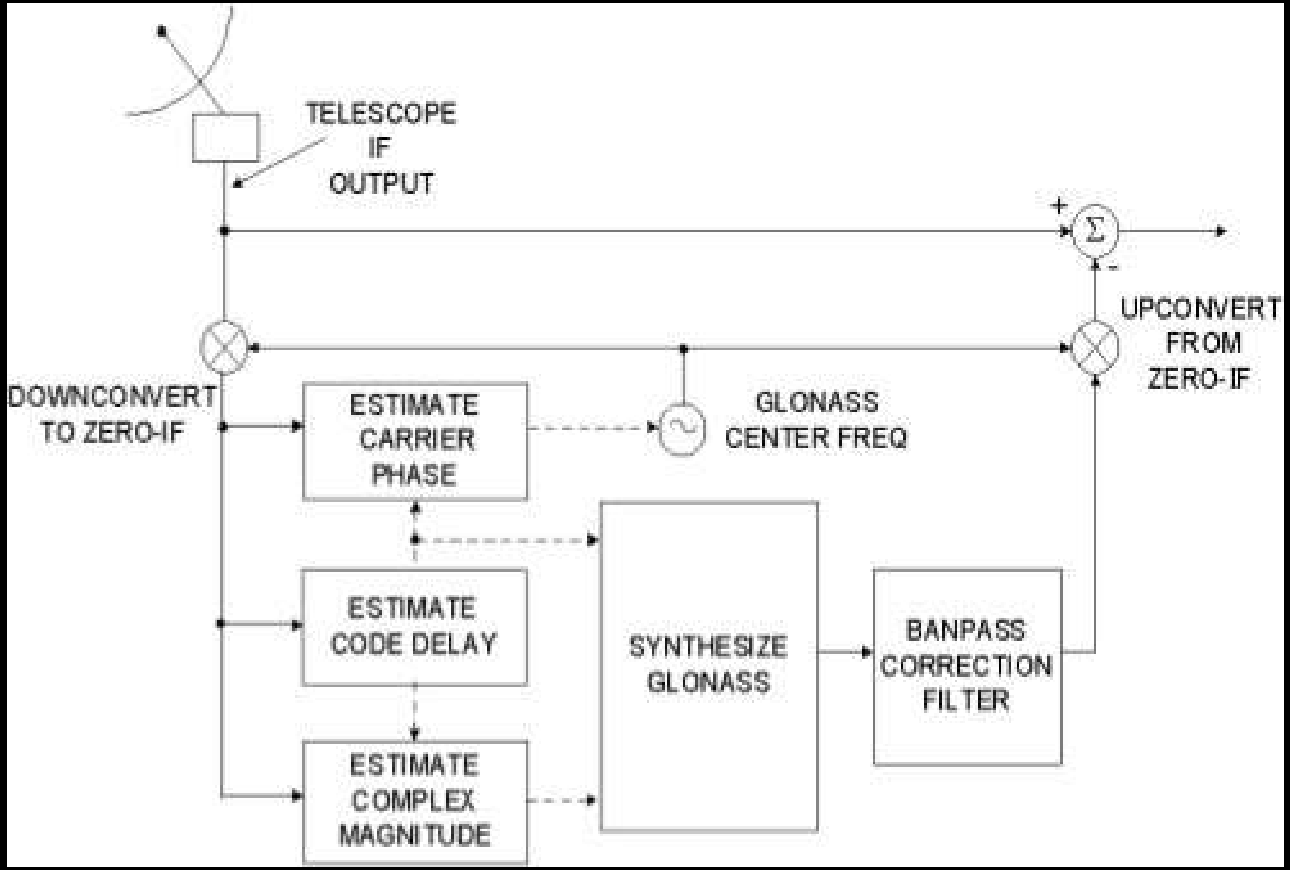


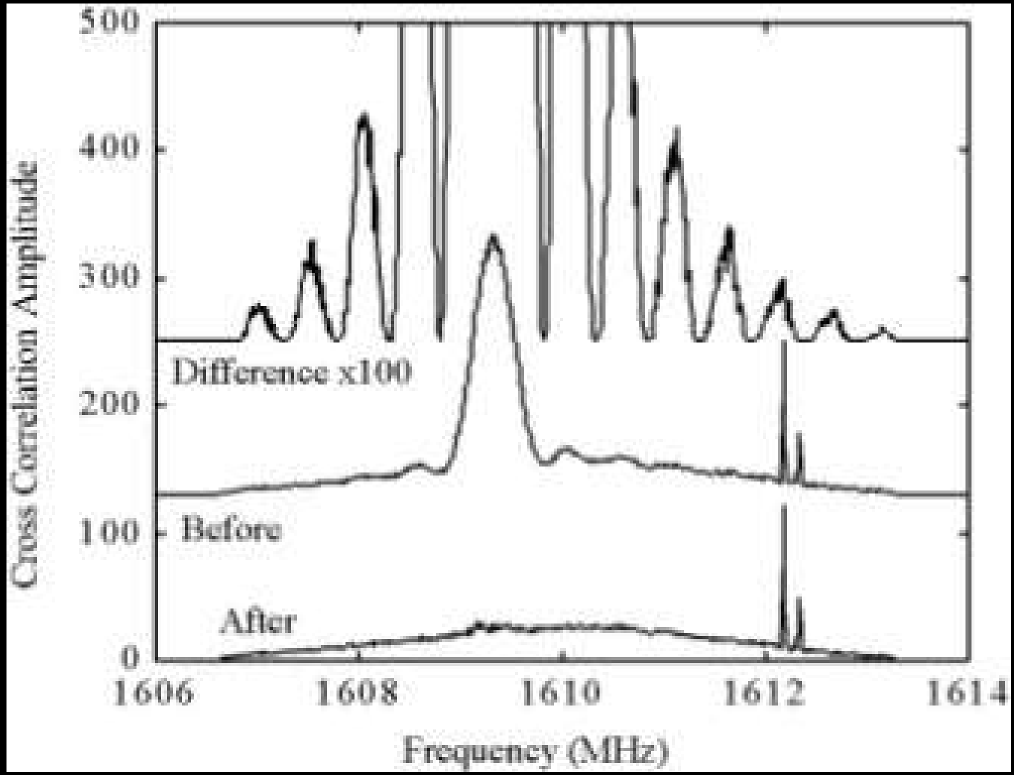
Median T–F filtering



Estimation & Subtraction

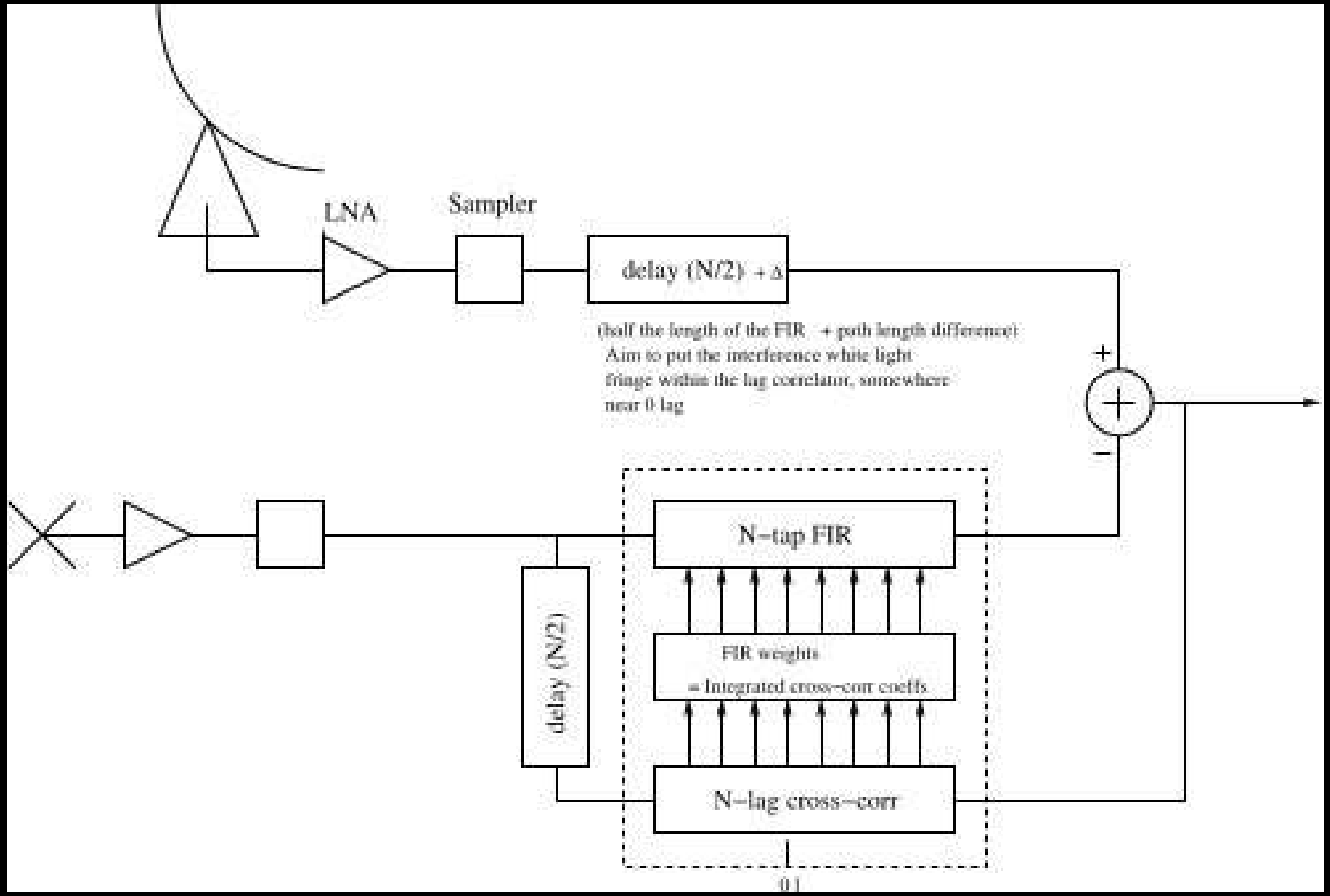
Ellingson et al. 2001
Estimation of modulation parameters from GLONASS C/A transmission, waveform modeling, and subtraction from ATCA single antenna signal

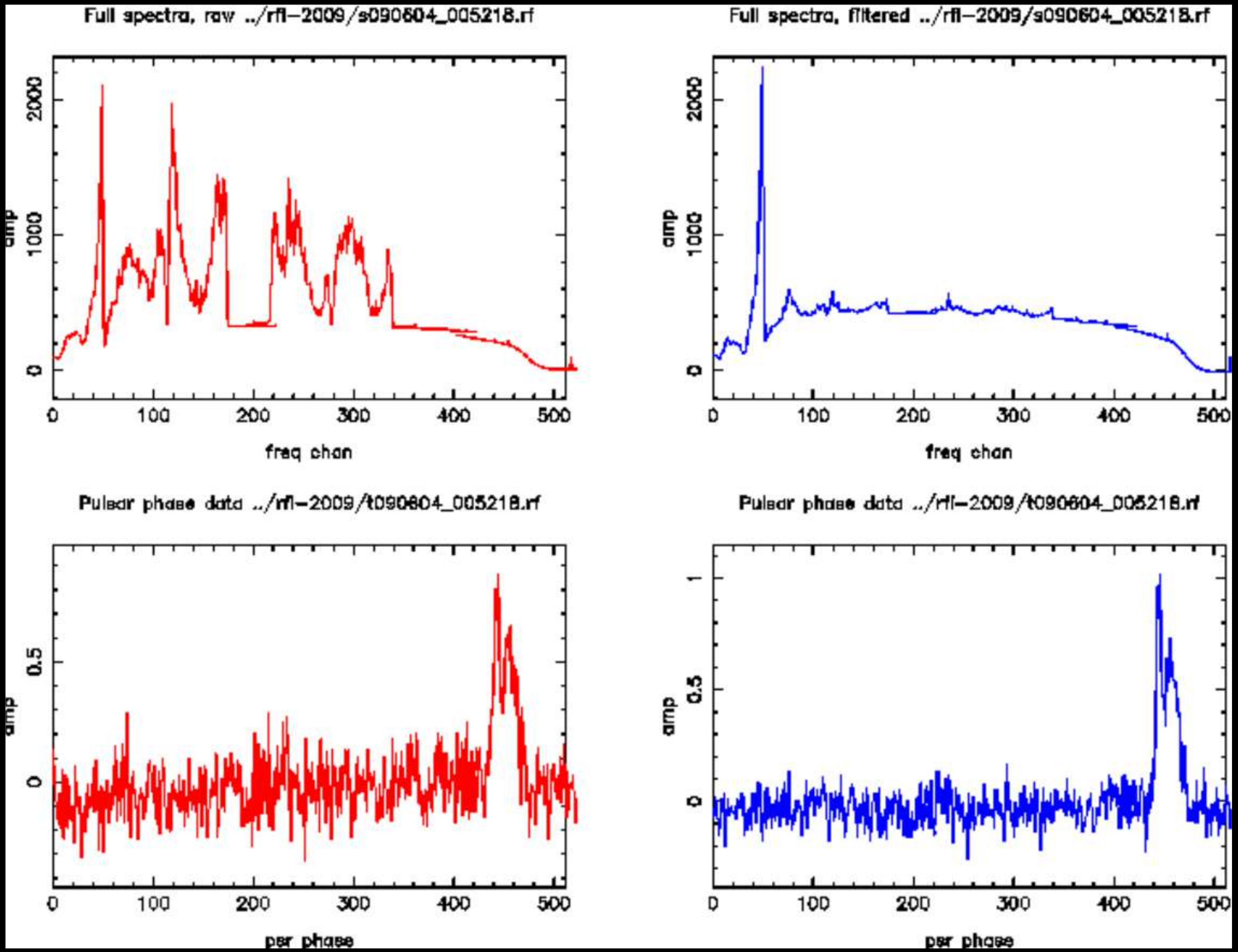




Adaptive filtering

Kesteven et al. 2005

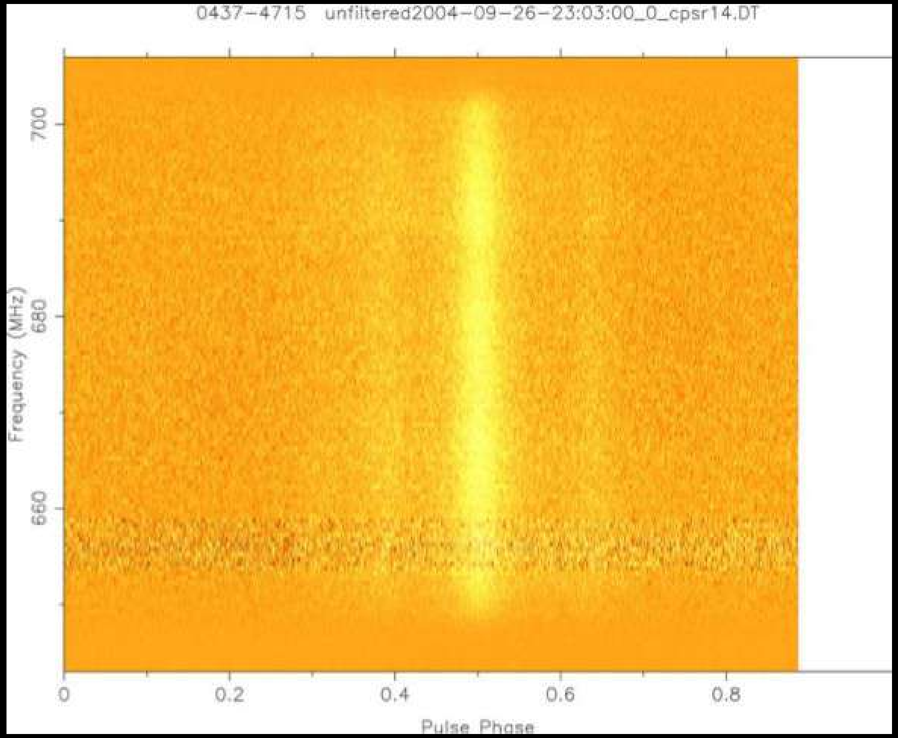




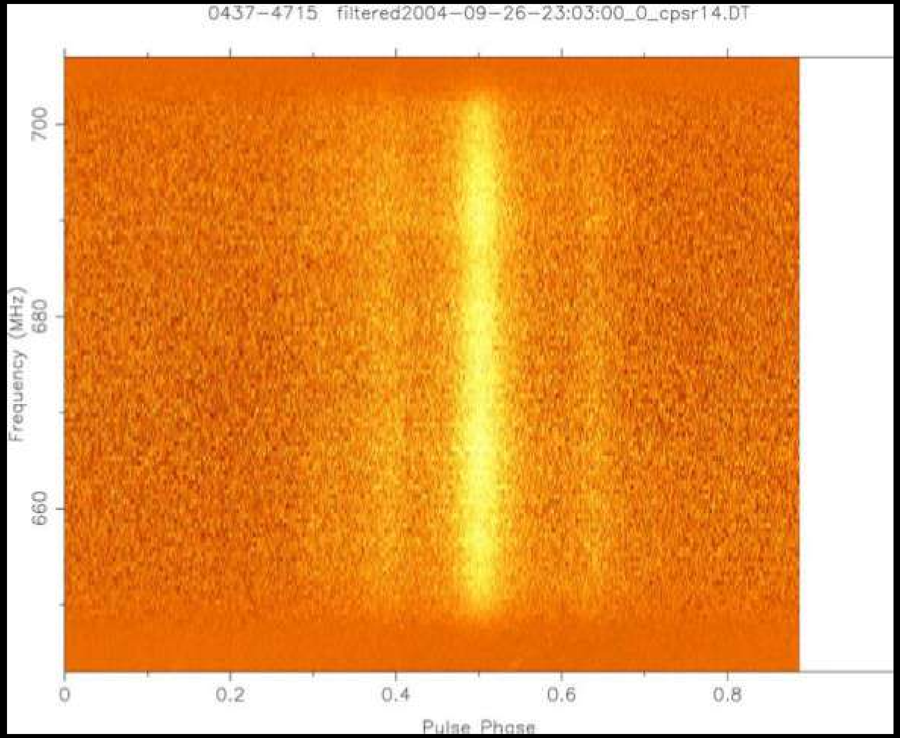
Adaptive filtering

- Suitable for single dish observation (pulsar or VLBI)
- Not suitable for multiple transmitters
- Robust to transmission channel changes (multipath, fading)
- Requires additional reference antenna + a priori information

No filter



With filter

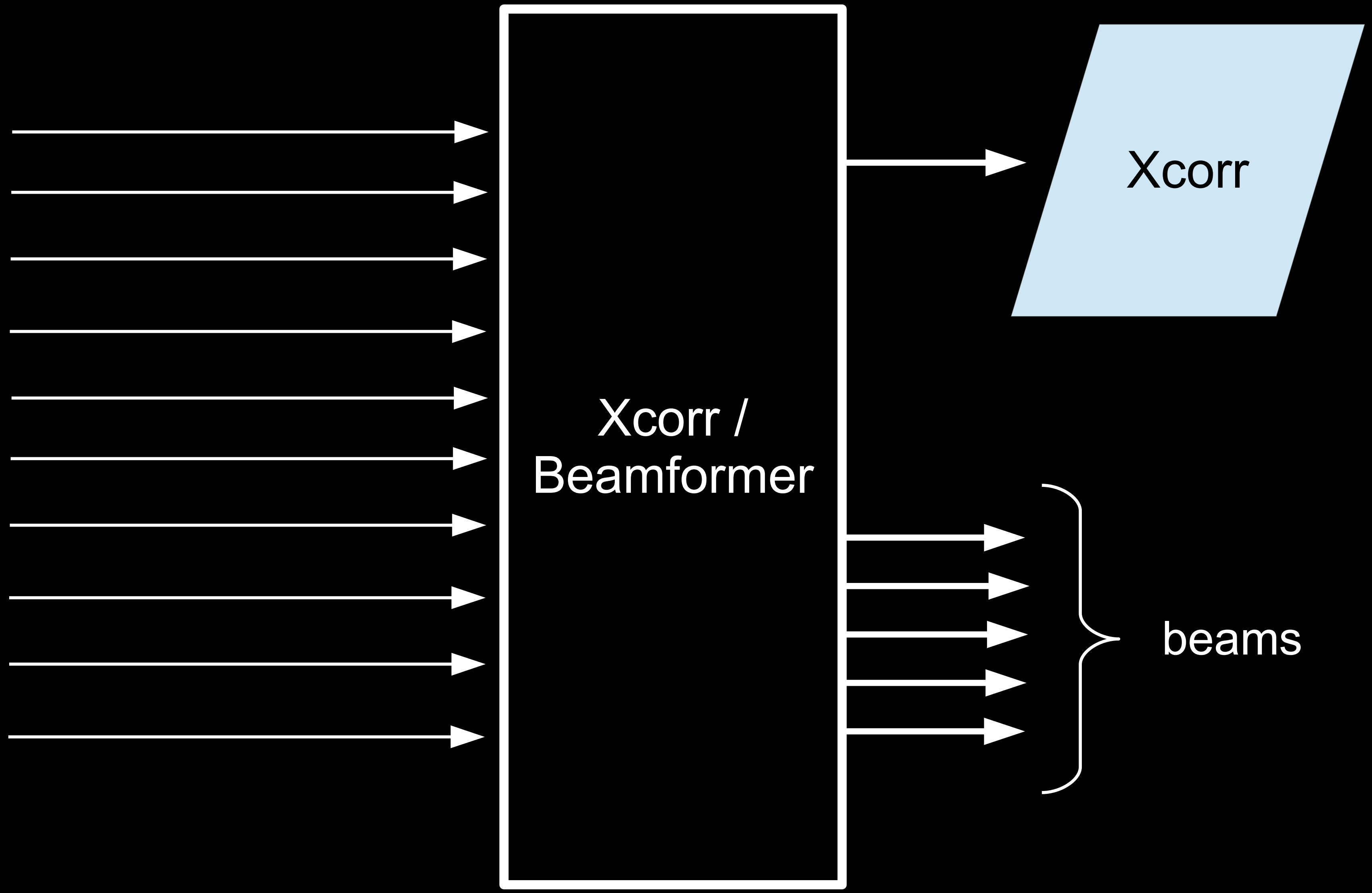


Spatial filtering

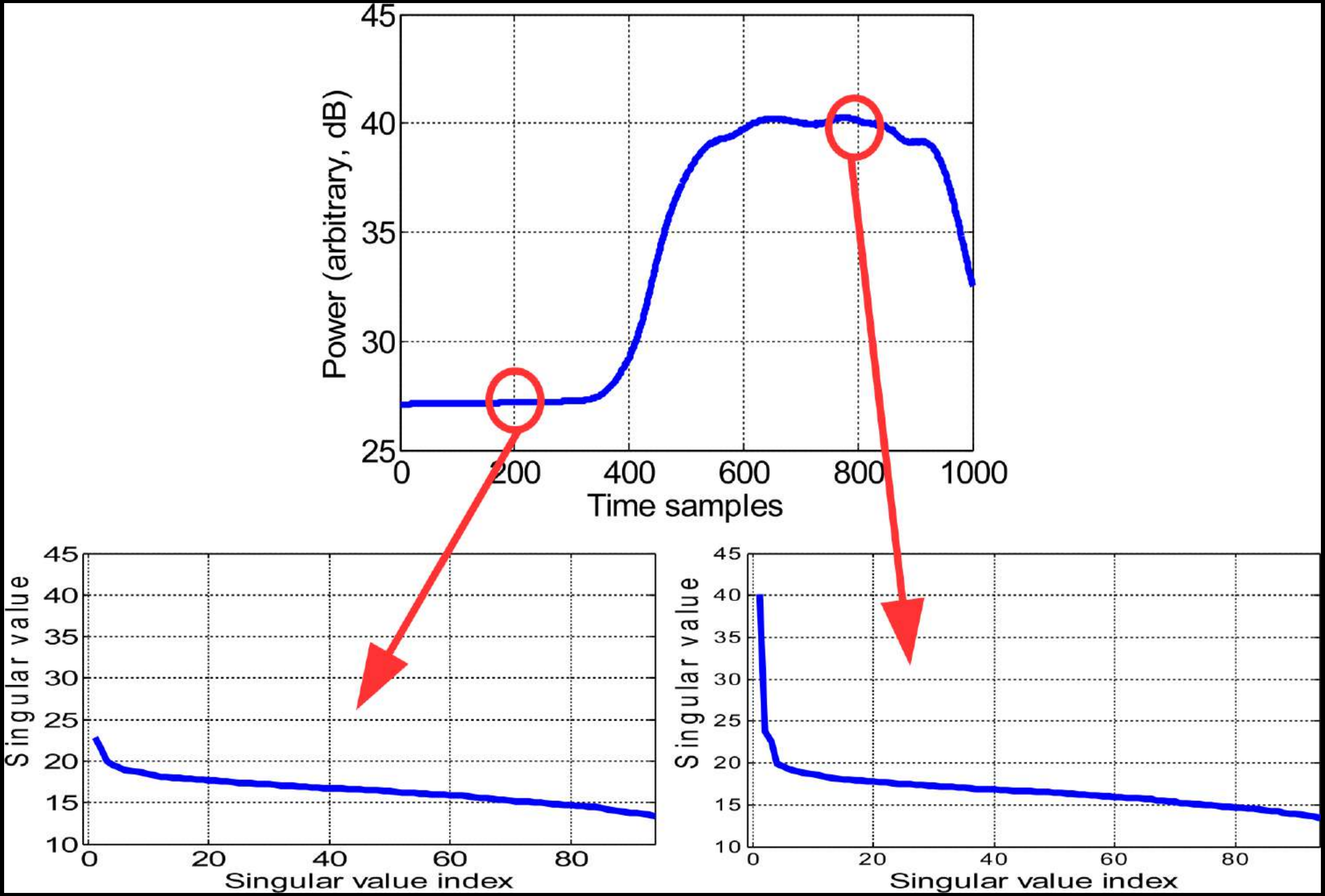
Spatial filtering

Spatial filtering

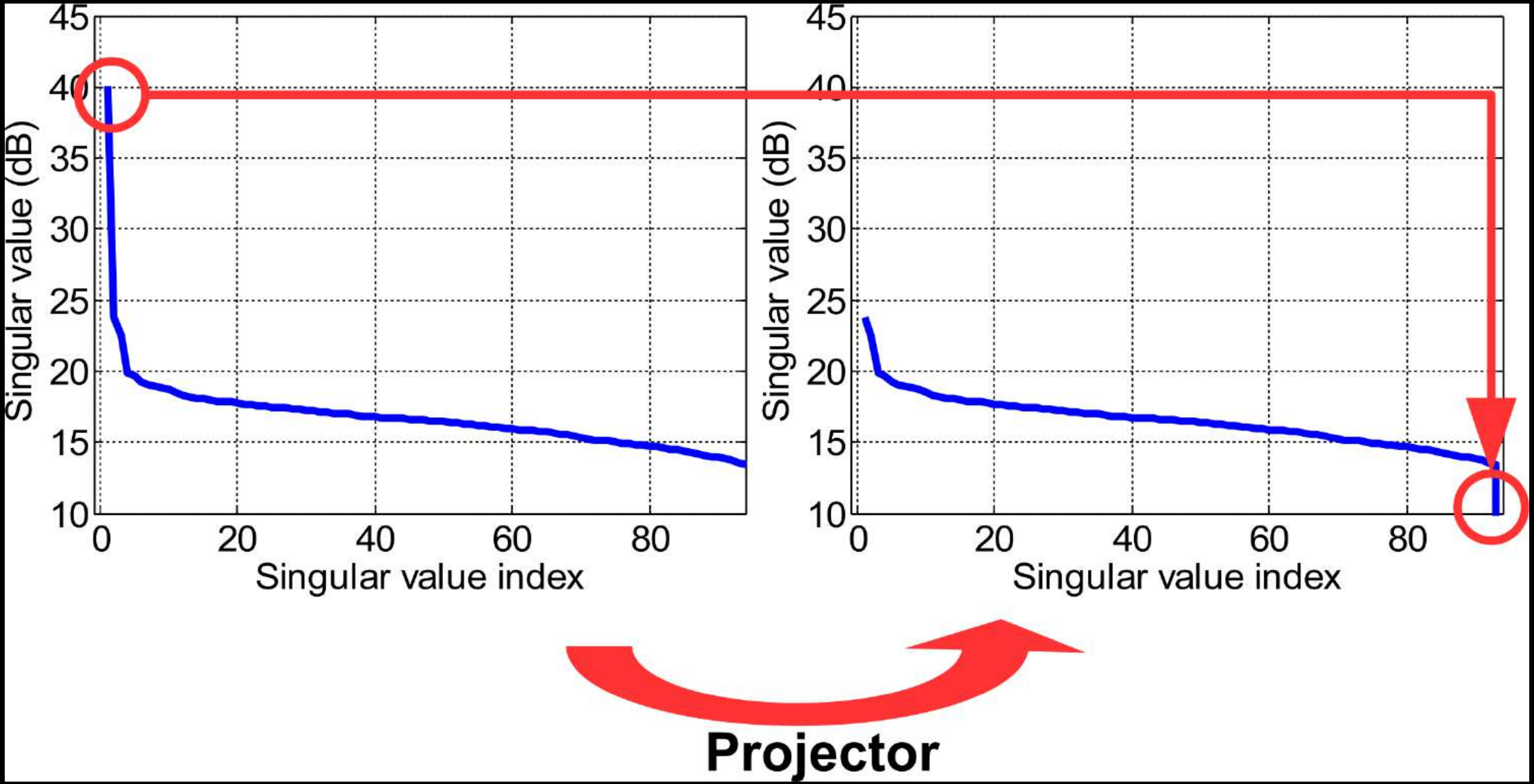
Spatial filtering



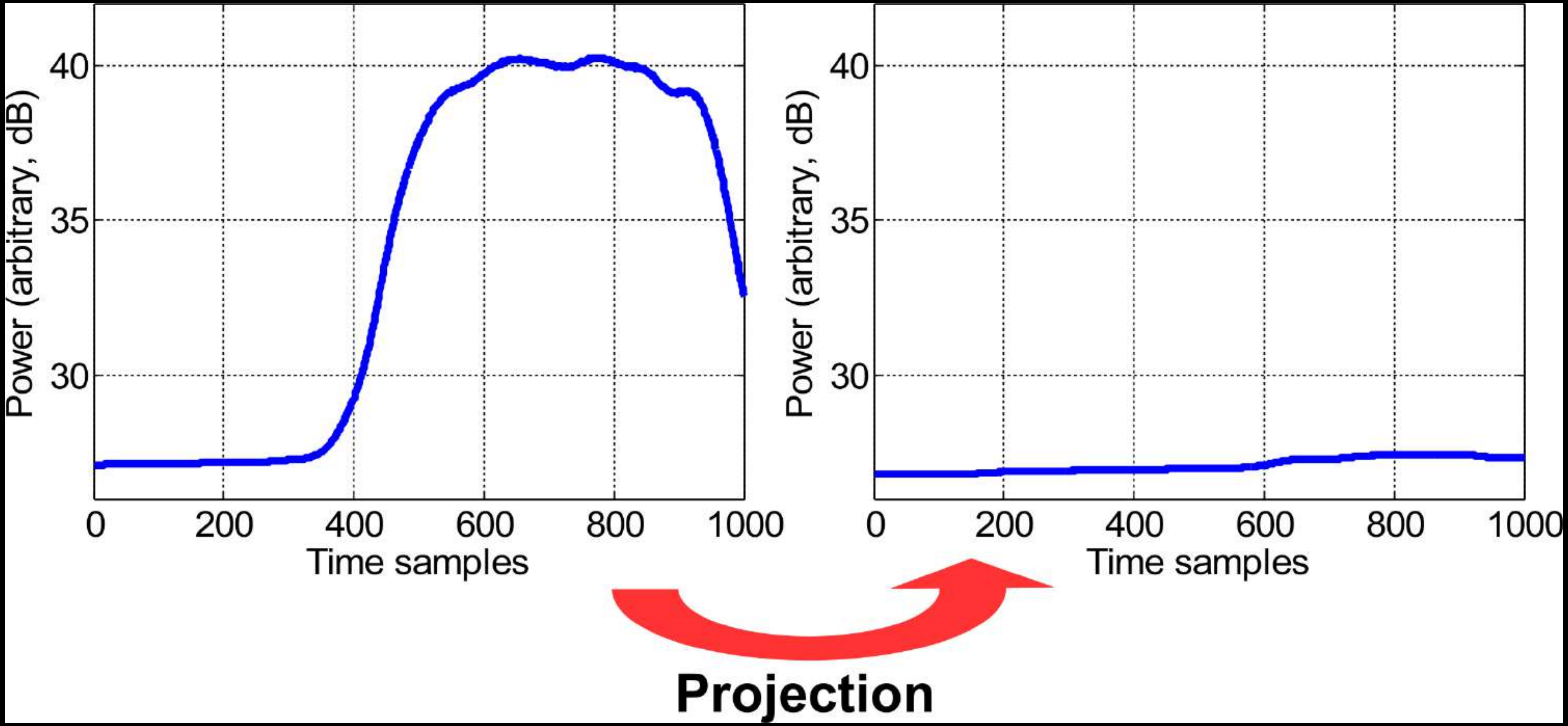
Spatial filtering



Spatial filtering



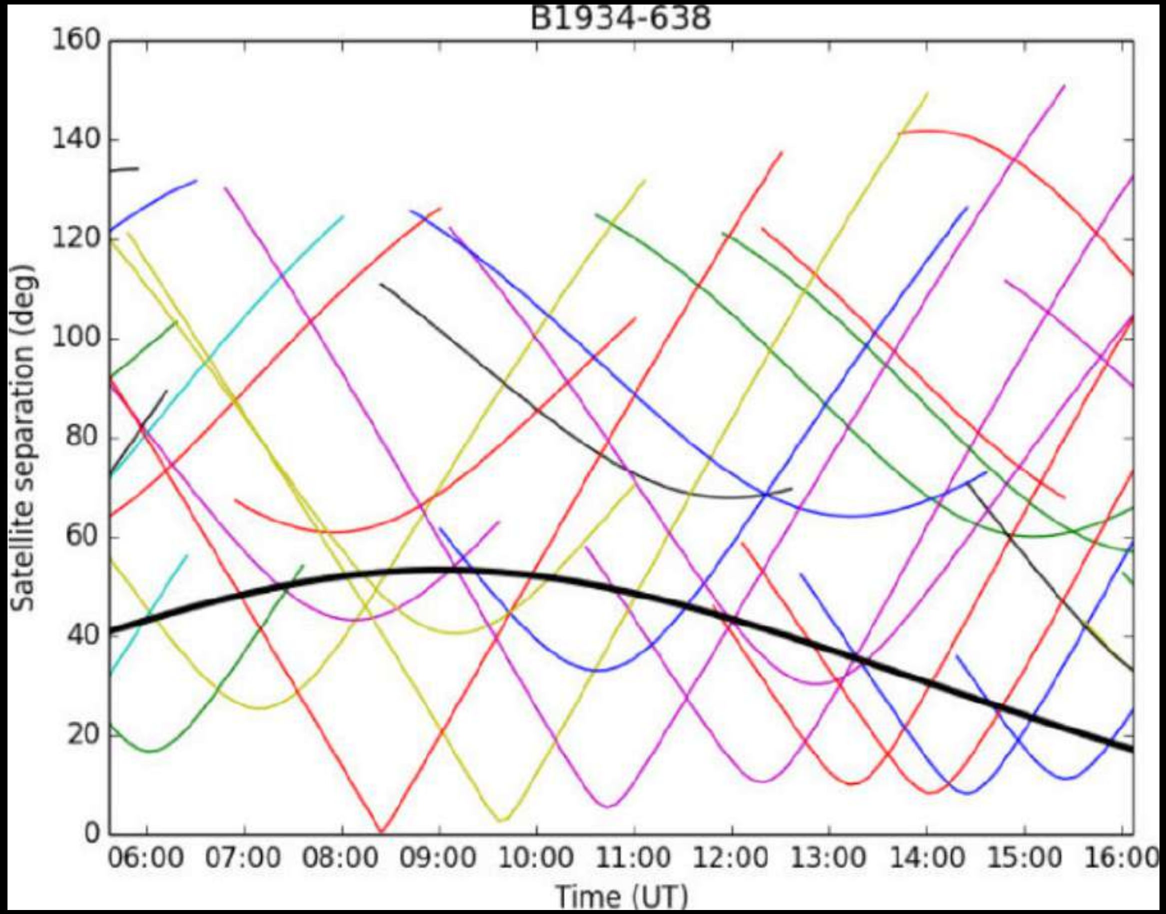
Spatial filtering



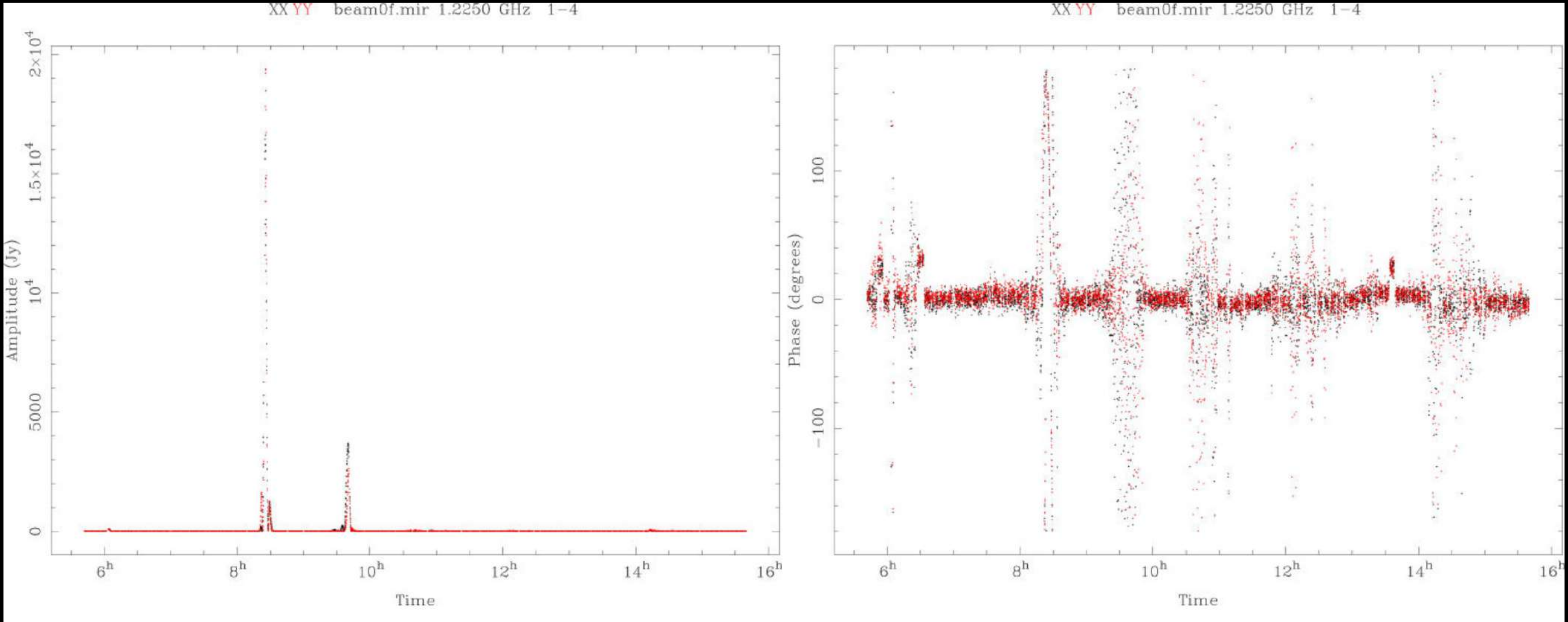
Spatial filtering

Hellbourg et al. 2016

- **1 MHz bandwidth processed at f0 = 1,225 MHz (GPS L2 band)**
- **10 h observation of PKS B1934−63**
- **5 BETA antennas**
- **9 beams/antenna initialized by same MaxSNR beamformer**
- **Xcorr matrix integrated over 2 s**

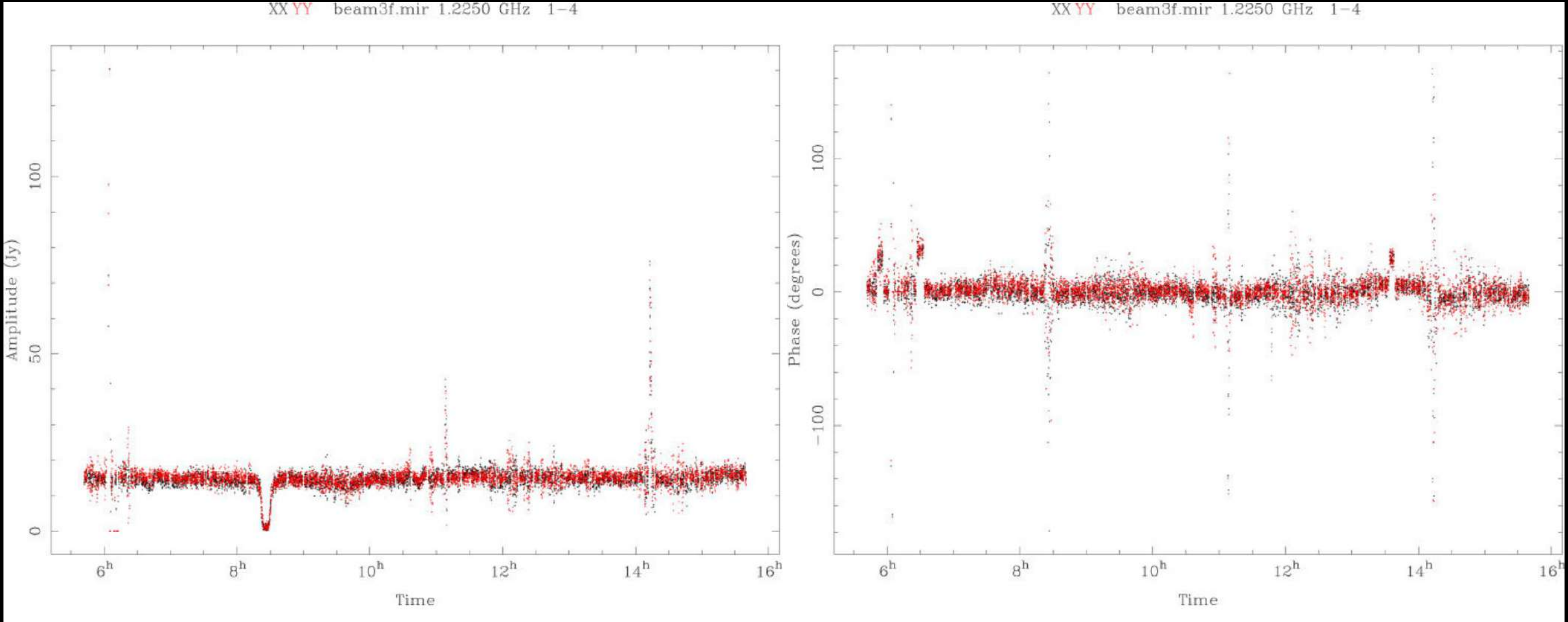


Spatial filtering



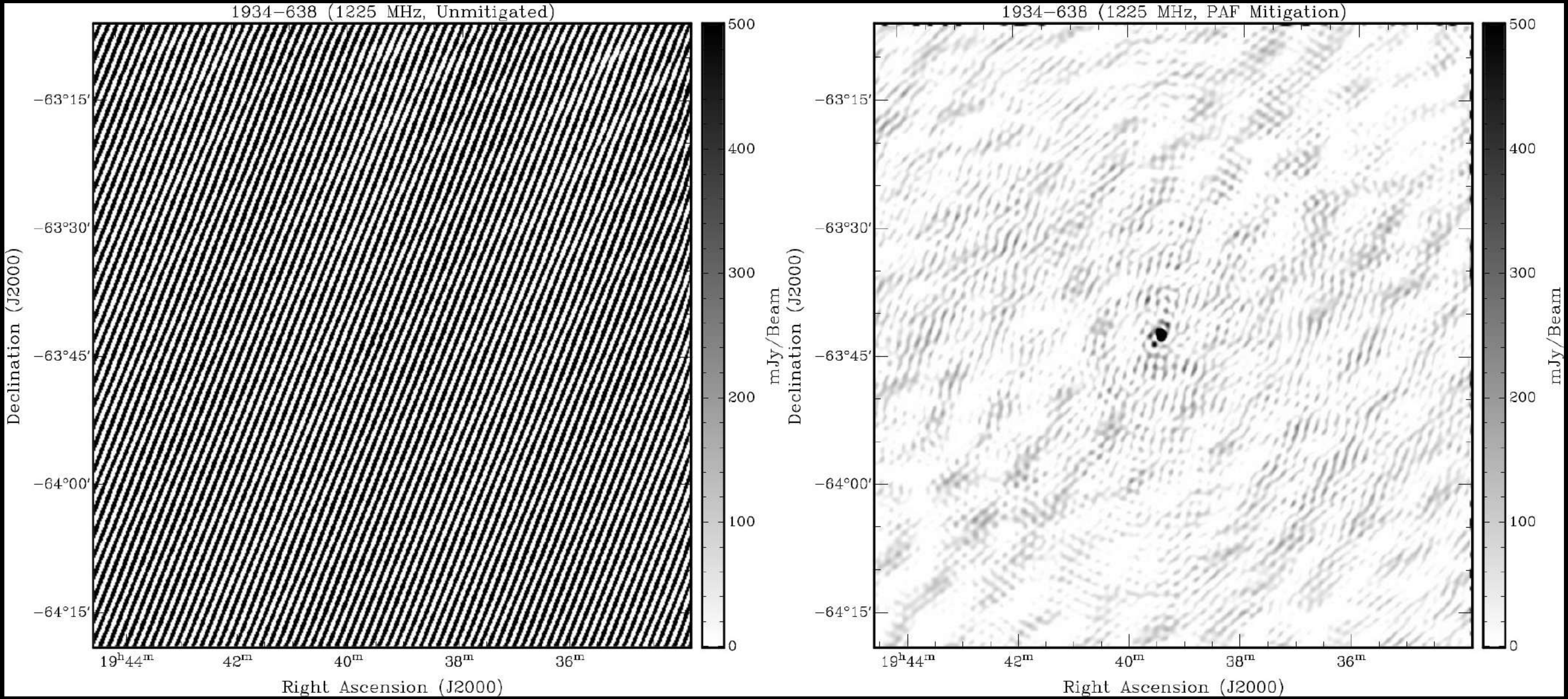
AK01 - AK06

Spatial filtering



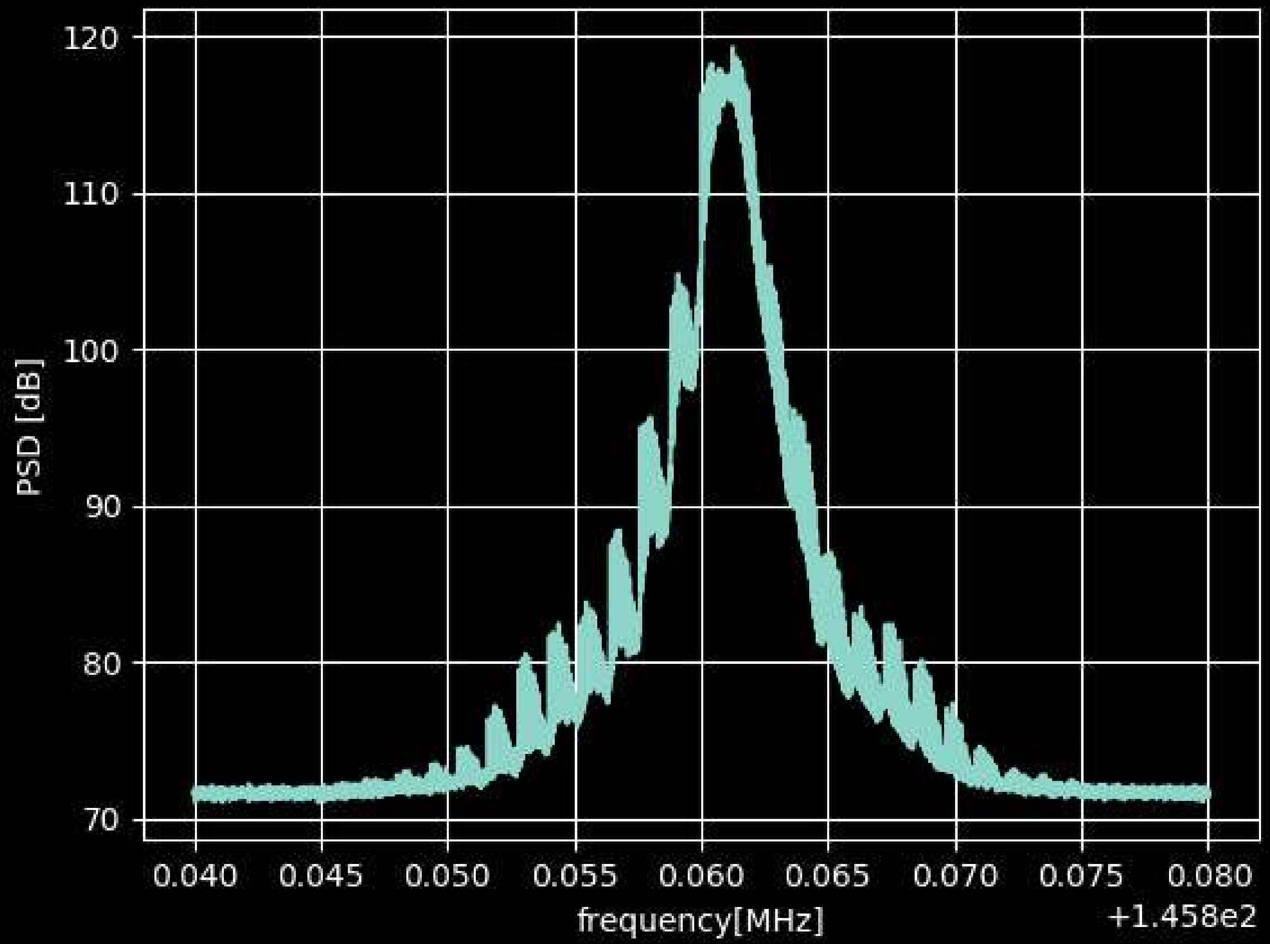
AK01 - AK06

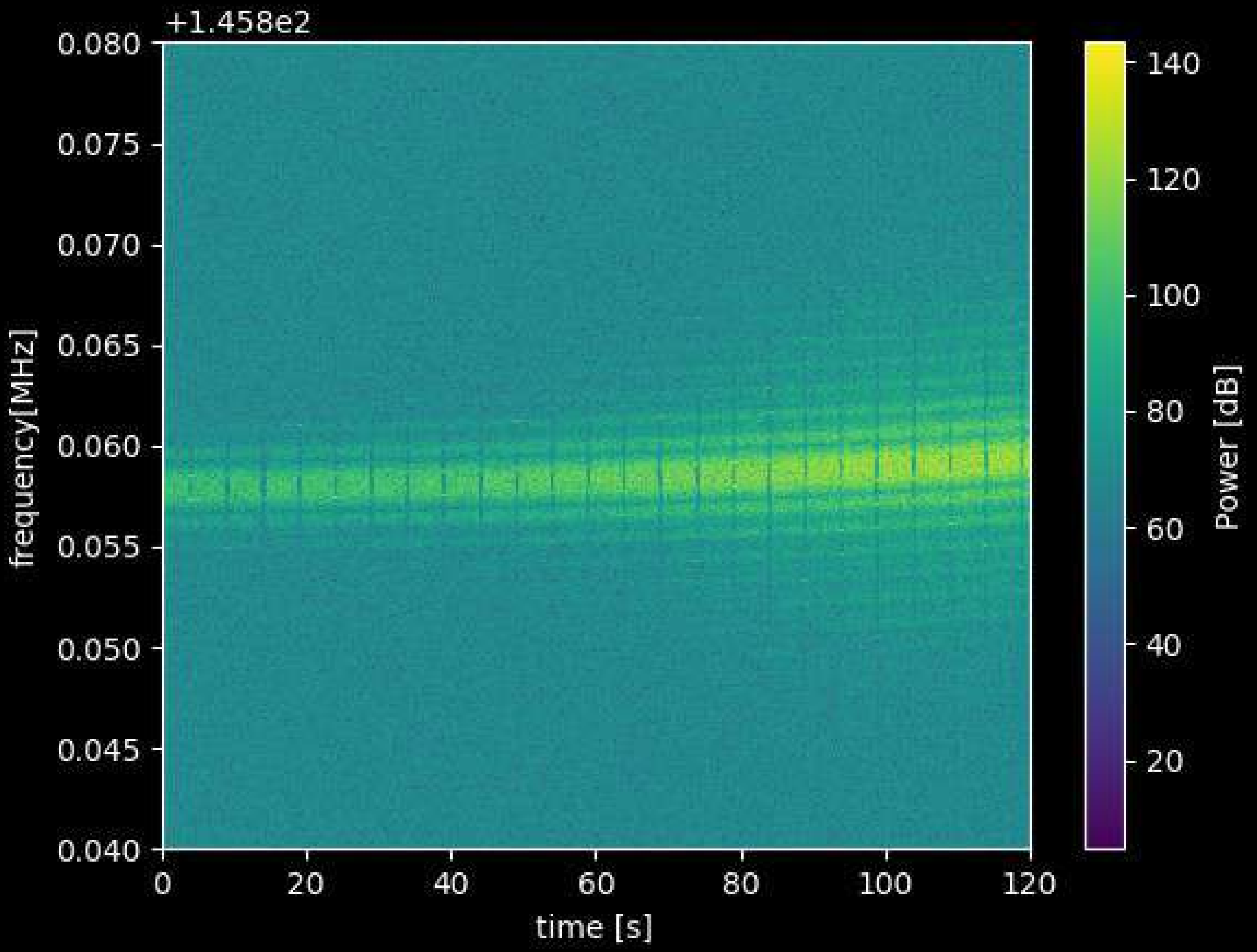
Spatial filtering

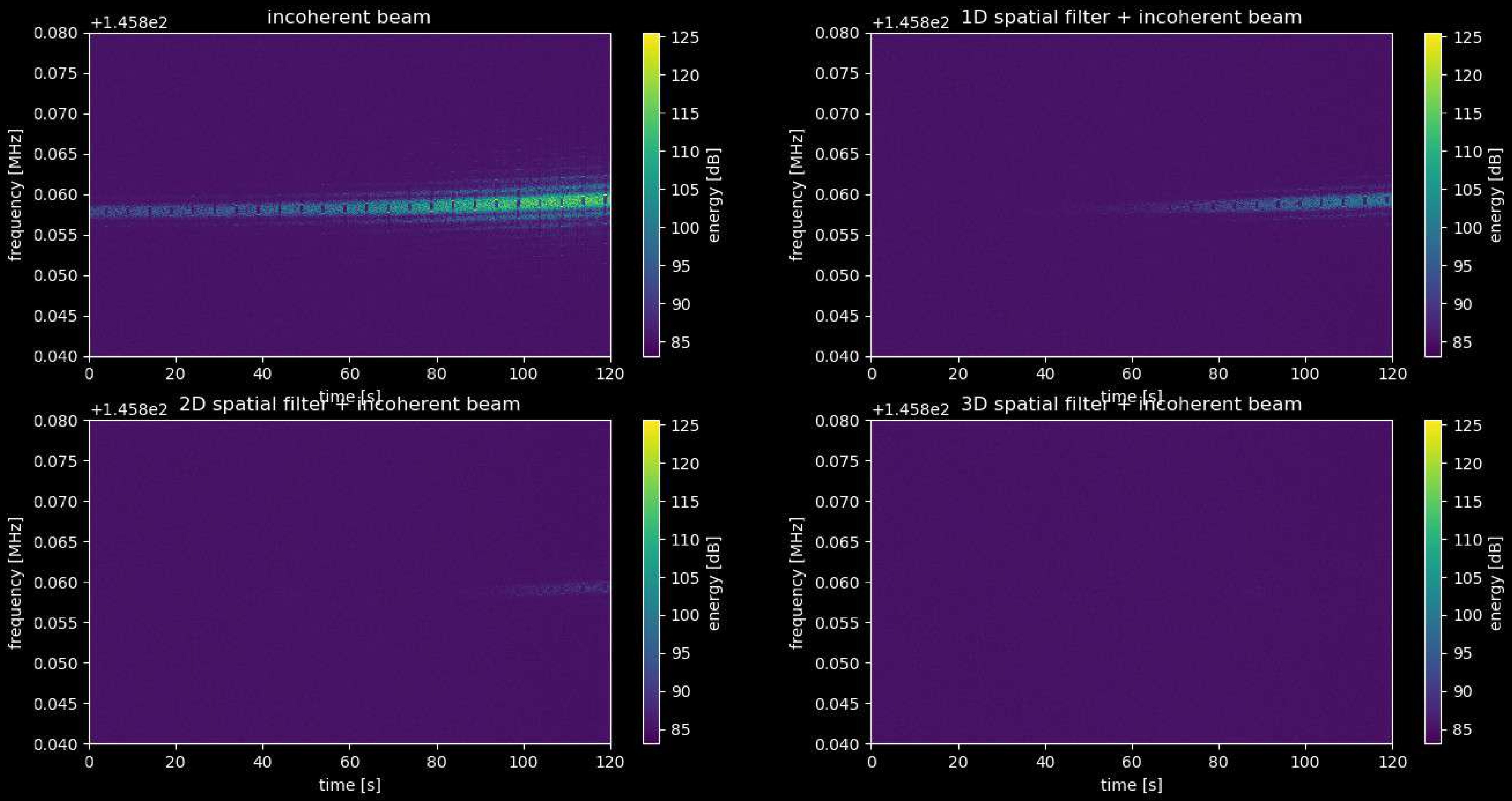


Spatial filtering

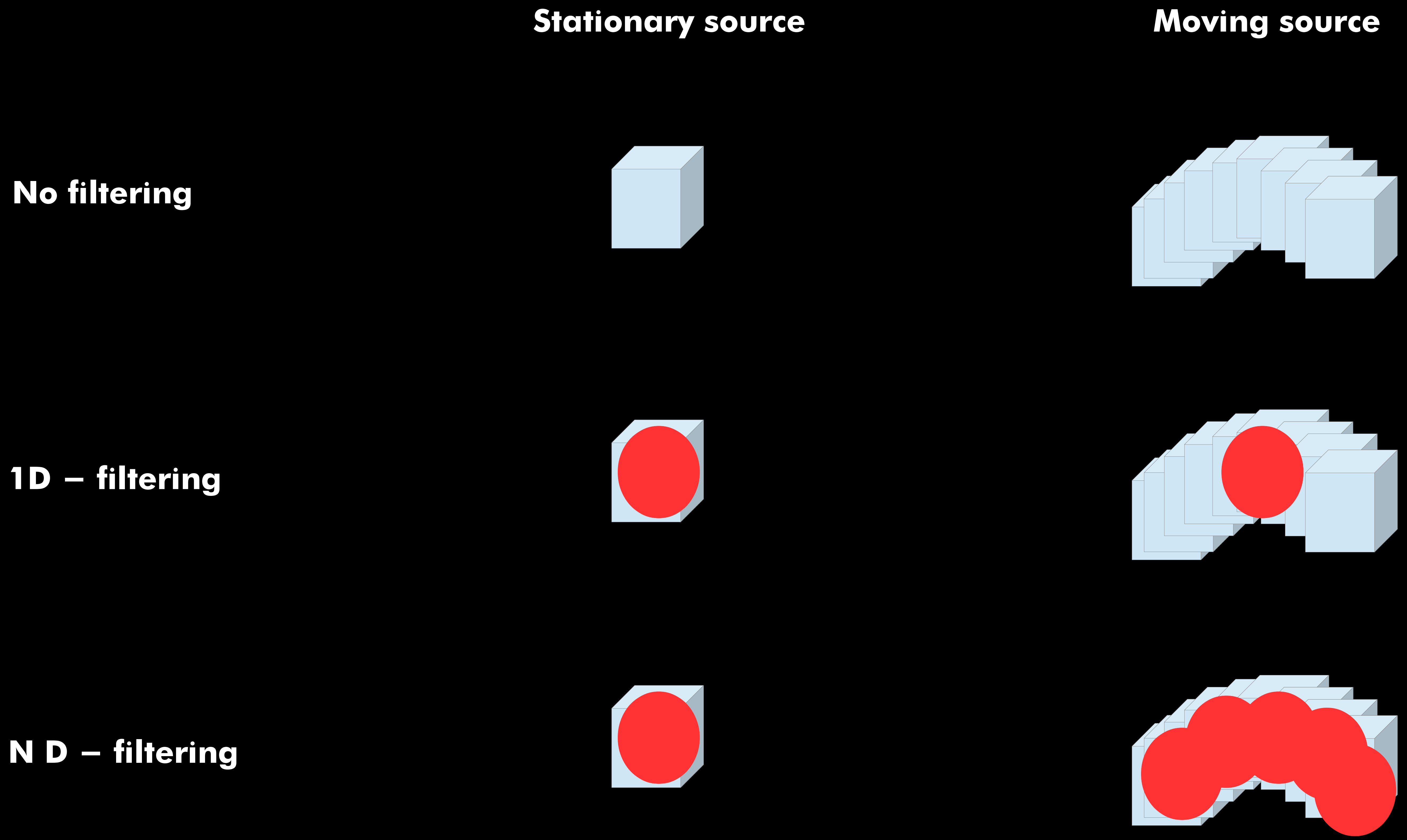
Hellbourg et al. 2019

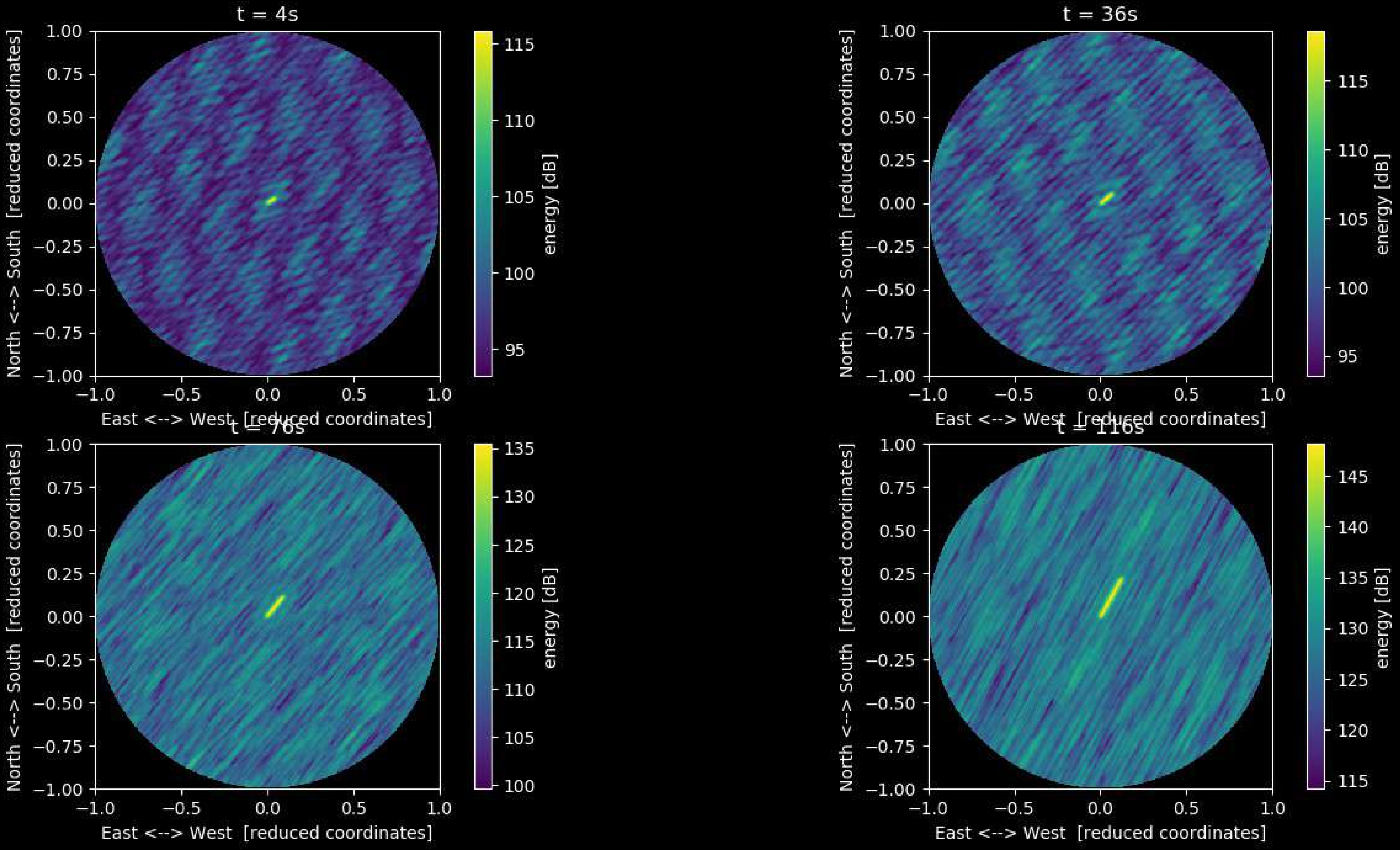


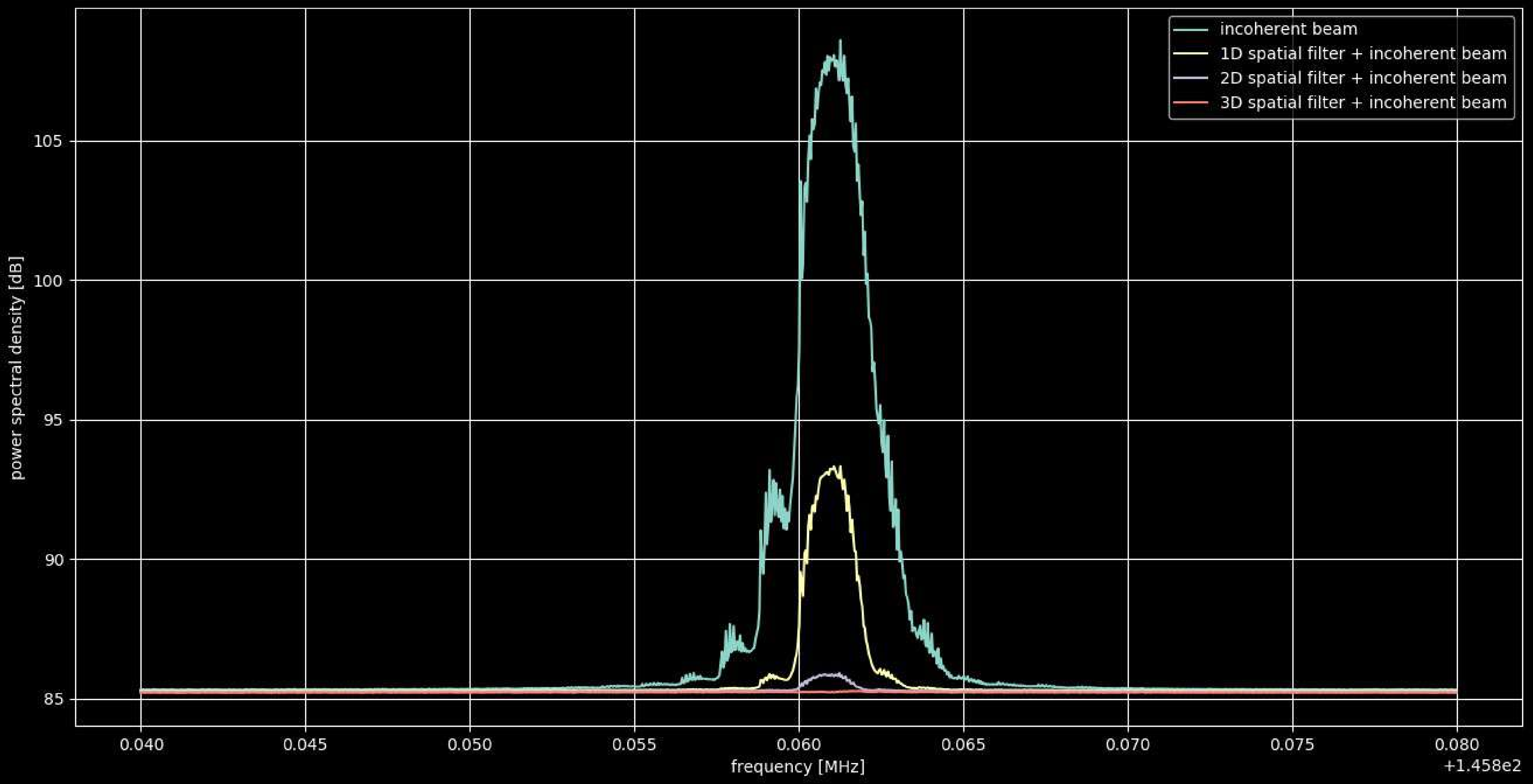




incoherent beam
1D spatial filter + incoherent beam
2D spatial filter + incoherent beam
3D spatial filter + incoherent beam
+1.458e2
frequency [MHz]
0.080
0.075
0.070
0.065
0.060
0.055
0.050
0.045
0.040
time [s]
0
20
40
60
80
100
120
energy [dB]
125
120
115
110
105
100
95
90
85


Stationary source
Moving source
No filtering
1D – filtering
N D – filtering


t = 4s
t = 36s
t = 76s
t = 116s
North <--> South [reduced coordinates]
East <--> West [reduced coordinates]
energy [dB]
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
−1.0
−0.5
0.0
0.5
1.0
95
100
105
110
115
120
125
130
135
140
145

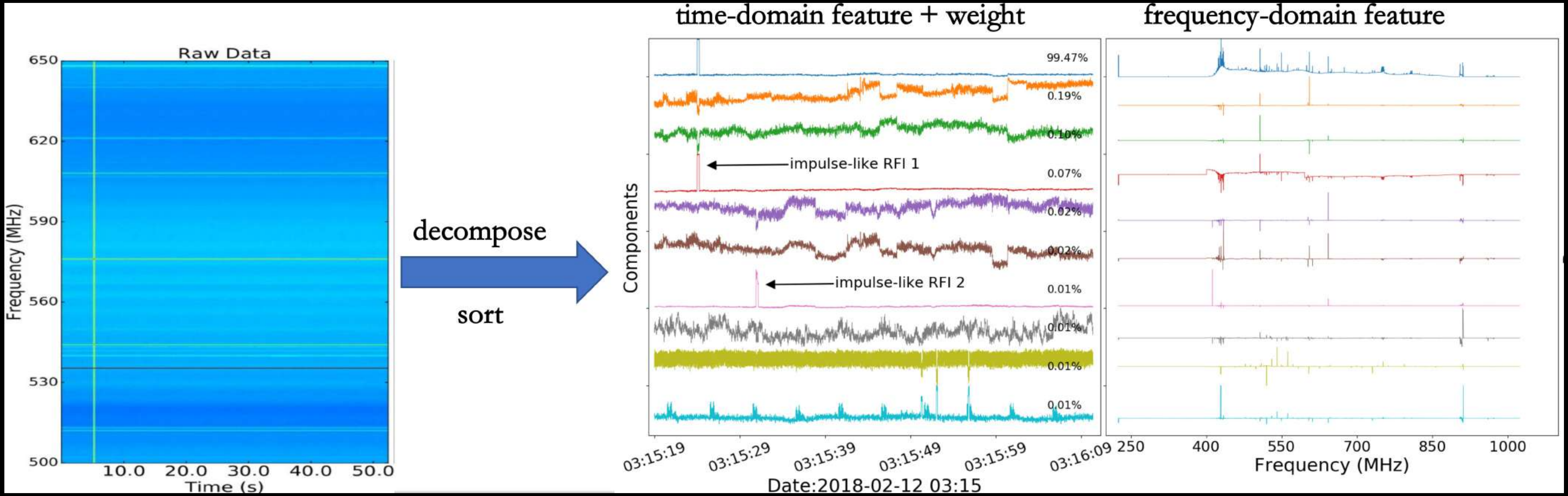

incoherent beam
1D spatial filter + incoherent beam
2D spatial filter + incoherent beam
3D spatial filter + incoherent beam
power spectral density [dB]
105
100
95
90
85
0.040
0.045
0.050
0.055
0.060
0.065
0.070
0.075
0.080
frequency [MHz]
+1.458e2

RFI filtering

- Potential for recovering underlying astronomical information
- Better sensitivity recovered with early filtering (ideally before data integration)
- Computational complexity significantly higher — trade−off to be found
- Filtering might impact calibration in unpredictable ways

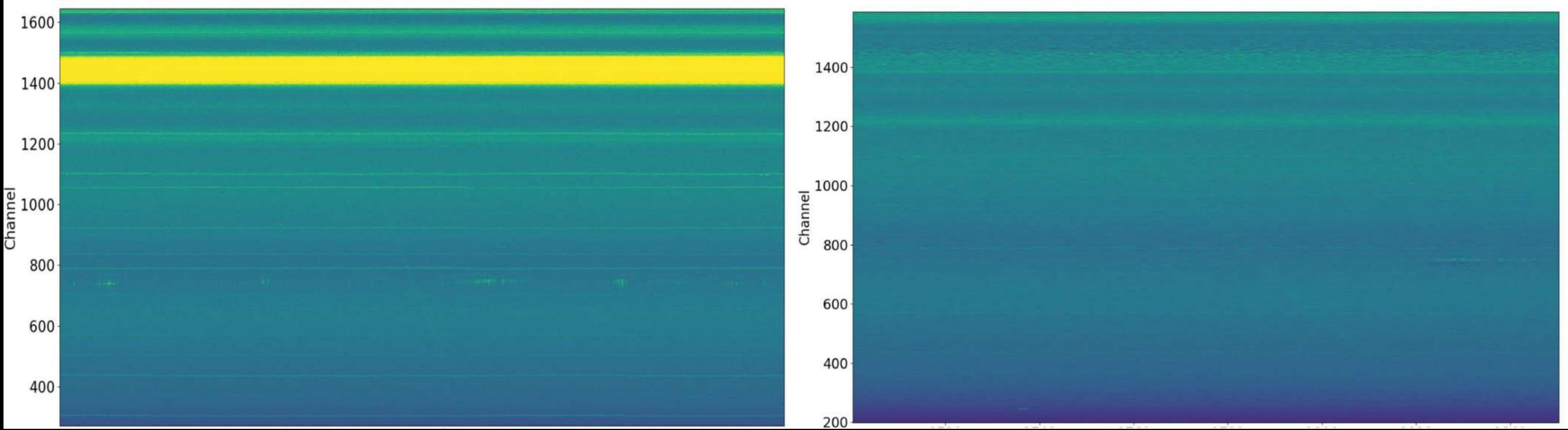
Principal Component Analysis

Yuan et al. 2019 – unpublished



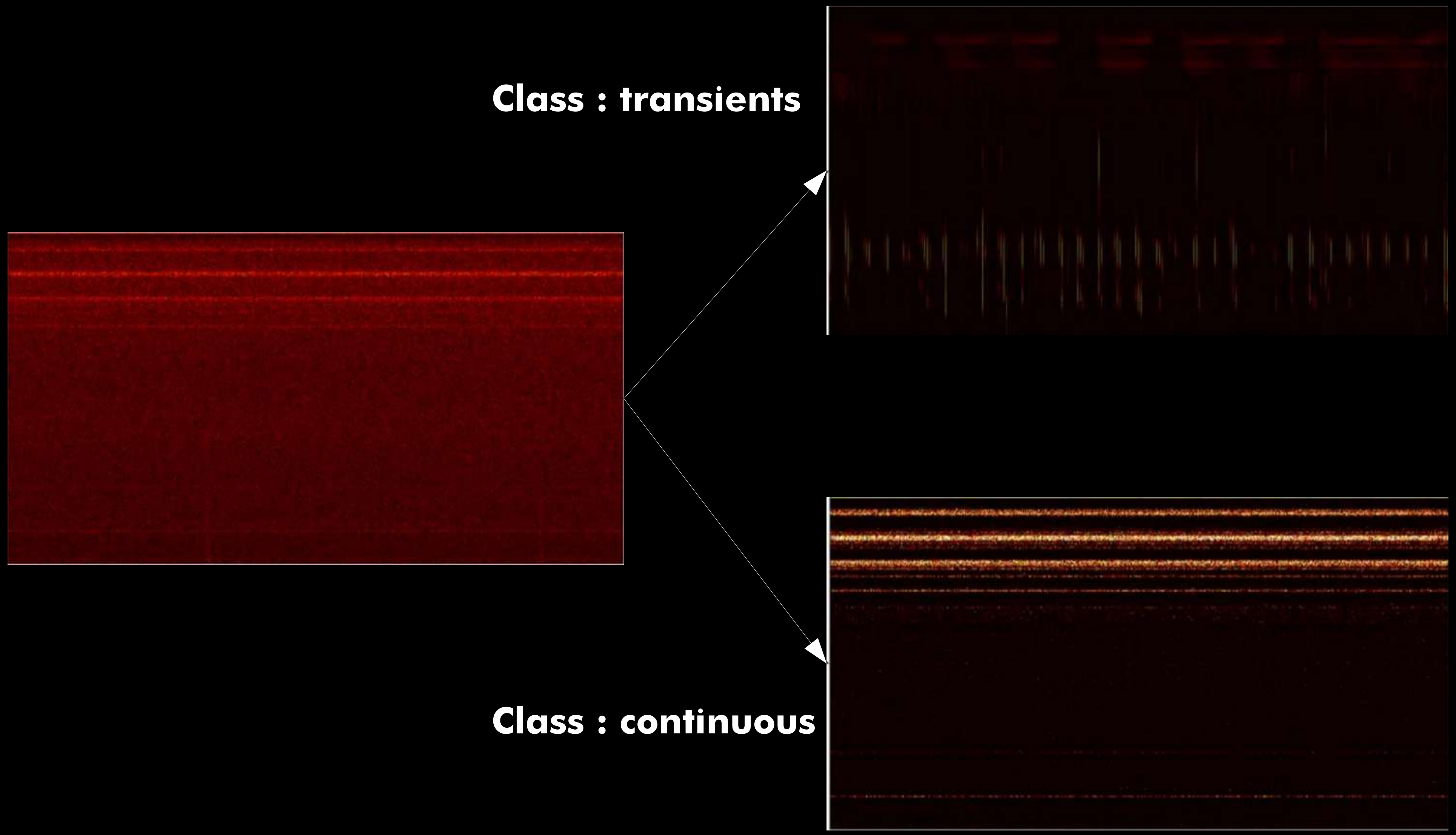
Principal Component Analysis

Raw data **Filtered data**



Machine learning

Hawkins 2019 – unpublished



- **U−net employed at GBO to distinguish between continuous RFI and transient natural sources (pulsars)**
- **Inappropriate for spectral lines**
- **Computationally very intensive (generating training sets, training model, processing data)**
- **Flagging performance ~80% better than classical methods (false positive flagging)**

Conclusions

- **RFI mitigation to be considered for any next–gen instrument design**
- **No "one–size–fits–all", complicated process of method selection**
- **Does not come at no cost, necessarily impacts sensitivity and efficiency of instrumentation**
- **Not an argument to give up frequencies : spectrum management remains best mitigation (and already fails in some cases)**
- **Flagging methods broadly accepted by the community, shift towards on–the–fly mitigation necessary in the SKA / ngVLA era**
- **Filtering methods become popular but not trusted — obvious need for more RFI filtering research and applied studies**