RFI, LOFAR & EoR

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CAASTRO Global EoR workshop
2012-11-21

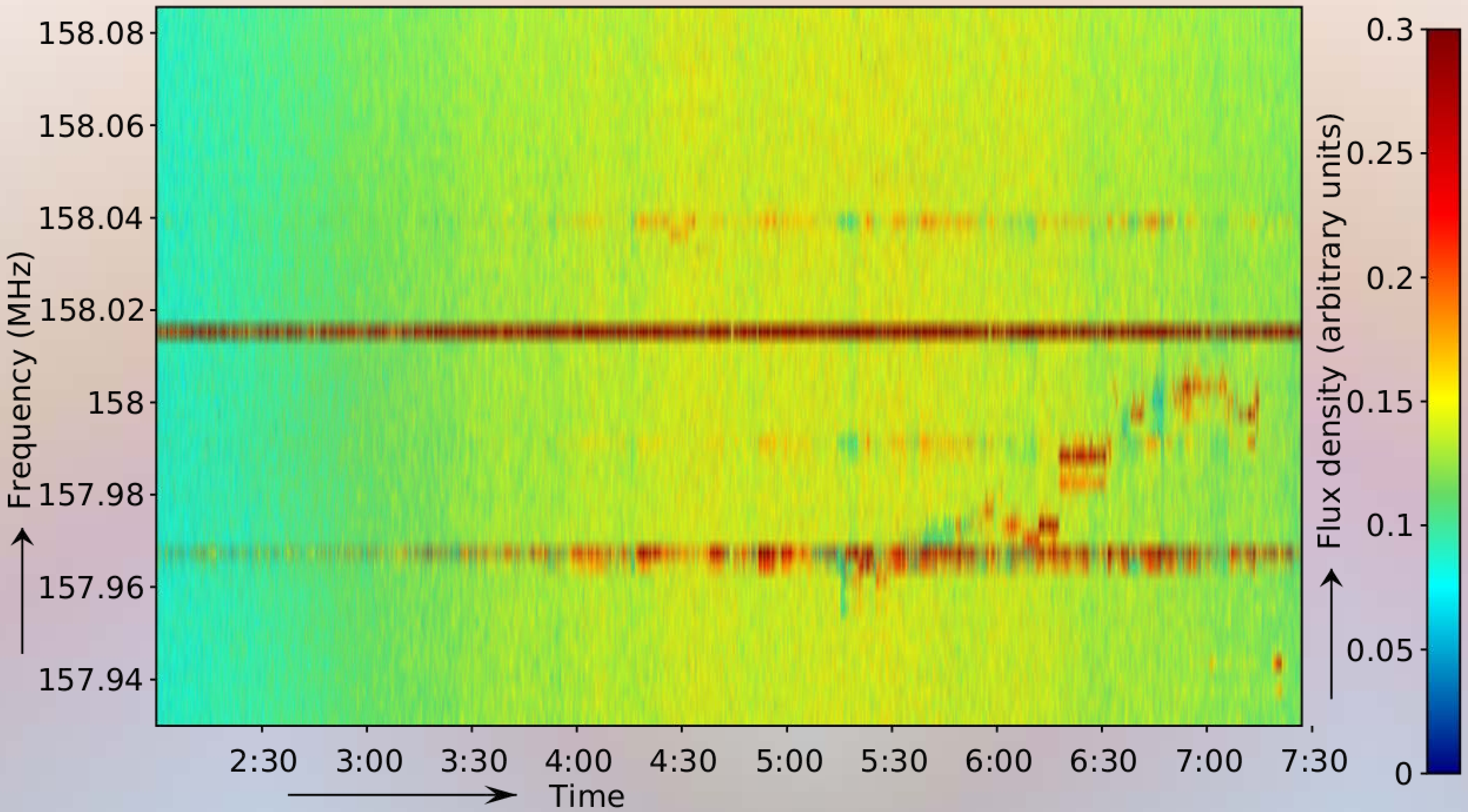
Outline

- Methods for accurately detecting RFI
- The LOFAR radio environment:
  - LOFAR's performance after RFI excision
  - Brightness distribution of RFI sources
  - Implications for EoR projects

Provocative statement

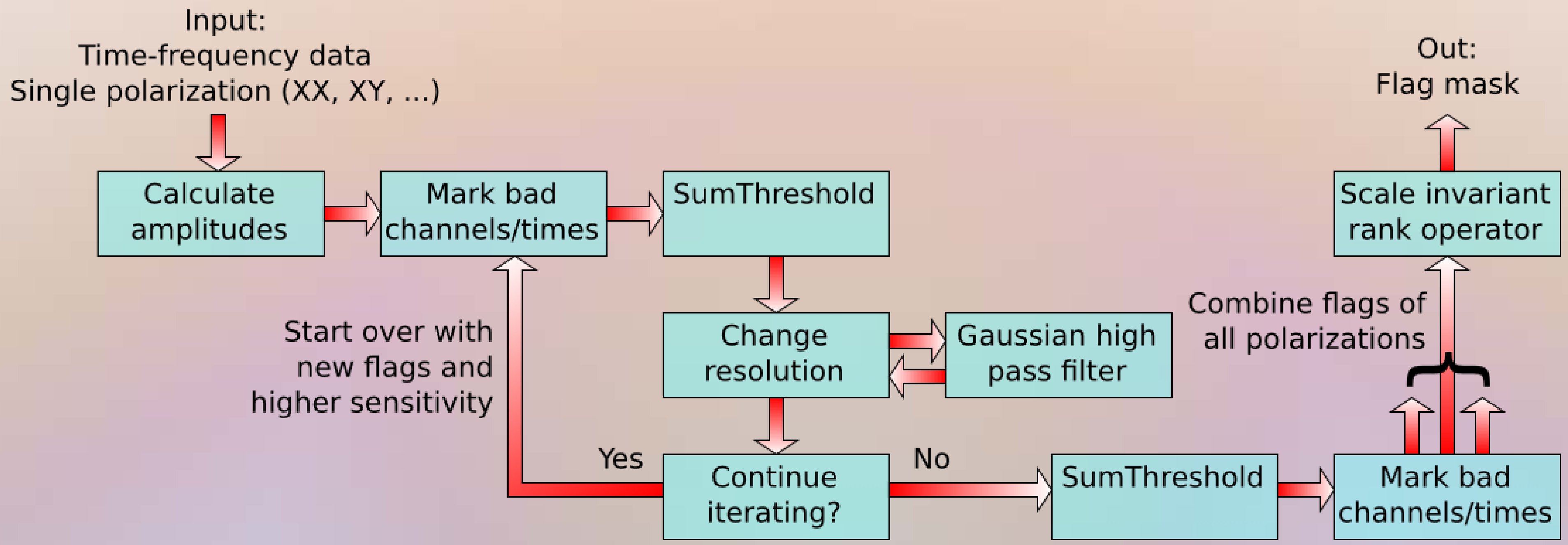
- Most EoR global experiments mention two problems:
  - RFI
  - Other
- But, considering that:
  - None of the recent detection methods are used
  - (Almost) no global experiment is yet using a resolution of > ~50.000 channels/100 MHz
  - LOFAR showed these make a huge difference
- We can not say that RFI is really a problem

Example of LOFAR data with RFI



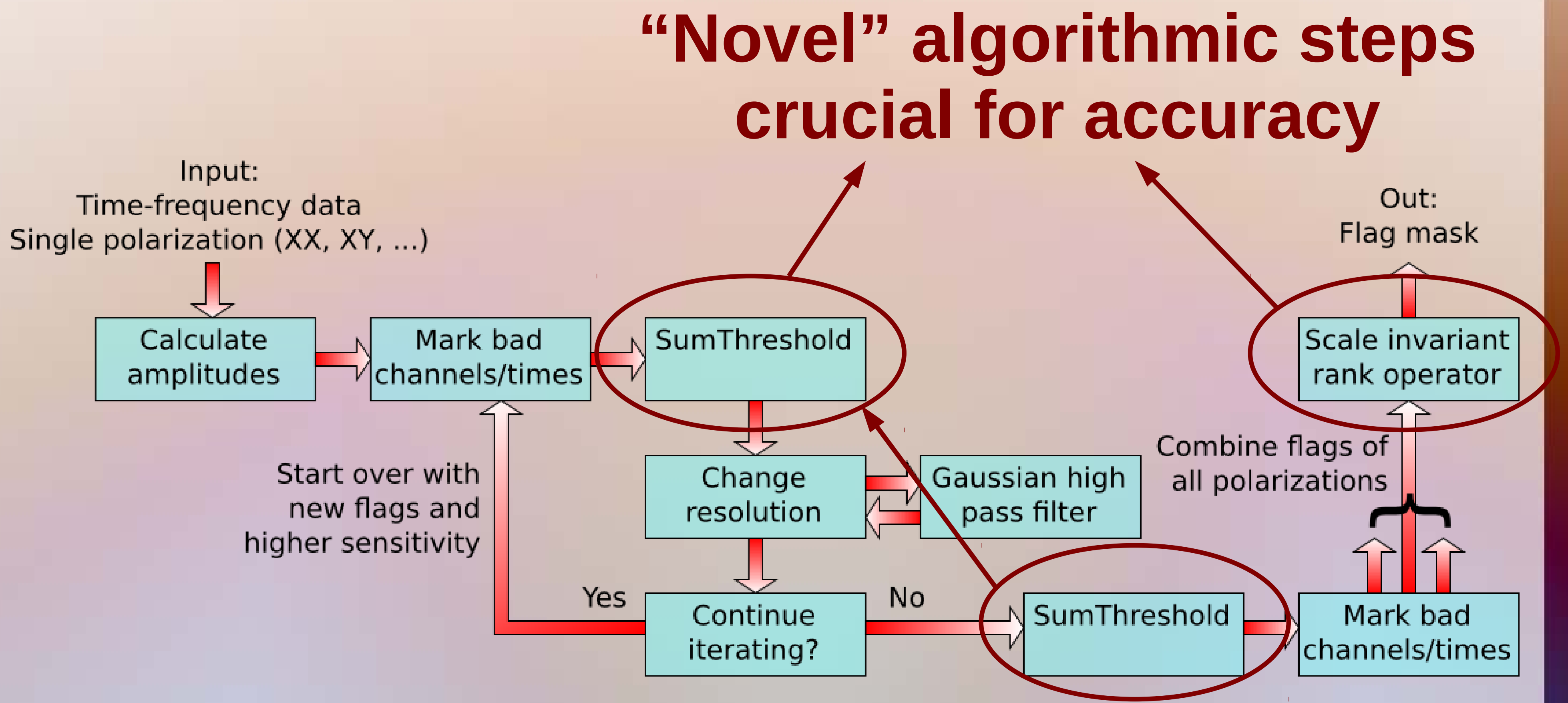
Cross-correlations of two stations showing strong RFI

The AOFlagger



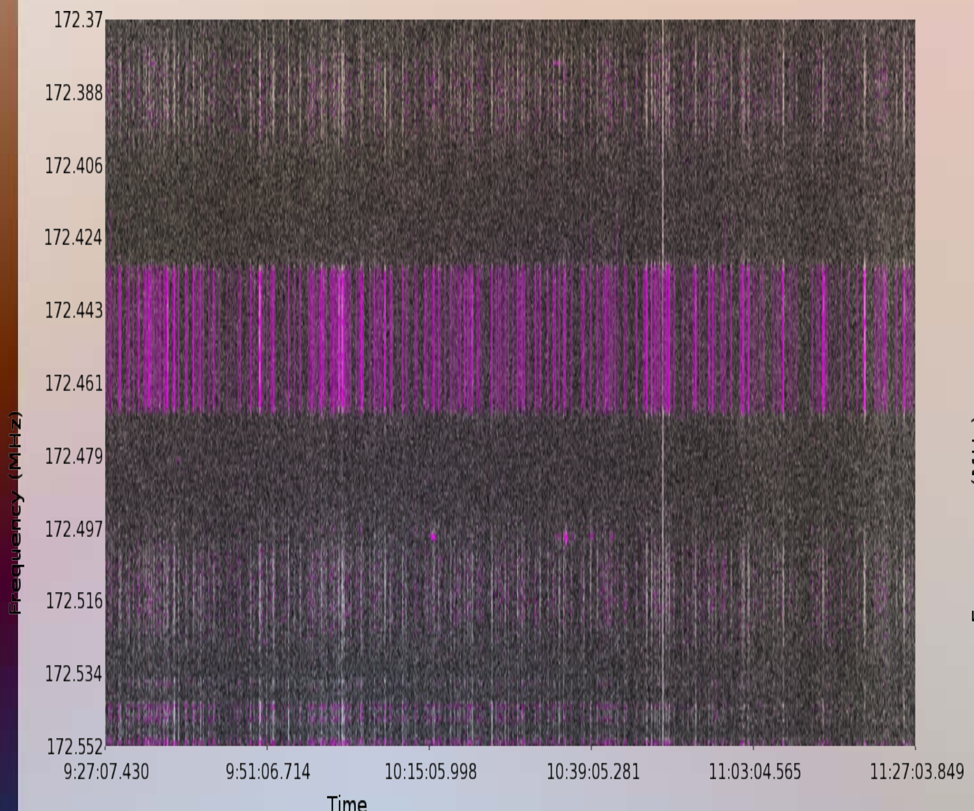
Offringa et al., MNRAS (2010), Offringa et al., A&A (2012a,b)

The AOFlagger

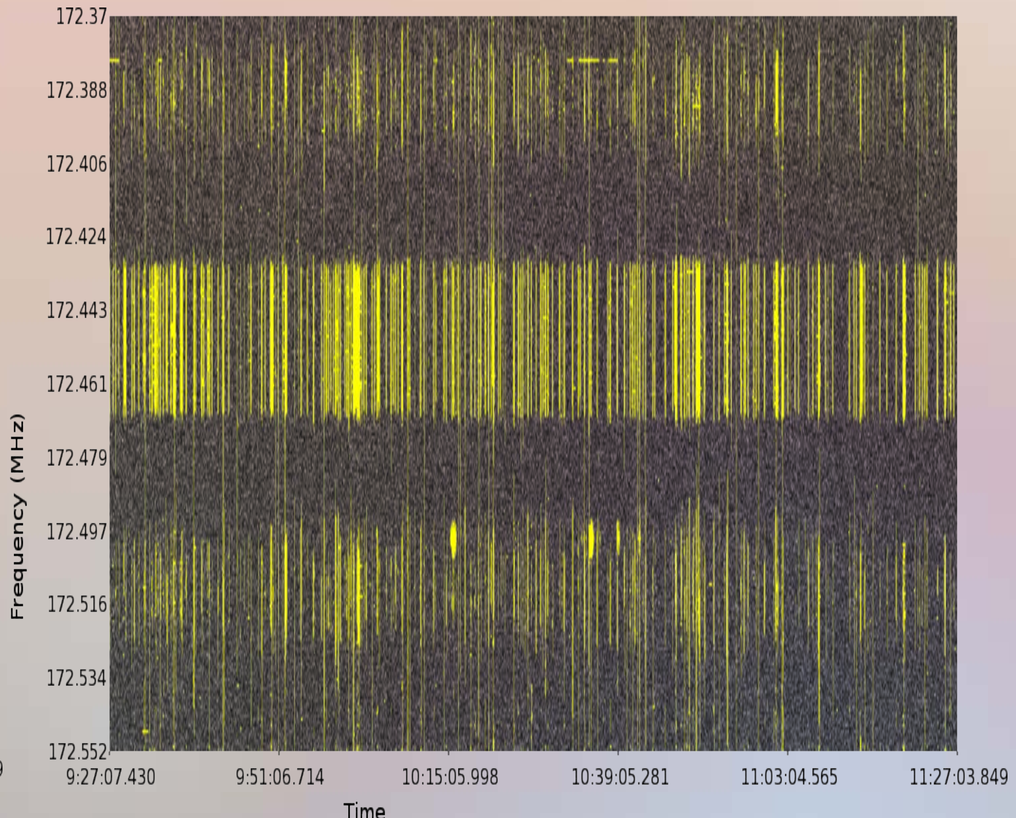


AOFlagger vs other flaggers

- Accuracy higher than other flaggers
- Fast

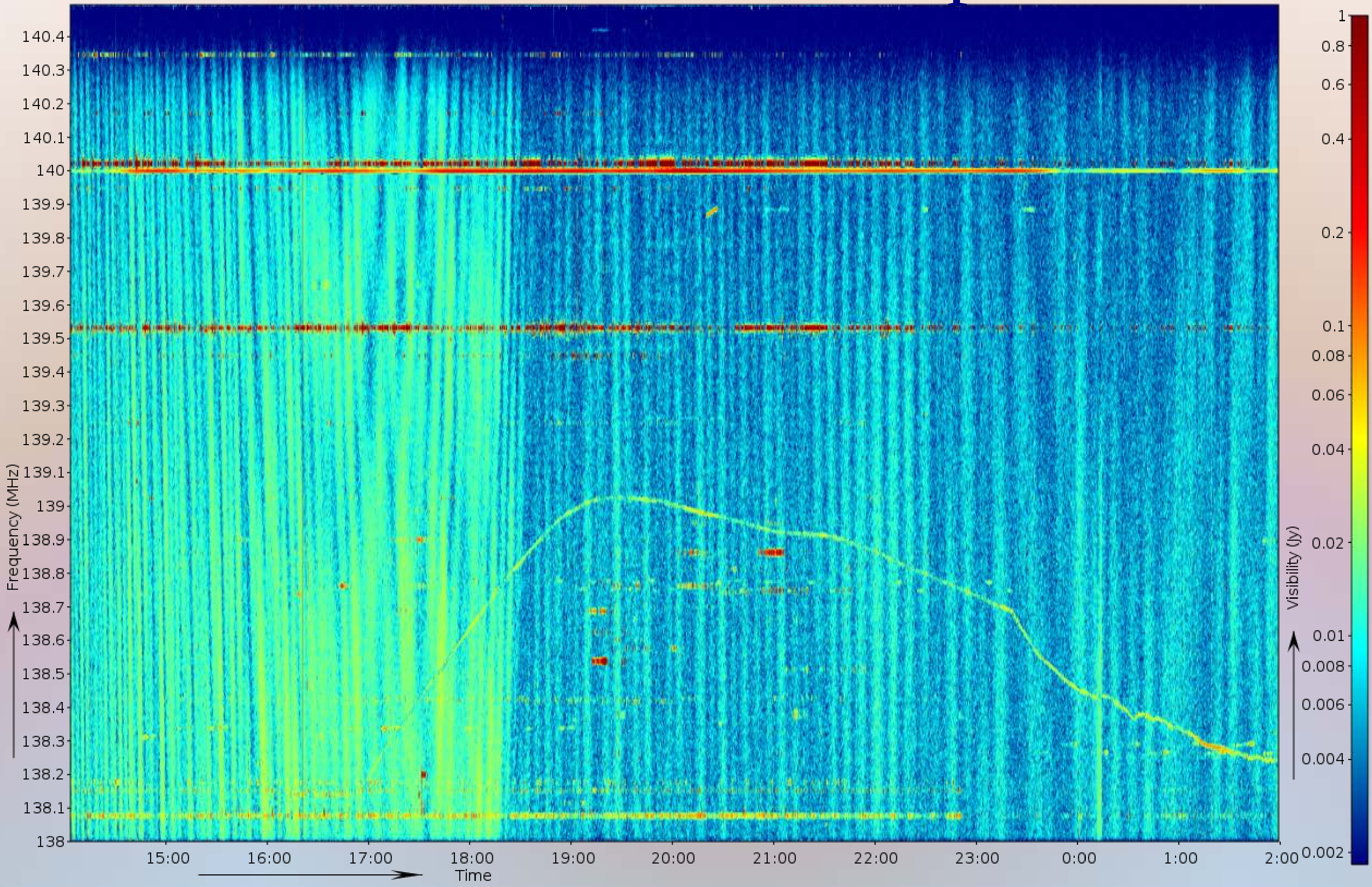


MAD flagger (comparable to Pyflag, Miriad's flagger, AIPS flagger)

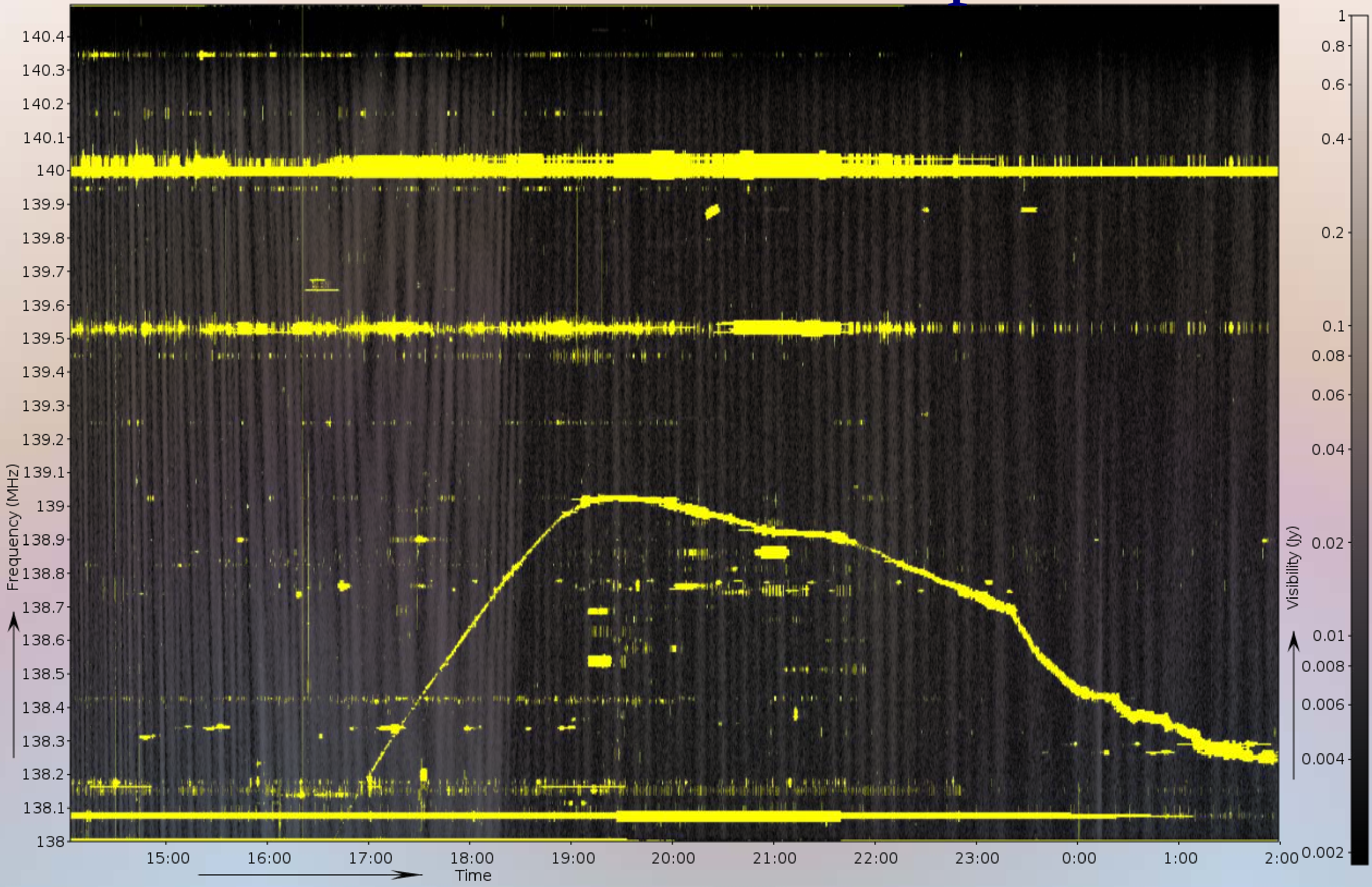


AOFlagger

WSRT data example



WSRT data example



Thresholding vs. AOFlagger

MWA 3 min observation with 32 tiles

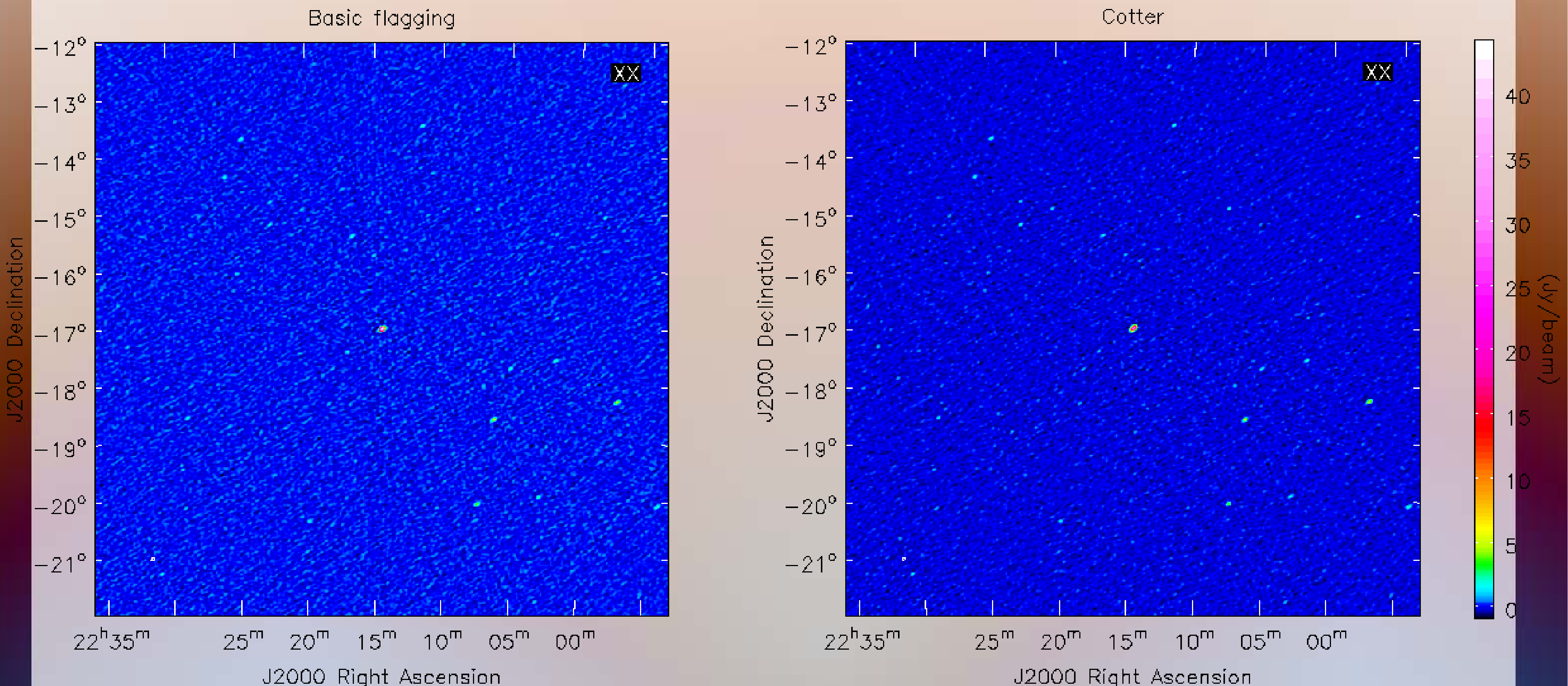


Image credit: Natasha Hurley-Walker

The LOFAR radio environment

Radio-Frequency Interference

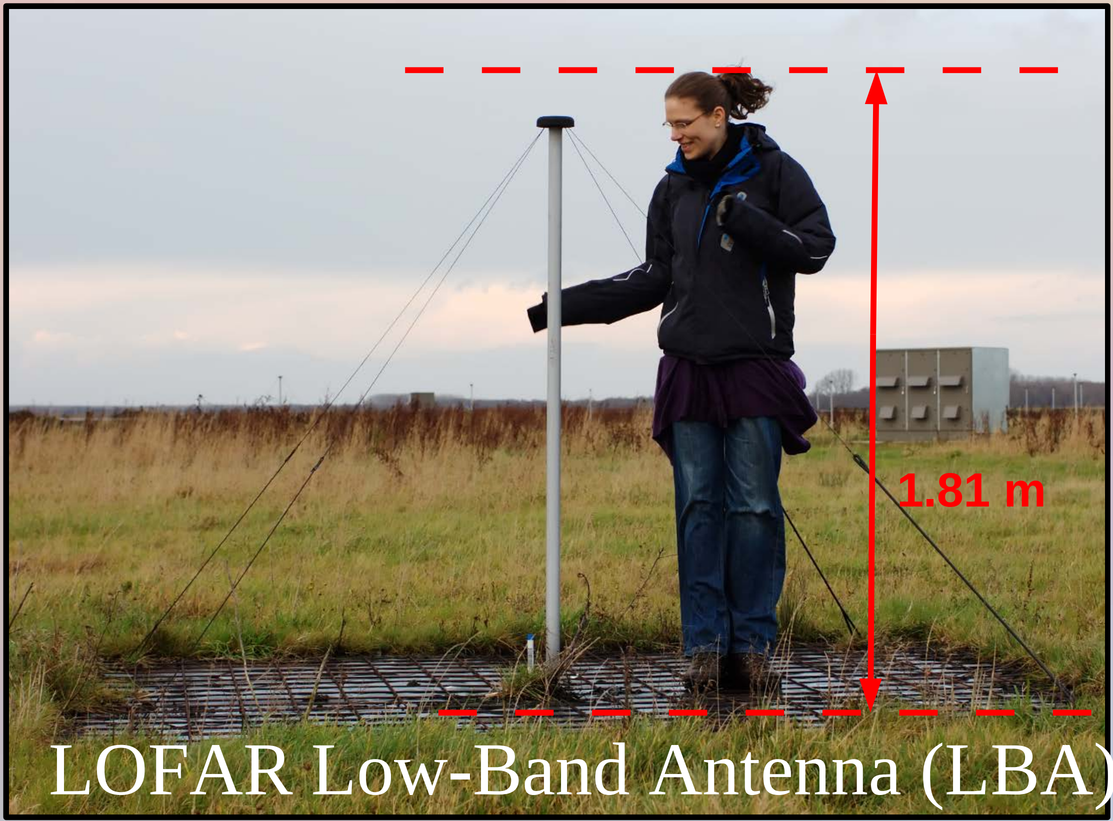
- The (Dutch) radio spectrum is almost entirely allocated to services other than radio astronomy

Dutch allocations:

Service type	**Frequency range(s) in MHz**
Time signal	10, 15, 20
Air traffic	10–22, 118–137, 138–144
Short-wave radio broadcasting	11–26
Military, maritime, mobile	12–26, 27–61, 68–88, 138–179
Amateur	14, 50–52, 144–146
CB radio	27-28
Modelling control	27–30, 35, 40–41
Microphones	36–38, 173–175
Radio astronomy	38, 150–153
Baby monitor (portophone)	39–40
Broadcasting	61–88
Emergency	74, 169–170
Air navigation	75, 108–118
FM radio	87–108
Satellites	137–138, 148–150
Navigation	150
Remote control	154
T-DAB	174–230
Intercom	202–209

The LOFAR radio environment

- Analysis of two LOFAR 24-h RFI surveys
- One for the LBA, one for the HBA



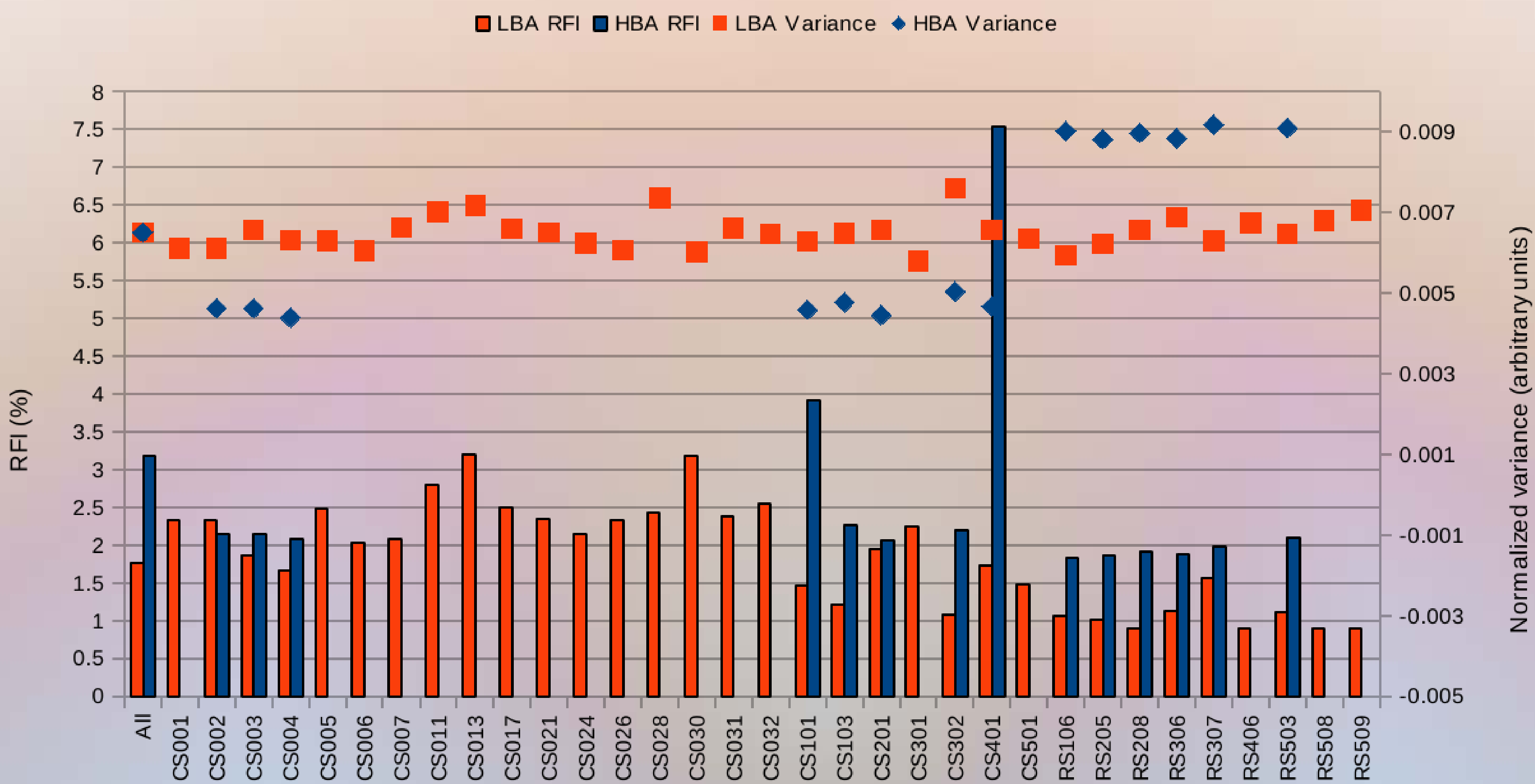
LOFAR Low-Band Antenna (LBA)

The survey data

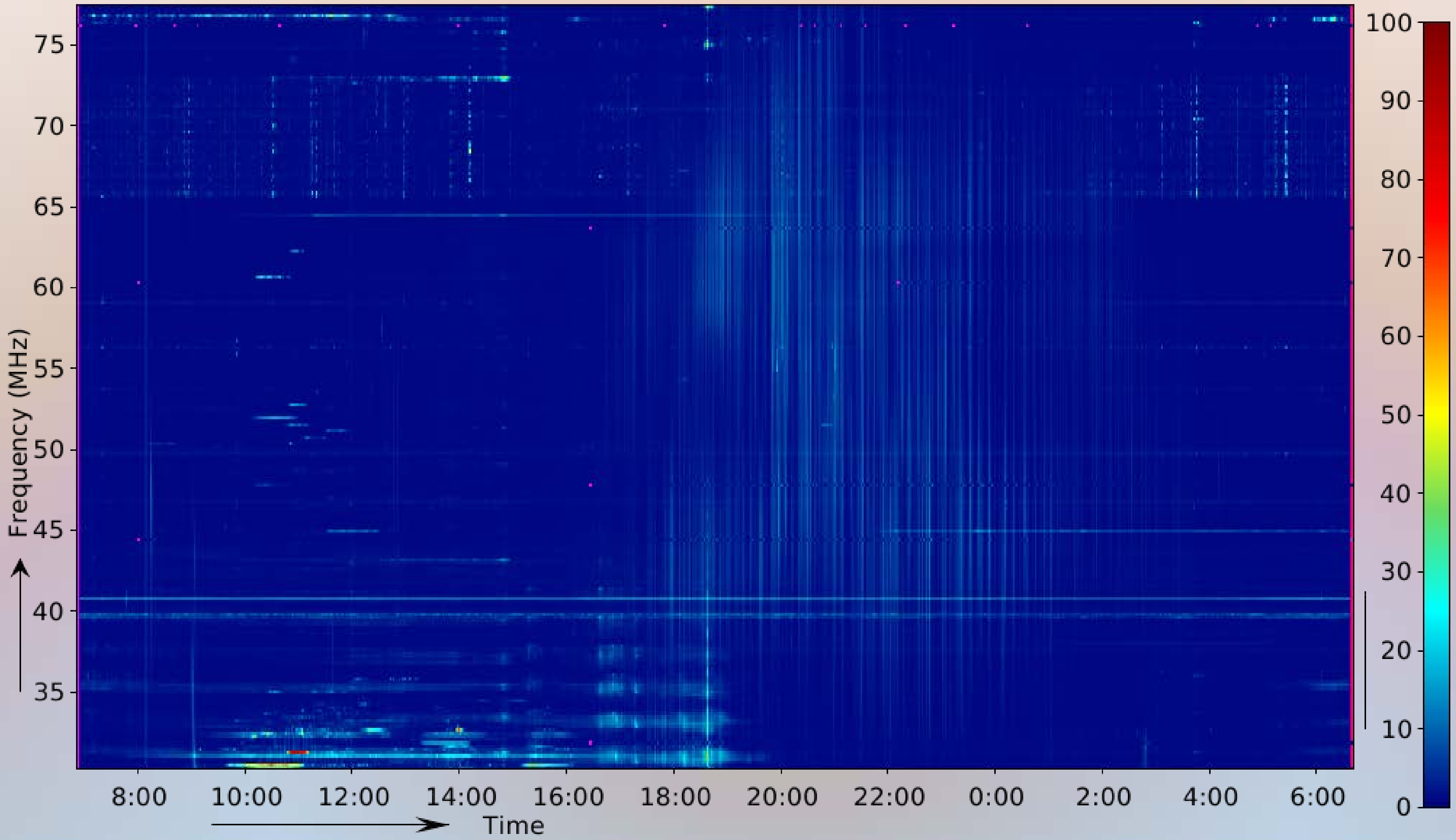
	LBA set	HBA set
Observation date	2011-10-09	2010-12-27
Start time	06:50 UTC	0:00 UTC
Length	24 h	24 h
Time resolution	1 s	1 s
Frequency range	30.1–77.5 MHz	115.0–163.3 MHz
Frequency resolution	0.76 kHz	0.76 kHz
Number of stations	33	13
Total size	96.3 TiB	18.6 TiB
Field	NCP	NCP
Amount RFI detected	1.77%	3.18%

Offringa et al., A&A 2012b.

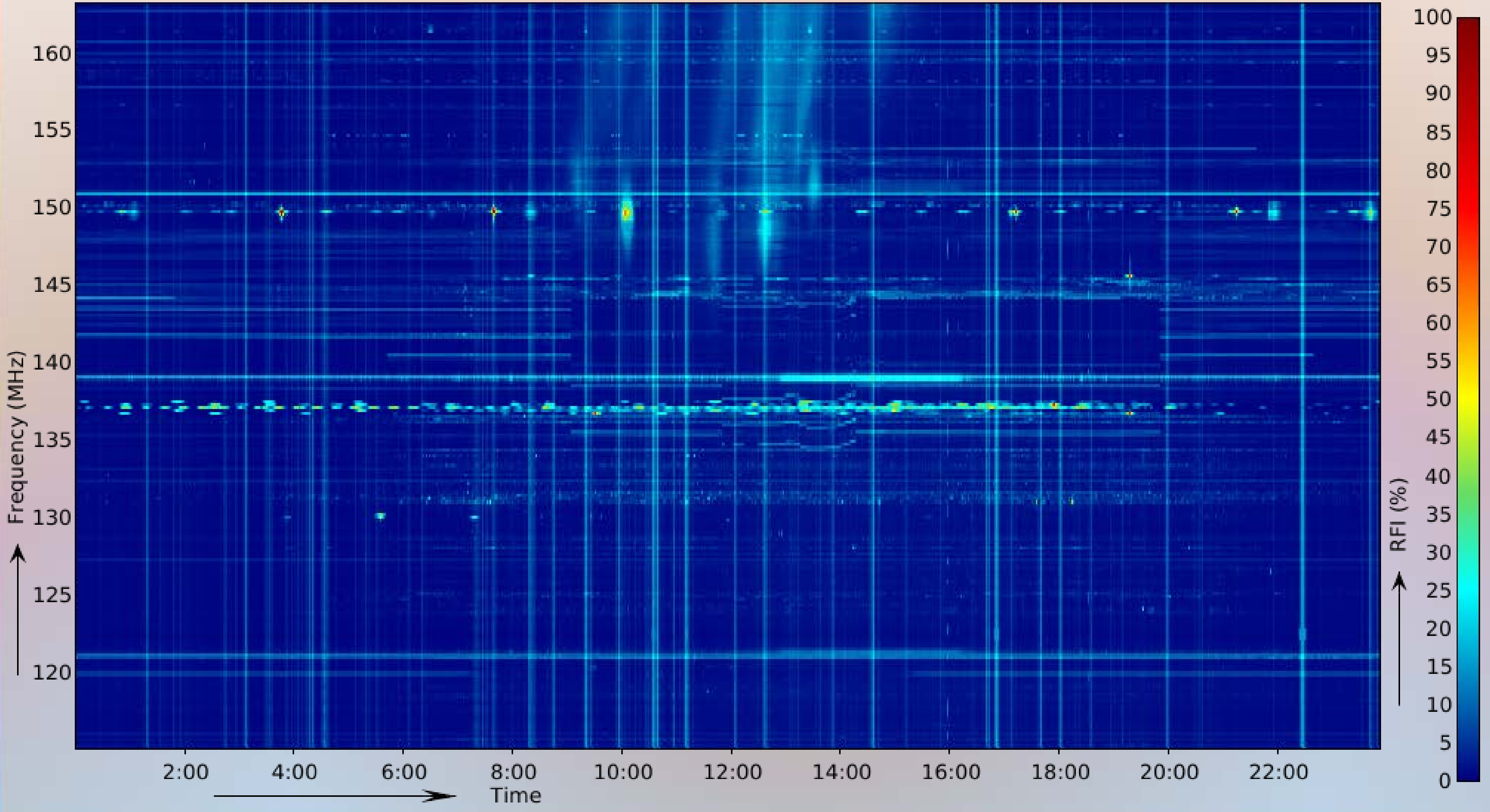
RFI and variance per station



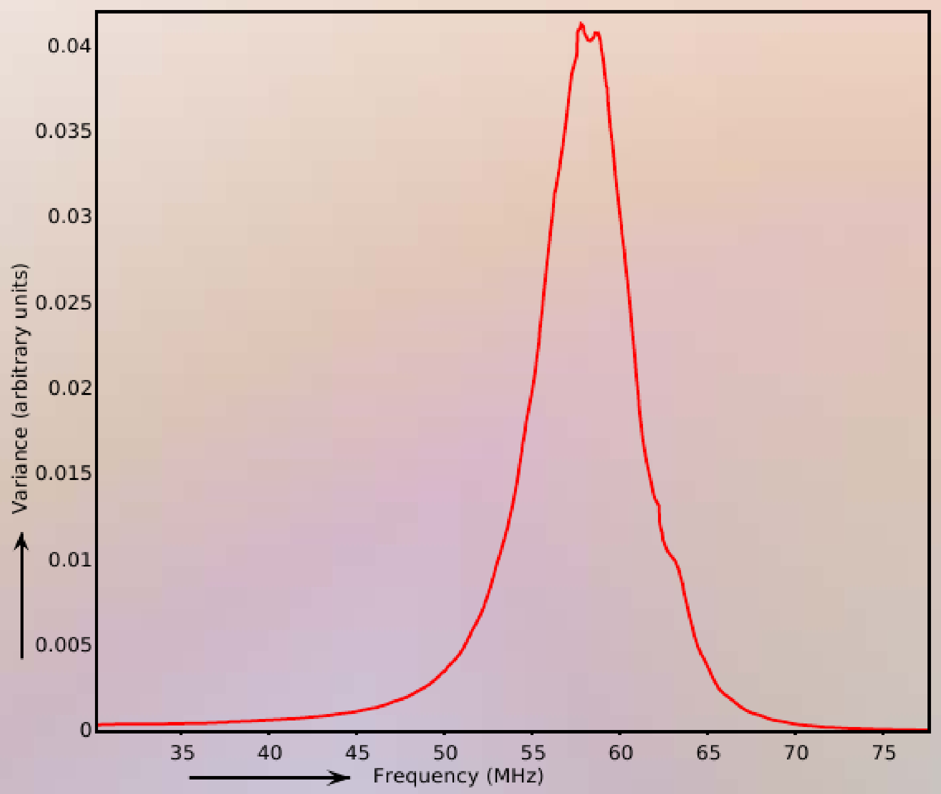
Detected RFI in the LBA

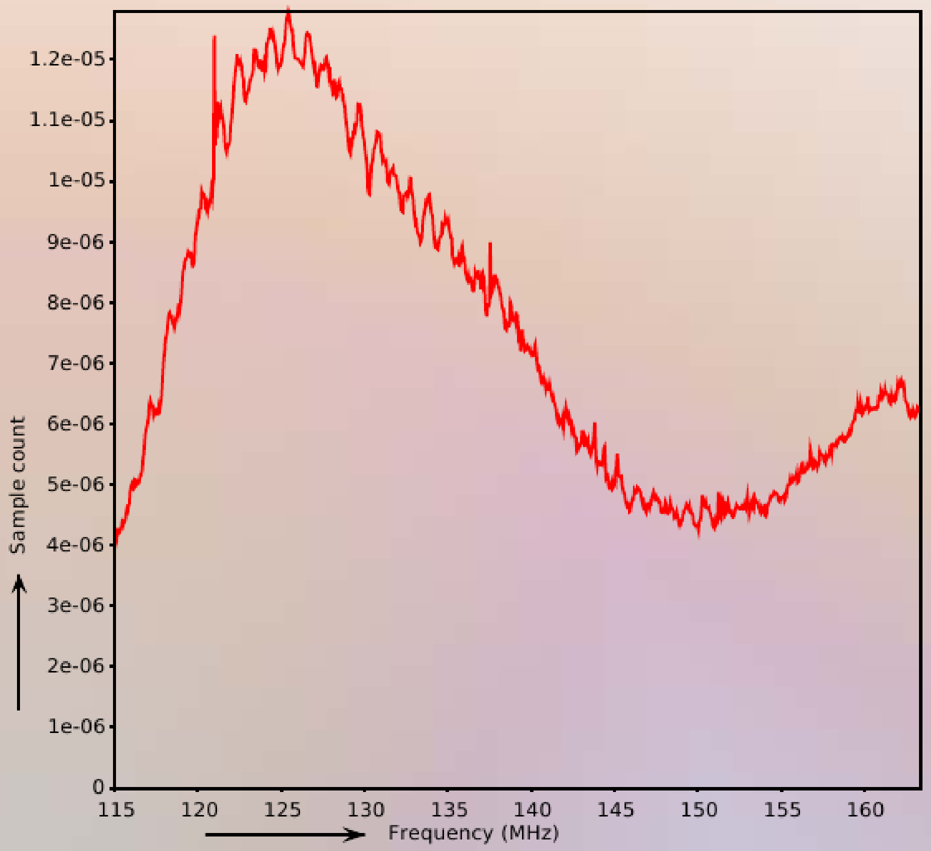


Detected RFI in the HBA



RFI excision results





- LBA (left) clean
- HBA (right) some small residuals

RFI excision results

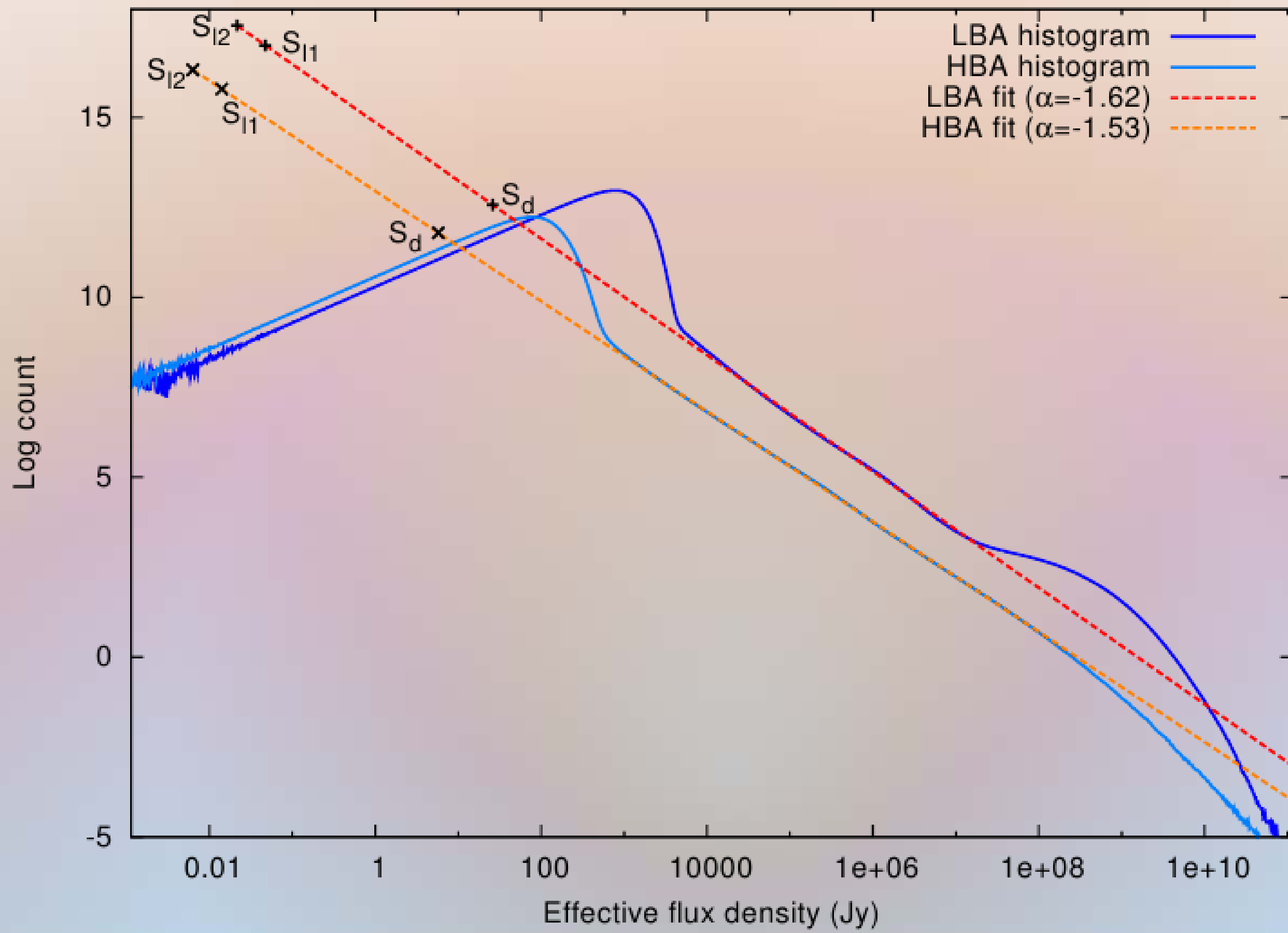
- “Leaked” RFI in HBA due to “smooth” transmitters
- These are only smooth at 1 s/1 kHz resolution
- A possible 2nd stage flagger at lower resolution could solve these residuals
- Because they are weak, they are currently not affecting the (imaging) sensitivity

RFI excision conclusions

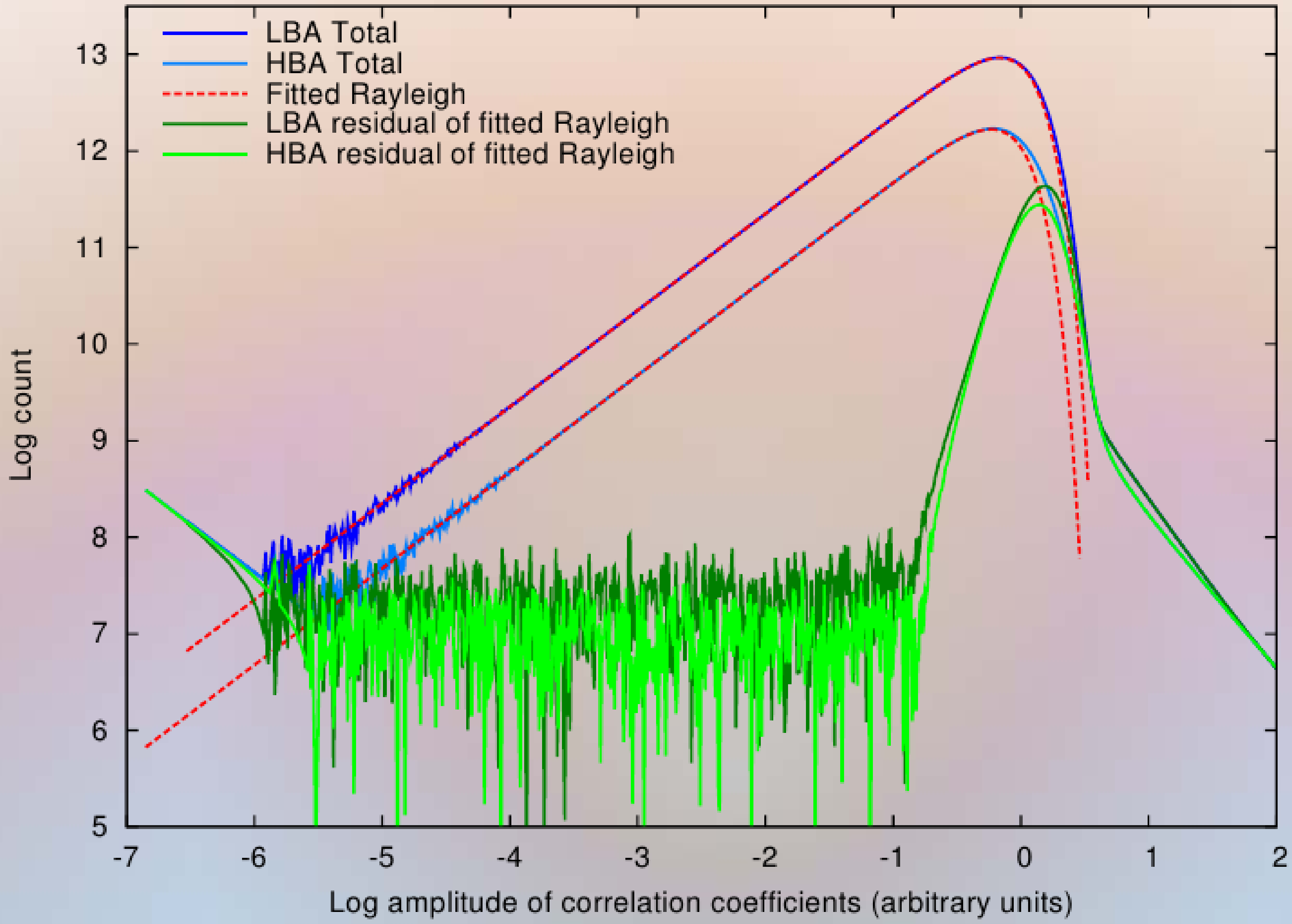
- LOFAR's environment:
  - Fully automated detection, only a few % lost data
  - Only small residuals, do not affect image quality
  - 2nd stage flagger not yet used
- Why such good results?
  - LOFAR has very high time/freq resolutions
  - Design has accounted for interference
  - Unprecedented accuracy of algorithms
- Some transmitters do remain problematic (e.g., DAB, FM, wind turbines)

Analysis of brightness distribution

Total brightness distribution



The left part is well-behaving noise...



First order distribution implications

- Bi-variate: left part (noise) and right part (RFI)
- Left part follows Rayleigh very accurately
  - Well explained
- Right part follows power-law distribution (~x^-1.6)
  - Why?

A uniform distribution of RFI sources

How they propagate:

$$S(r) = \frac{Ig}{r^2}.$$

(Brightness of a source at distance r)

Resulting in a distribution:

$$\begin{aligned} f_S(S) &= \frac{dF_{\text{amplitude} \leq r}}{dS} \\ &= \frac{c\pi Ig}{S^2}. \end{aligned}$$

(Differential nr. sources with amp < S)

I : instantaneous intrinsic strength of source
g : instrumental gain
r : distance of source to receiver
S : apparent brightness
c : constant that describes source density

Why don't we see -2 power law?

$$S(r) = \frac{Ig}{r^2}.$$

(Brightness of a source at distance r)

r^2 fall-off assumes free-space propagation

However, there are effects of diffraction, refraction and reflection

Why don't we see -2 power law?

$$S(r) = \frac{Ig}{r^2}.$$

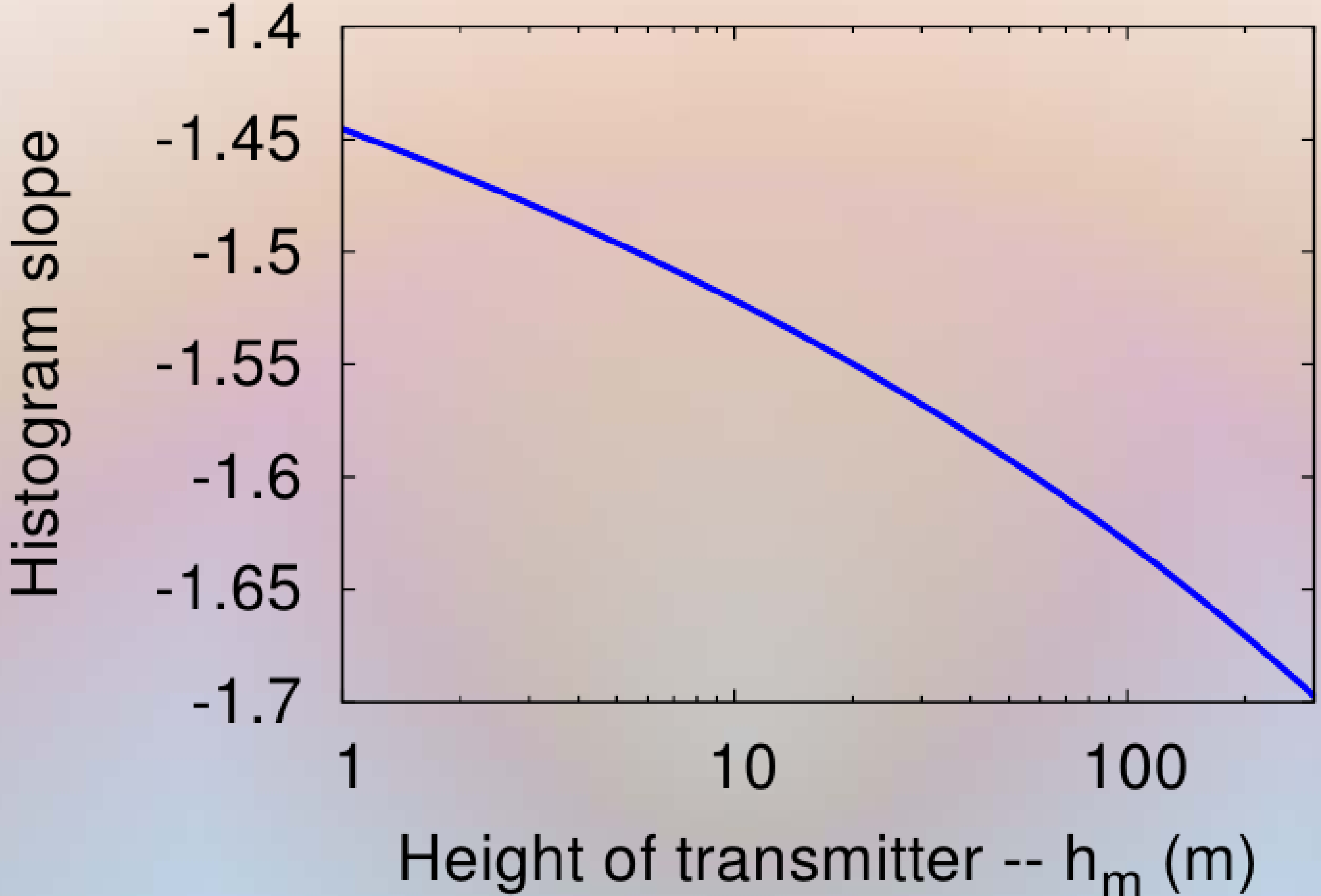
(Brightness of a source at distance r)

- There exists a well-established empirical propagation model by *Hata (1980)* for propagation of communication signals (υ > 150 MHz)

$$L_p = 69.55 + 26.16 \log_{10} f_c - 13.82 \log_{10} h_b - a(h_m) + (44.9 - 6.55 \log_{10} h_b) \log_{10} r$$

- Implies radiation fall-off faster than r^2

Slope as function of transmitter height



Actual slope found

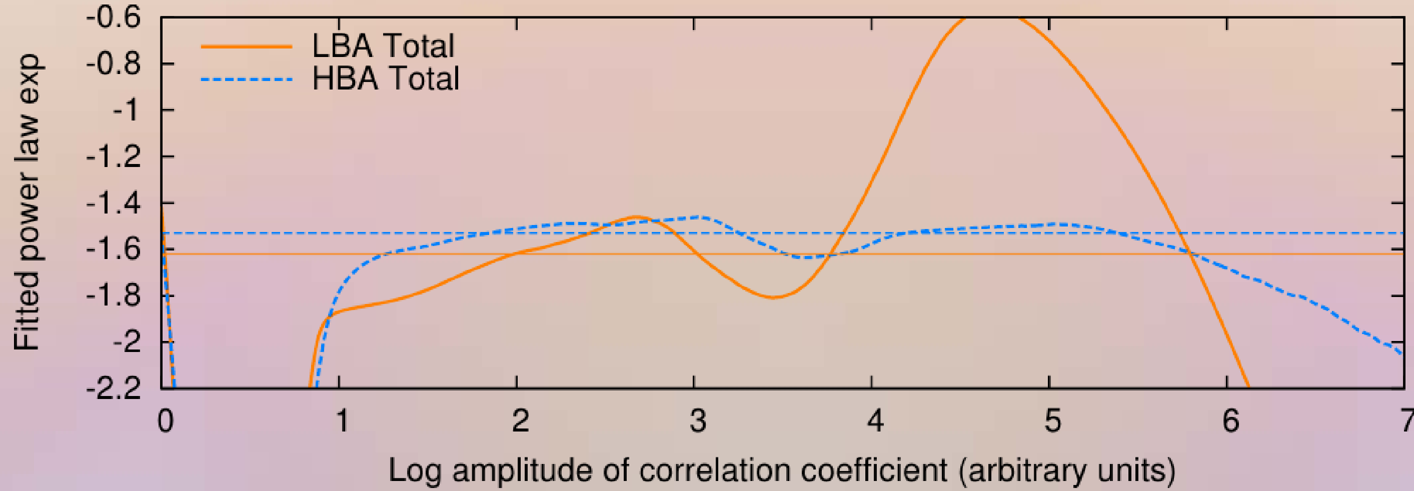
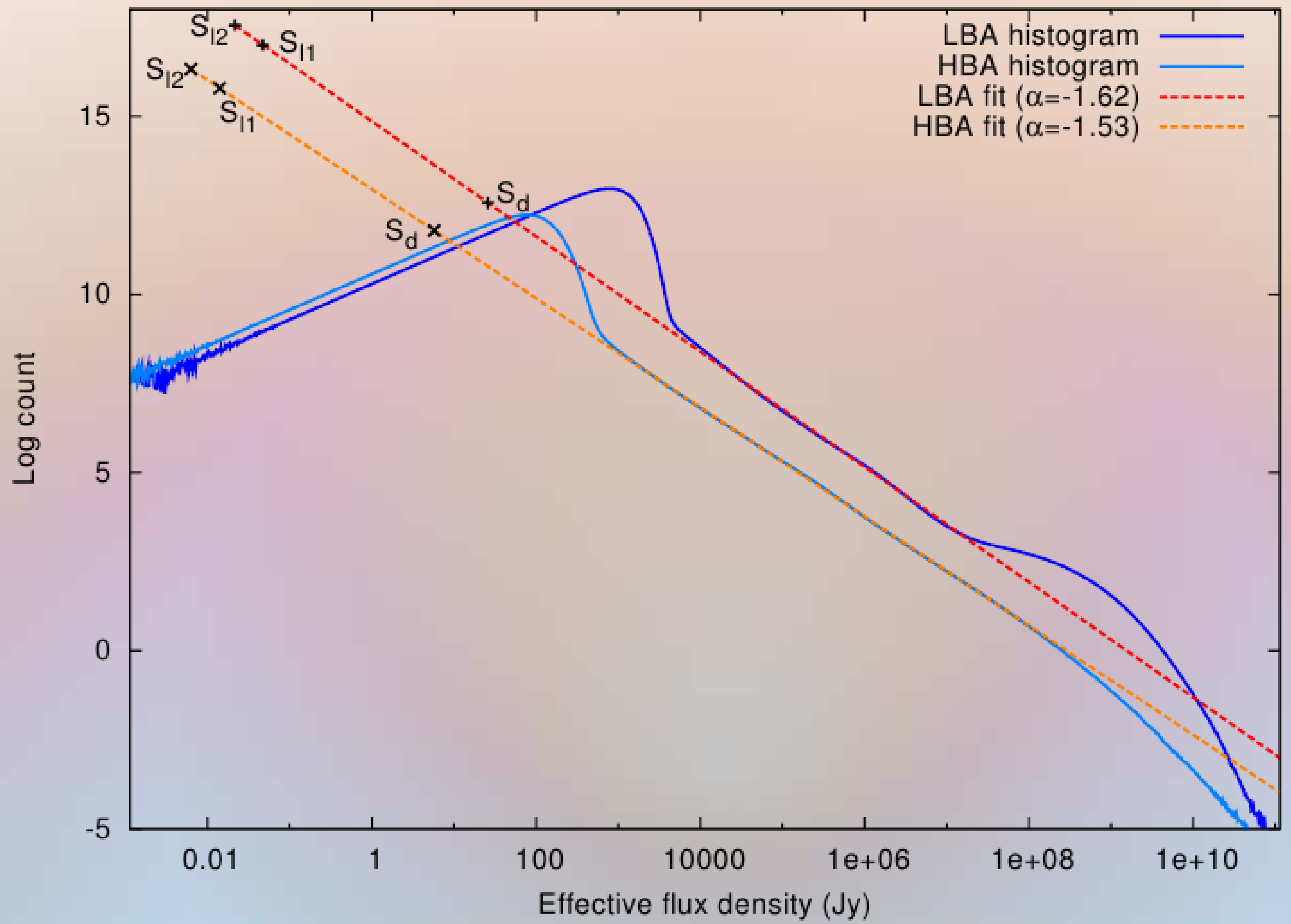


Figure 6.11: *The slope of the band-pass corrected log-log histogram as a function of the brightness. The horizontal lines indicate the fitted slope over the full (semi-) stable region. The horizontal axis is not calibrated.*

Total brightness distribution



Conclusions & best practices for EoR

- Learned a lot about RFI
- Significant detection improvement by:
  - High time/frequency resolution (~ 1 s / 1 kHz)
  - Recent detections algorithms* (not just thresholding)
  - Good signal path design (no ADC/amp saturation)
- Easy and cheap to try
- It is to be seen if RFI is a problem
  - Not (yet) an argument for more expensive alternatives

**AOFlagger code is publicly available at http://aoflagger.sourceforge.net/*