Data inspection, editing & **R**adio-**F**requency **I**nterference flagging

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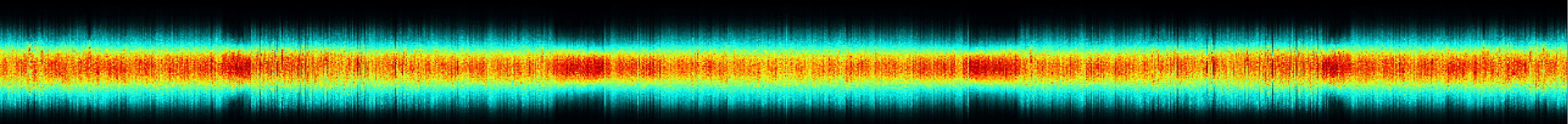


2015-09-06

Outline

- Introduction: Why data editing
- Radio Frequency Interference (RFI)
- Plotting data (CASA, aoqplot)
- Manual data flagging
- Automatic RFI flagging algorithms
- Data averaging
- Sources of imaging errors

Introduction

Why data editing?

Introduction

Why data editing?

Some antennas might not have been functioning properly...

Introduction

Why data editing?

- Broken elements (antennas/stations)
- Correlator malfunctions
- Shadowing
- Initial pointing delay

- Bandpass issues
- Low elevation
- Correlated noise on some baselines
  (e.g. LOFAR split stations)
- Interference

Introduction

Why data editing?

- Broken elements → remove antennas
- Correlator malfunctions → remove timesteps
- Shadowing → remove antennas in time range
- Initial pointing delay → remove first timesteps

- Bandpass issues → remove channels
- Low elevation → remove antennas with low elevation
- Correlated noise on some baselines (e.g. LOFAR split stations) → Flag baselines
- Interference → remove antennas, timestep, frequencies or baselines...

Data can't be (self-)calibrated when any of these issues are still in the data.

Therefore, data inspection & editing is the first step :

INSPECTION + EDITING

↓

(DATA AVERAGING)

↓

CALIBRATION

↓

IMAGING

First step in data reduction: Data inspection
(example of `casaplotms` on other screen)

- Start casaplotms
- Open MS ('3c196_spw5_sub1.ms')
- Press 'plot' (plots amplitude vs time)
- Goto 'axes', select "frequency" as x-axis

  RFI is visible
- Select 'antenna1'

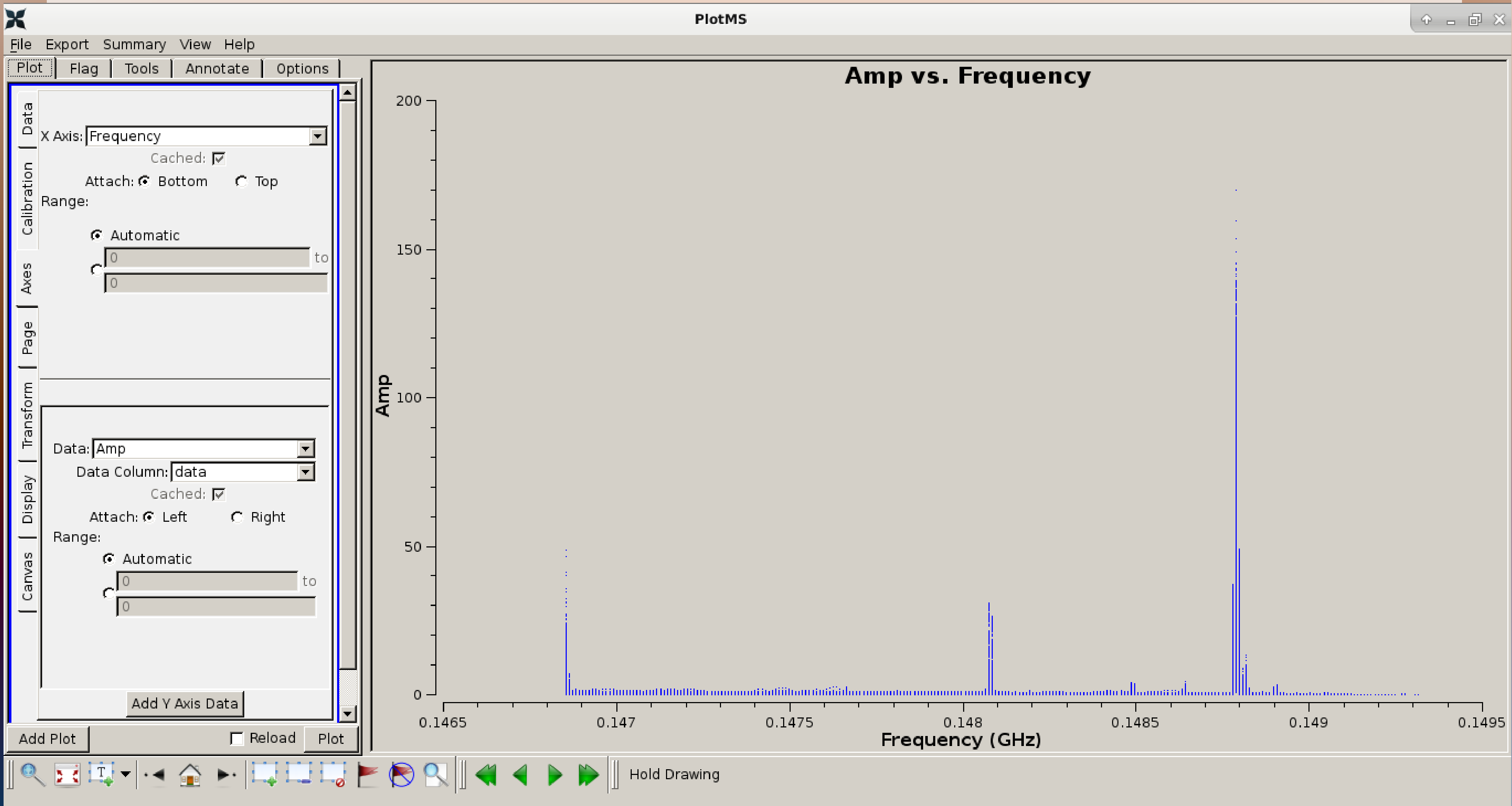
  antenna5 has no data

- (Enter:

  antenna: "0;13"

  msselect: "ANTENNA1!=ANTENNA2")

casaplotms



PlotMS
File
Export
Summary
View
Help
Plot
Flag
Tools
Annotate
Options
Data
Calibration
Axes
Page
Transform
Display
Canvas
X Axis: Frequency
Cached:
Attach: Bottom
Top
Range:
Automatic
to
Data: Amp
Data Column: data
Cached:
Attach: Left
Right
Range:
Automatic
to
Add Y Axis Data
Add Plot
Reload
Plot
Amp vs. Frequency
Amp
200
150
100
50
0
0.1465
0.147
0.1475
0.148
0.1485
0.149
0.1495
Frequency (GHz)
Hold Drawing

casaplotms

- What should we see in casaplotms (time vs amplitude) if we observe a single unresolved (=delta function) source with a certain flux?

(That's what we want calibrators to be – strong (i.e. dominating / 'single') and unresolved)

casaplotms

- casaplotms is useful for many things:
  - Browsing for bad antennas, frequencies, etc.
  - Also useful for inspecting calibration results
  - Or getting an idea of model data
  - Further discussed in Andy Biggs' tutorial
- Many observatories have specialized plotting tools

Removing data

- If an issue is found (bad antenna, baseline, channels, ...) how do we remove it from our dataset?
    - We don't actually remove data, we **'flag'** data and ignore these in further processing.
    - Flagging is not the same as setting to zero(!)
- 'taql' is a useful tool for data editing.

TaQL (Table Query Language)

- TaQL is an 'SQL'-like language for quick data editing of CASA data.
- Command line tool 'taql' available, easy for scripting
- Be careful when editing! Always keep backups.
- Some examples: (from the cmdline)
  - `taql “select unique TIME from obs.ms”`
  - `taql “update obs.ms set FLAG=true where ANTENNA1==ANTENNA2”`
- → See taql doc (“casacore note 199”)
  http://www.astron.nl/casacore/trunk/casacore/doc/notes/199.html

Other ways to edit data...

- CASA task '`flagdata`'

  → Andy Biggs' tutorial

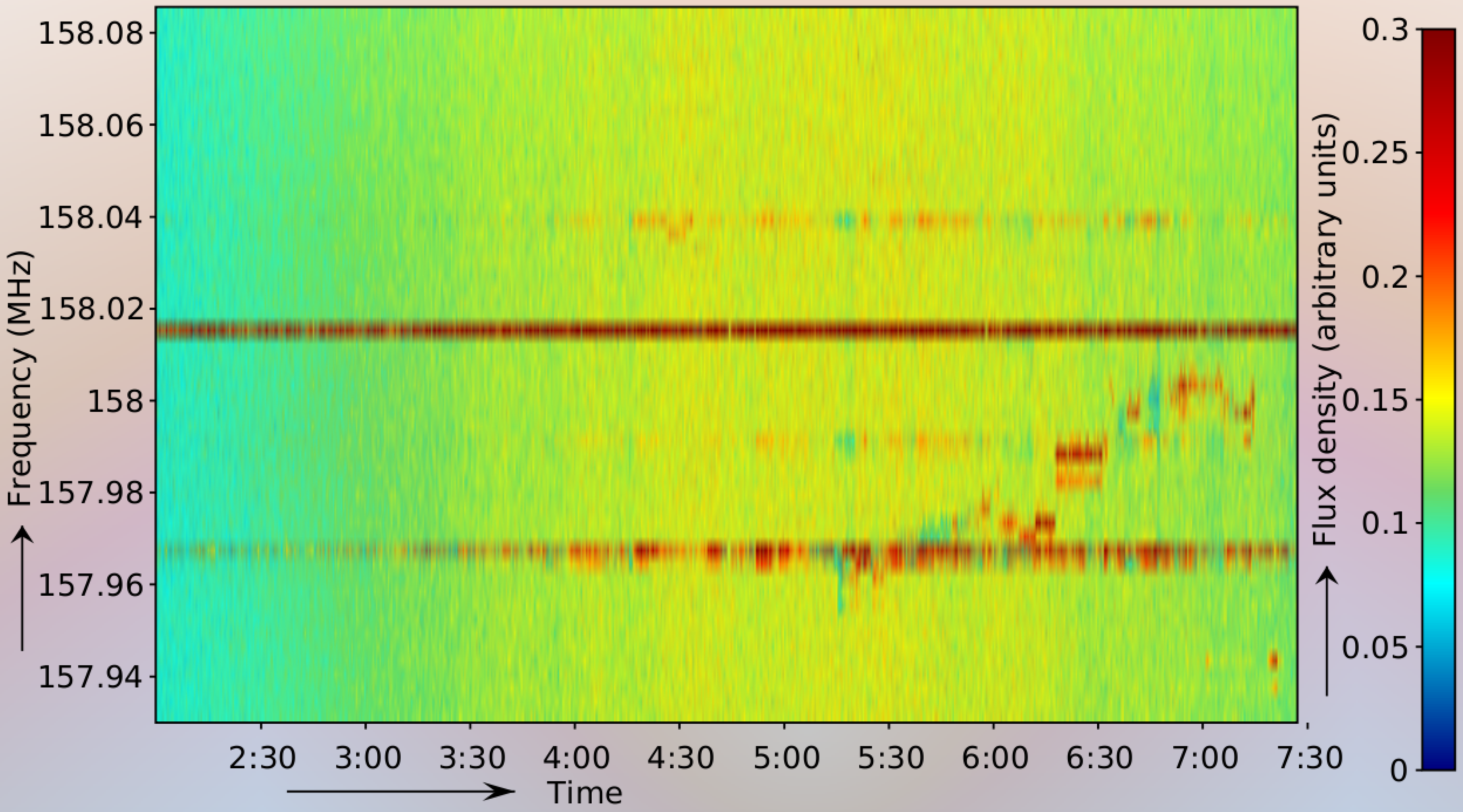
- Or, for CASA data: Write Python scripts
- Other packages have their own scripting languages / tasks

Radio-Frequency Interference

- Our radio spectrum is almost entirely allocated to services other than radio astronomy
- FM, airplane communication, satellite downlink, remote controls, digital broadcasts, …
- Also “accidental” and natural occurrence of RFI:
  - Cars, electrical fences, high-voltage lines (anything that sparks), lightning, the sun, etc.

- RFI can cause (self-)calibration to fail and/or reduce imaging sensitivity

Example of LOFAR data with RFI



Cross-correlations of two stations showing strong RFI

RFI

- Lots of interference at low frequencies (<1.5 GHz, e.g. LOFAR, GMRT, WSRT, EVLA, MWA, …)
- Less of an issue for
  - higher frequencies (ALMA); or
  - VLBI

but mitigation still required in most cases.

Excising RFI

- Detection methods are common in radio astronomy

- Common methods:
  - Manual selection by data reducing astronomer
  - Thresholding / specialized project pipelines
    (e.g. Baan et al. 2004, Winkel et al. 2007)
- **Manual selection is not practical for modern observatories:**
  - Enormous data volumes, computationally fast algorithms required.
  - Needs to be more accurate than thresholding

RFI stages / strategies

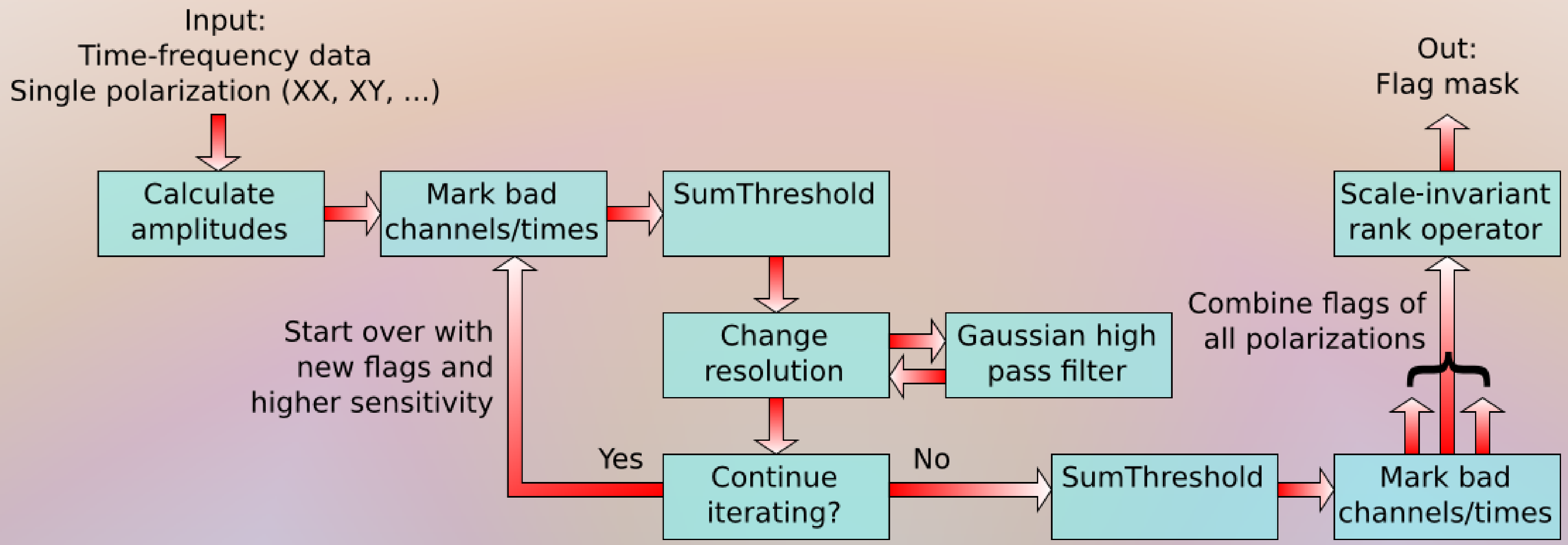
Many RFI excision options:

- Online pre-/post-correlation mitigation
  - Memory/computational constraints
  - Required for coherent (high time res) modes
- Offline mitigation
  - Post-optimizable, not real-time, data can be reordered
- LOFAR: Station level spatial filtering
  - Expensive, low SNR, only “one chance”
  - Allows data recovery
-

Automated excision of RFI

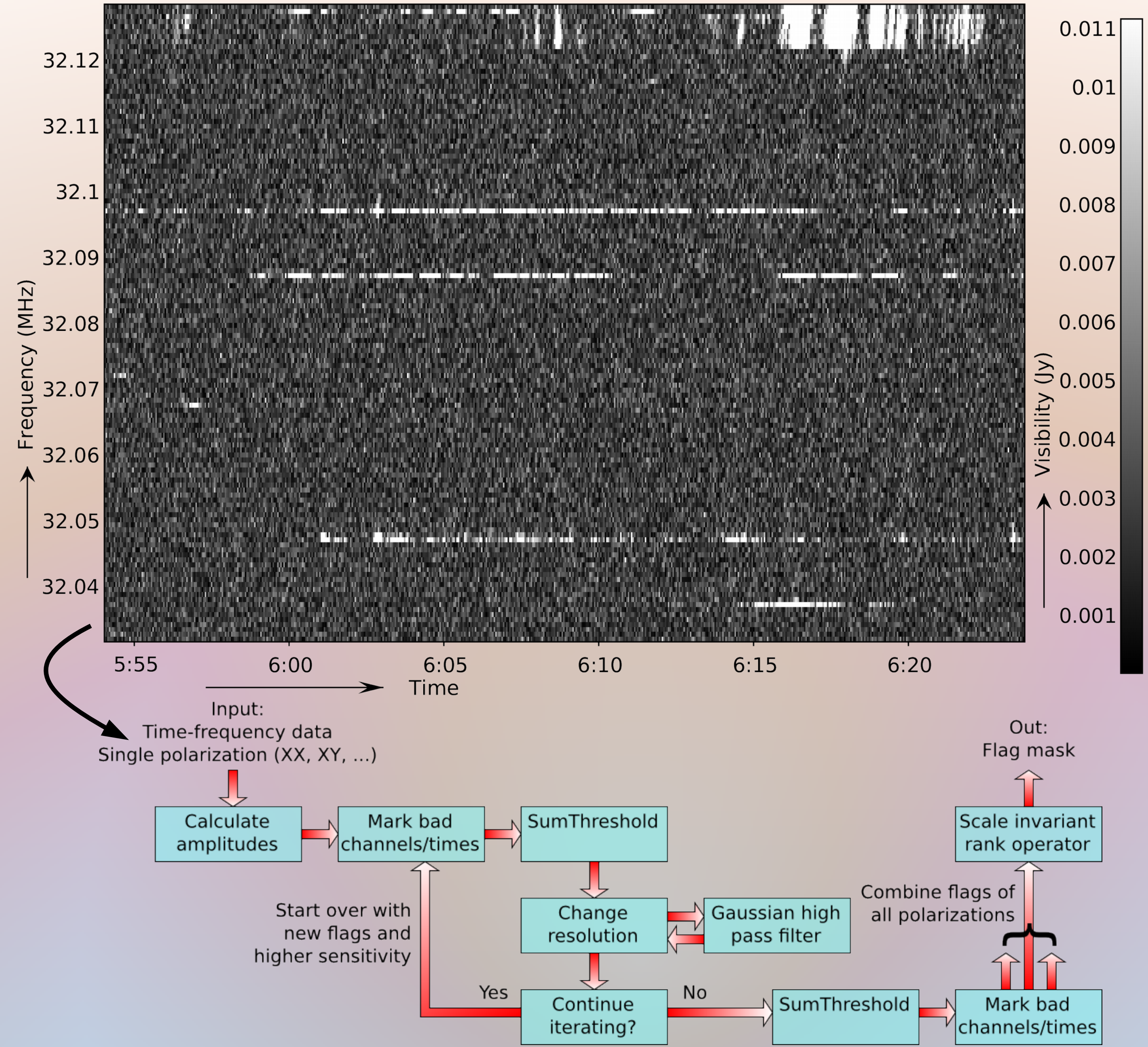
- Two classes of RFI excision methods:
  - Detection: find & throw away affected data
  - Filtering or subtracting: estimate RFI contribution and restore affected data
- Detection methods (“flagging”) commonly used
  - Some specialized pipelines for surveys or instruments
- Filtering RFI is harder
  - Resulting data quality is not well understood
  - Requires more resources
  - Lack of full (automated) filtering pipelines

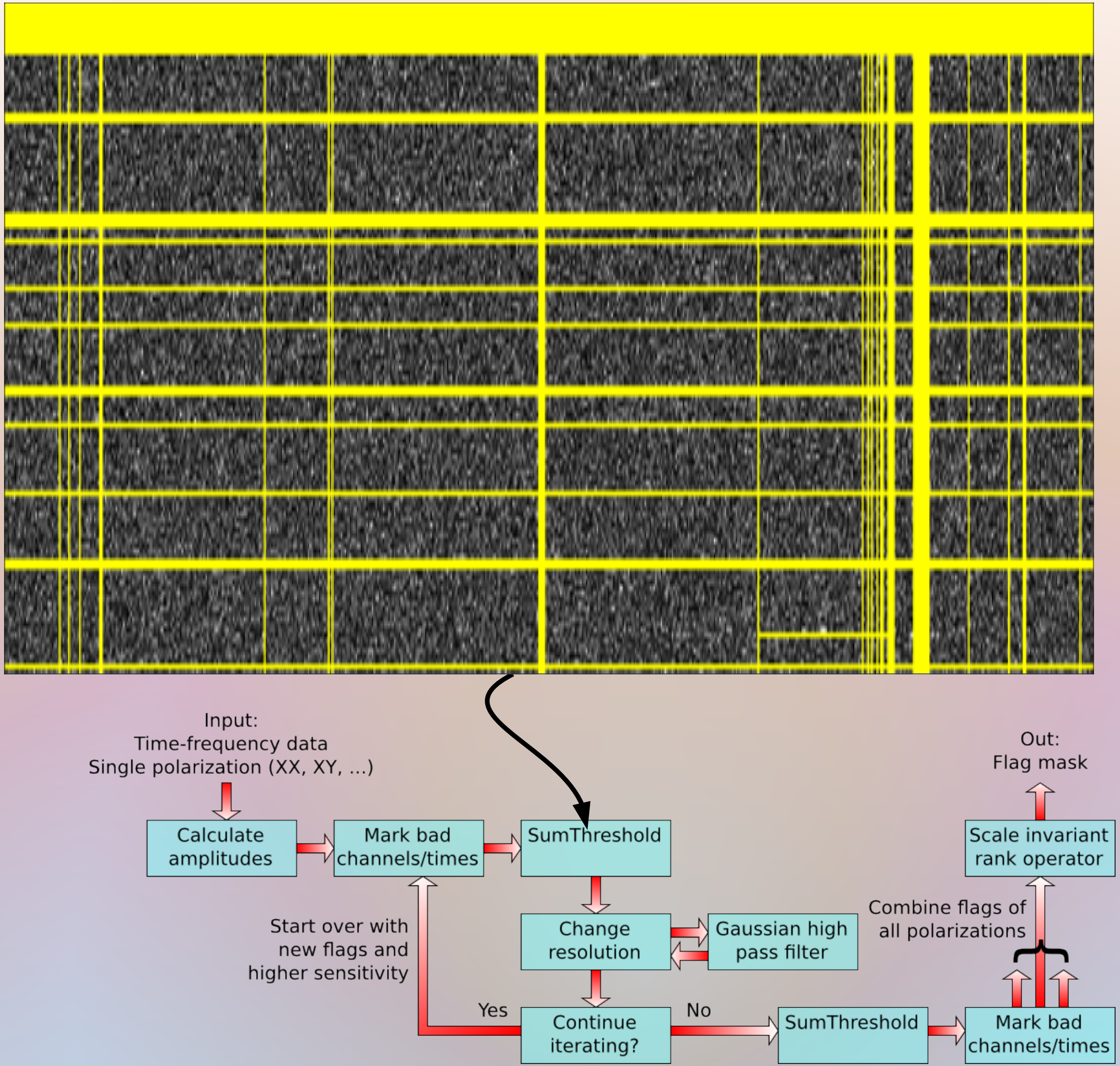
The AOFlagger
(example of automated RFI detection)
External package[1], works with CASA sets



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

[1]AOFlagger can be downloaded from http://aoflagger.sourceforge.net/


Frequency (MHz)
32.12
32.11
32.1
32.09
32.08
32.07
32.06
32.05
32.04
5:55
6:00
6:05
6:10
6:15
6:20
Time
Visibility (Jy)
0.011
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
Input:
Time-frequency data
Single polarization (XX, XY, ...)
Calculate amplitudes
Mark bad channels/times
SumThreshold
Change resolution
Gaussian high pass filter
Start over with new flags and higher sensitivity
Yes
Continue iterating?
No
SumThreshold
Mark bad channels/times
Combine flags of all polarizations
Scale invariant rank operator
Out:
Flag mask



Input:
Time-frequency data
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Mark bad channels/times
SumThreshold
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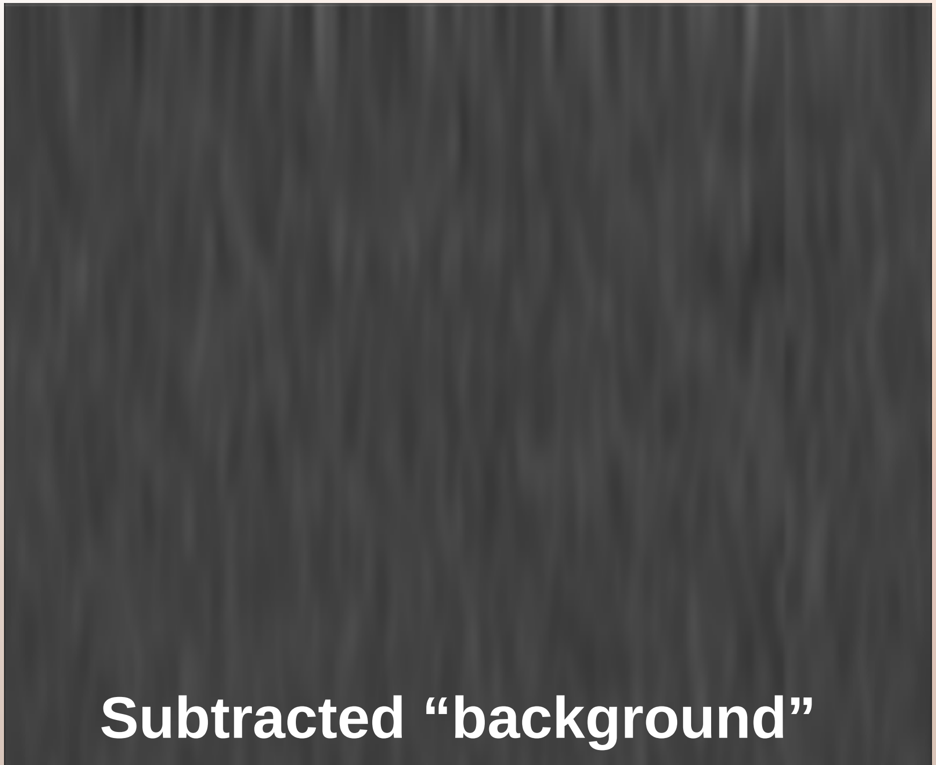
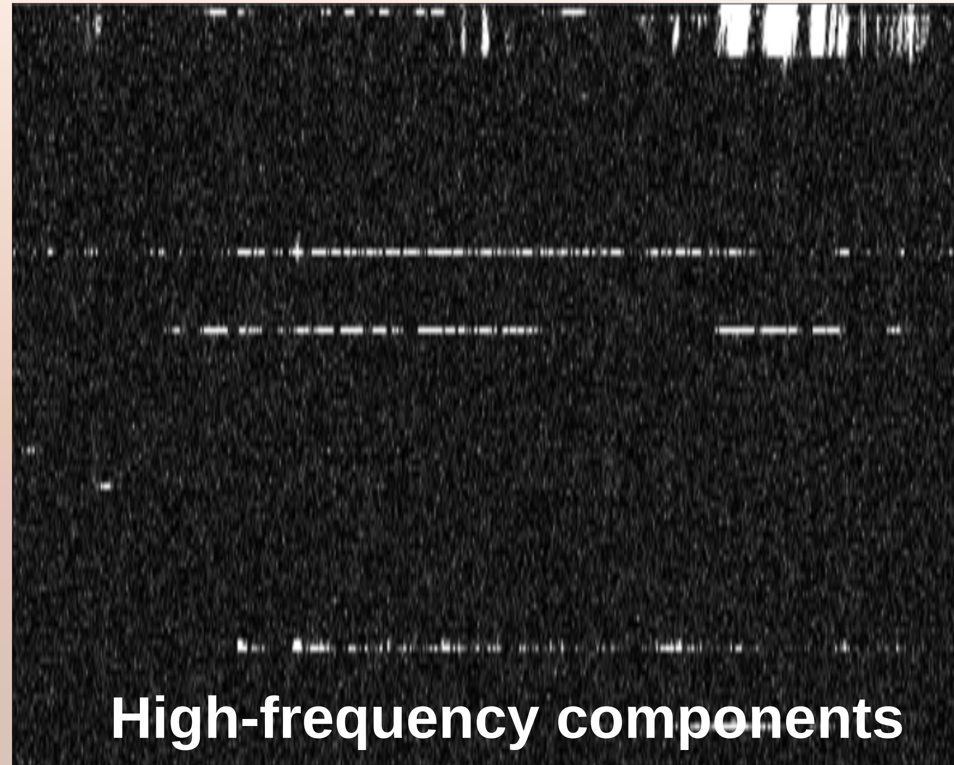
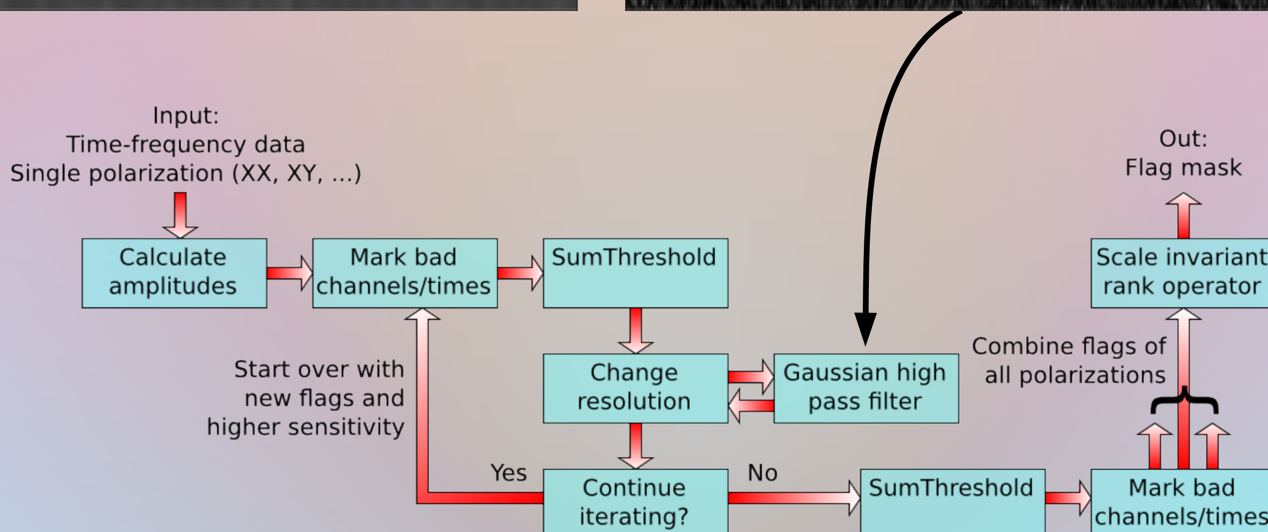
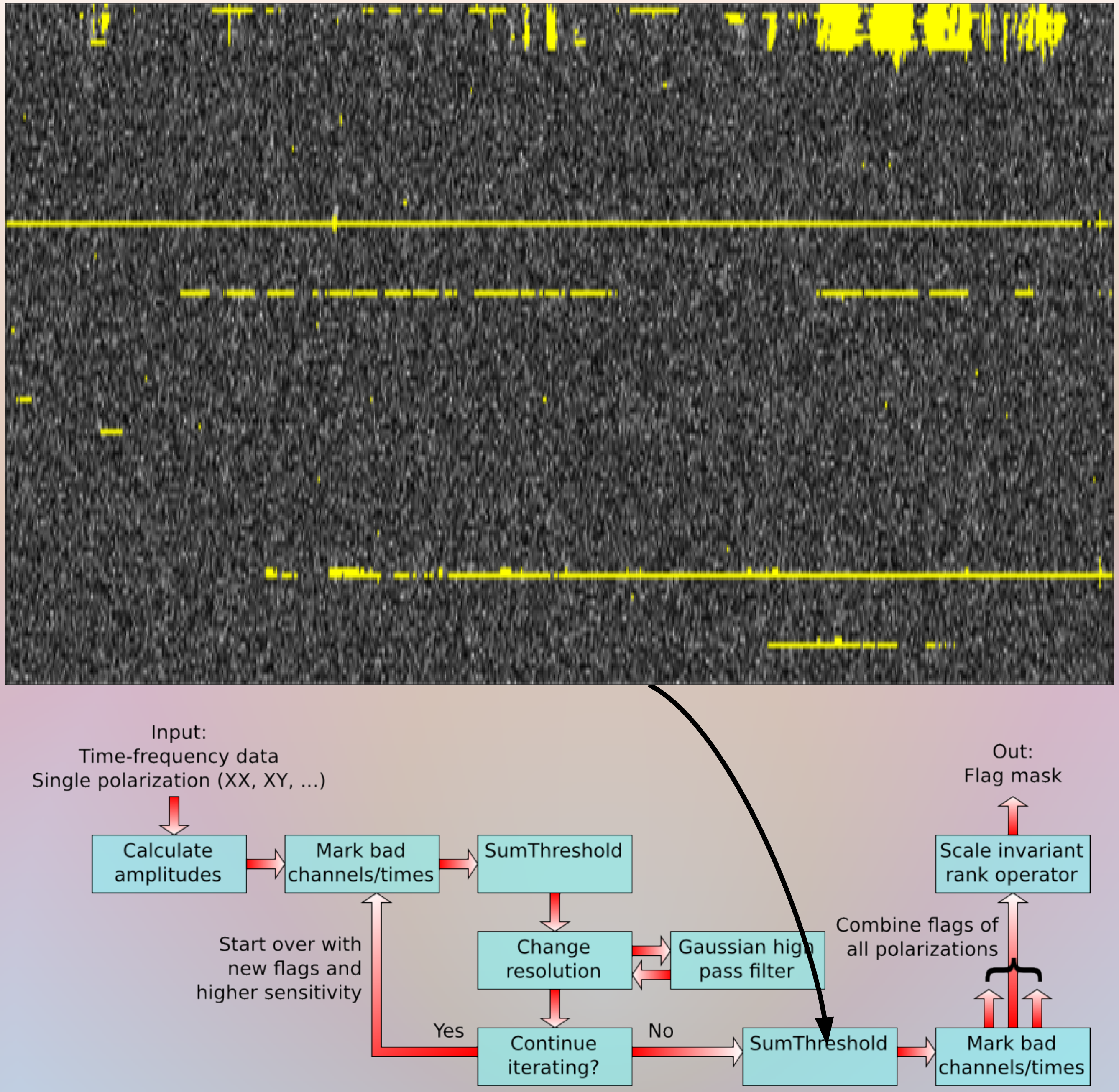

Subtracted “background”


High-frequency components


Input:
Time-frequency data
Single polarization (XX, XY, ...)
Calculate amplitudes
Mark bad channels/times
SumThreshold
Change resolution
Gaussian high pass filter
Start over with new flags and higher sensitivity
Yes
Continue iterating?
No
SumThreshold
Mark bad channels/times
Combine flags of all polarizations
Scale invariant rank operator
Out:
Flag mask


Input:
Time-frequency data
Single polarization (XX, XY, ...)
Calculate amplitudes
Mark bad channels/times
SumThreshold
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Yes
Continue iterating?
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Combine flags of all polarizations
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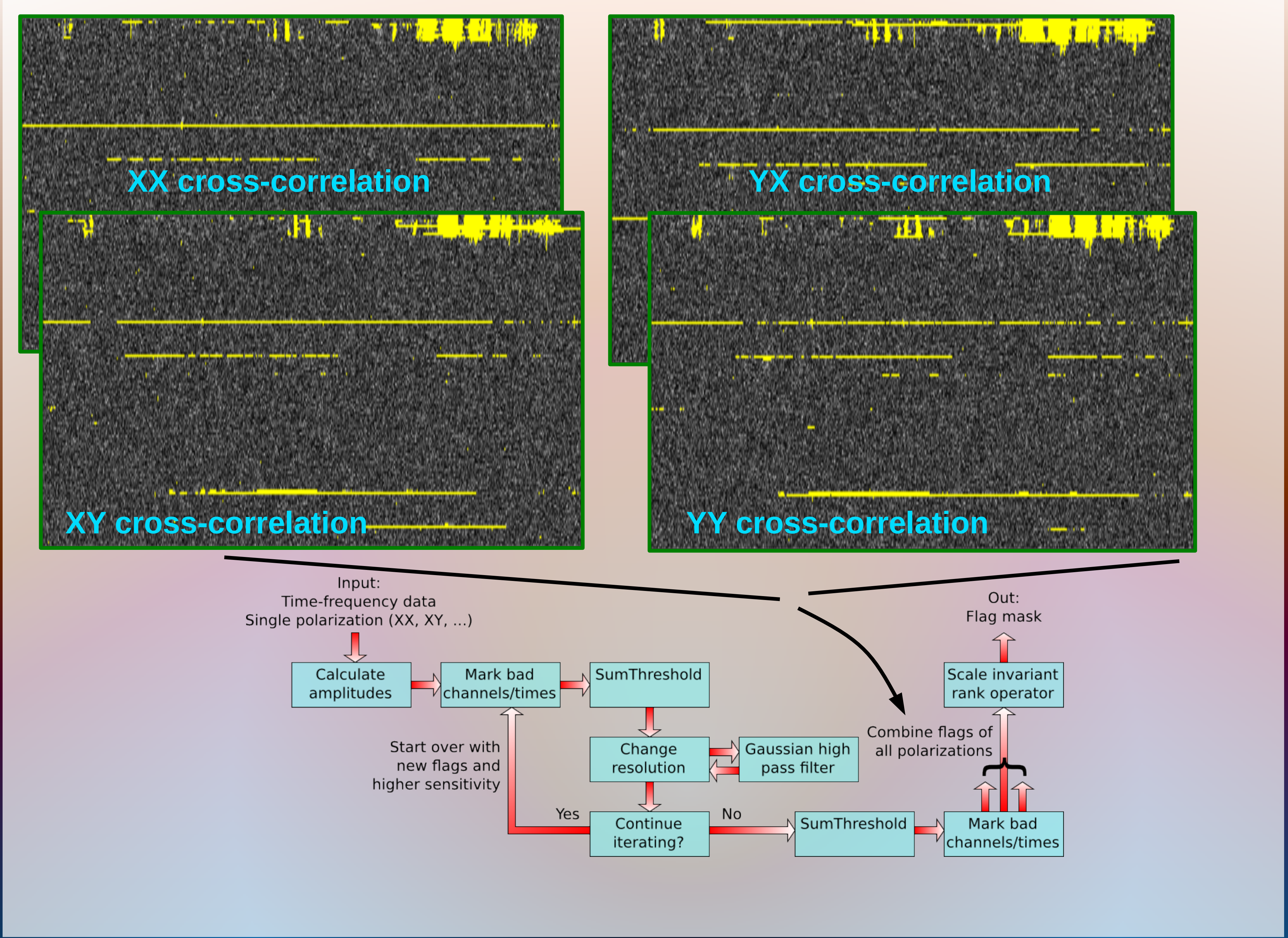
Out:
Flag mask


XX cross-correlation
YX cross-correlation
XY cross-correlation
YY cross-correlation
Input:
Time-frequency data
Single polarization (XX, XY, ...)
Calculate amplitudes
Mark bad channels/times
SumThreshold
Change resolution
Gaussian high pass filter
Start over with new flags and higher sensitivity
Yes
Continue iterating?
No
SumThreshold
Mark bad channels/times
Combine flags of all polarizations
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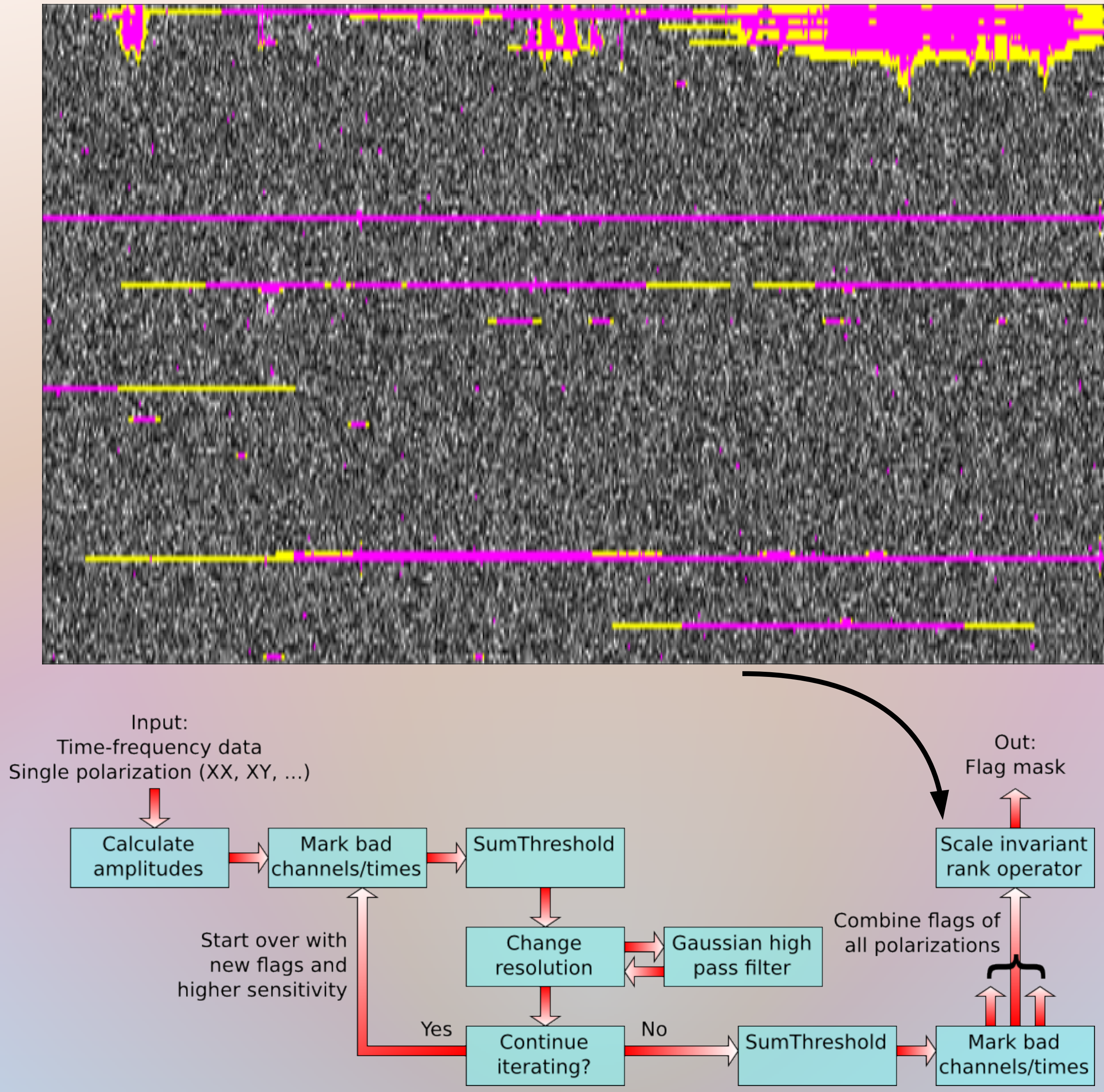
Out:
Flag mask


Input:
Time-frequency data
Single polarization (XX, XY, ...)
Calculate amplitudes
Mark bad channels/times
SumThreshold
Change resolution
Gaussian high pass filter
Start over with new flags and higher sensitivity
Yes
Continue iterating?
No
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Combine flags of all polarizations
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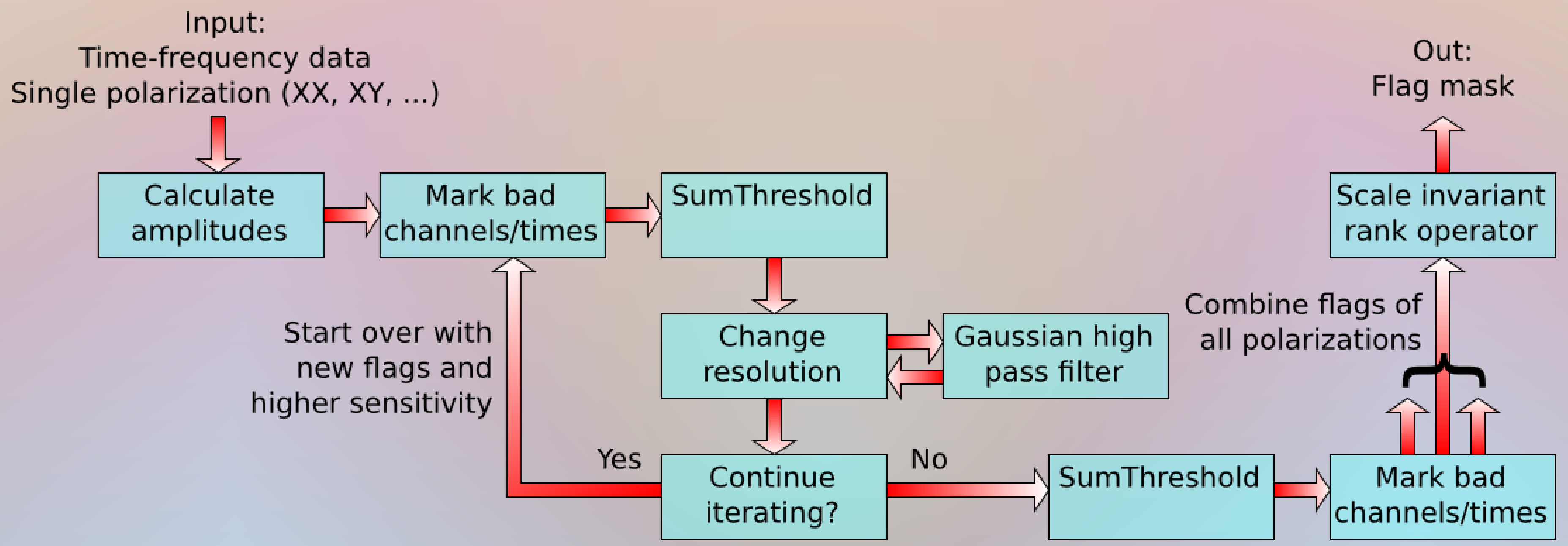
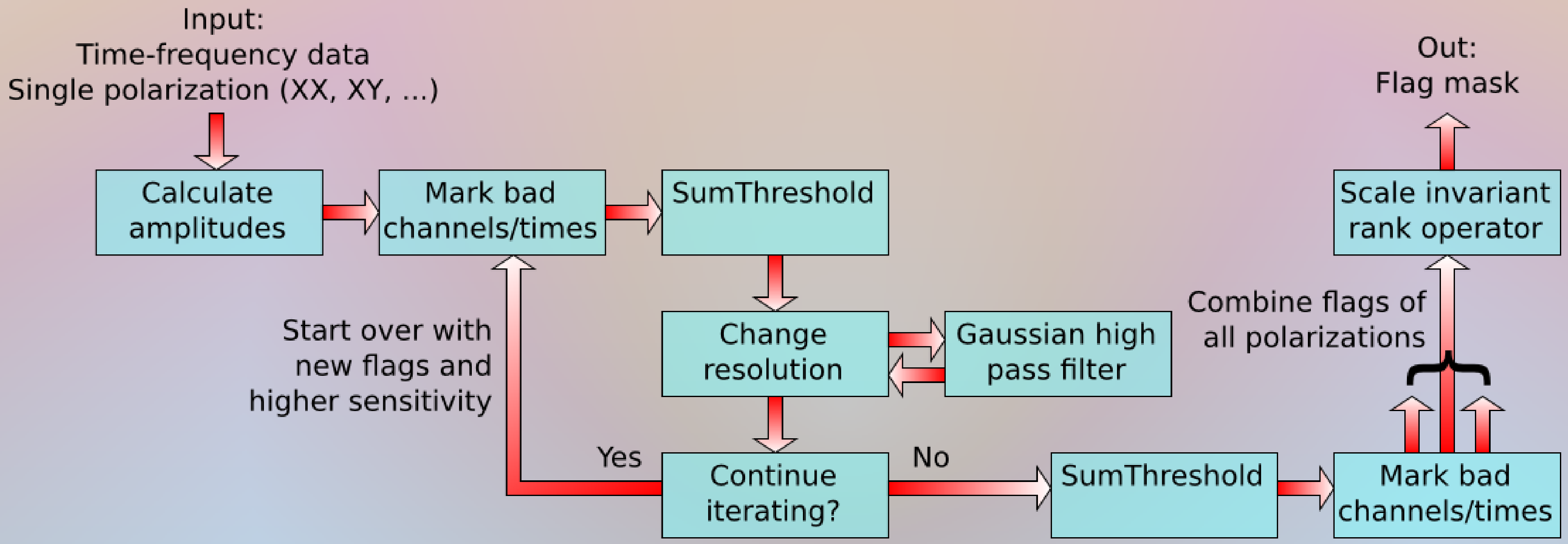
Flag mask

- What could go wrong??

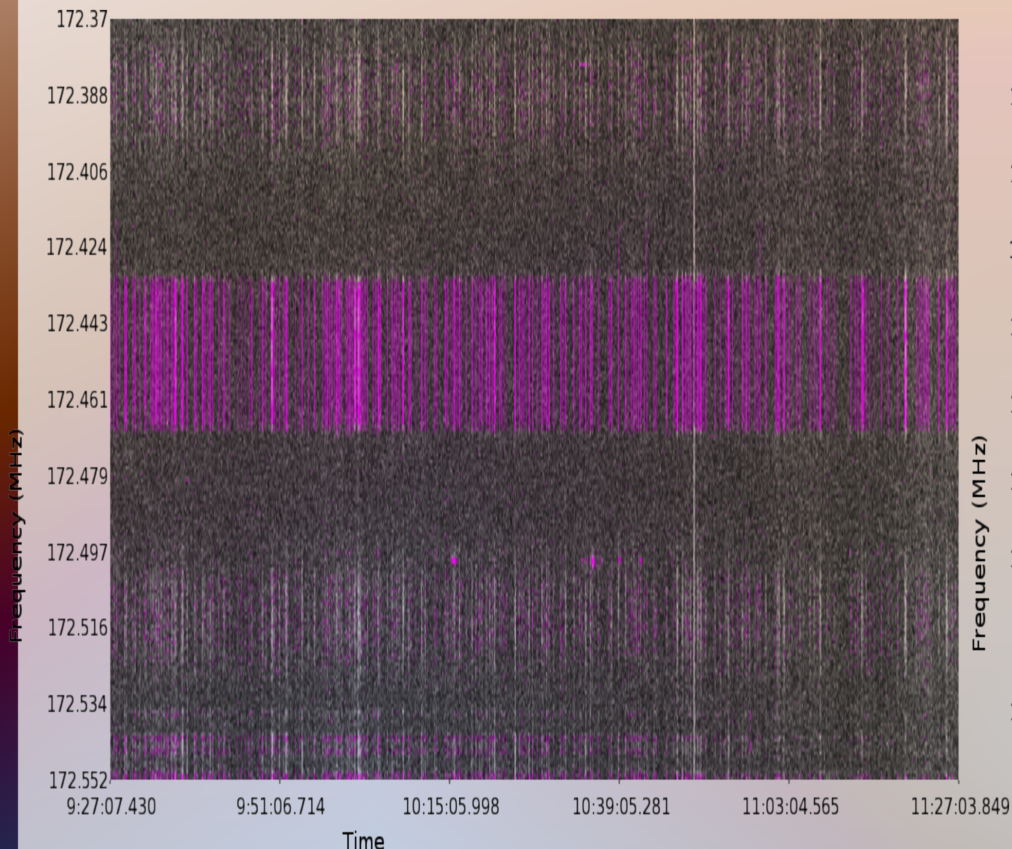


- What could go wrong?
  - Some astronomical sources vary quickly in time (sun, pulsars, …)
  - Quick fringes are line-like patterns
  - Spectral line observations
- Mostly not an issue – sources are ***mostly*** much weaker than RFI, and invisible in single correlations.

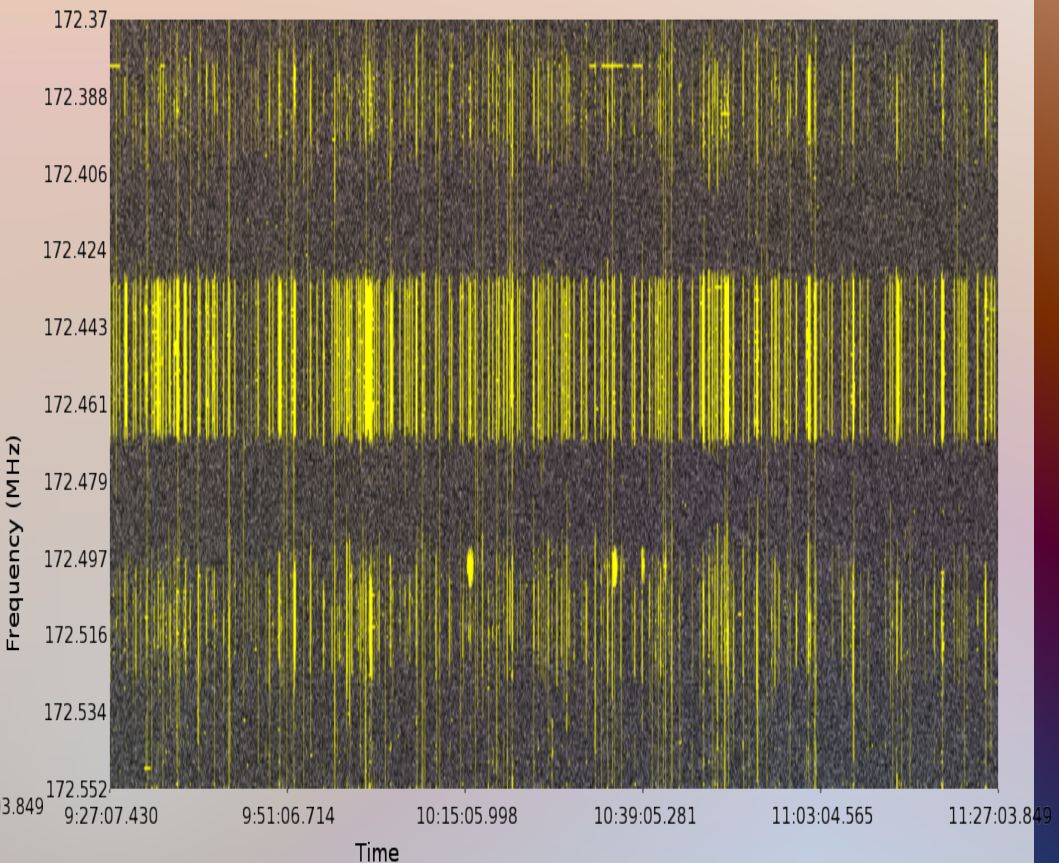


Accuracy & speed

- Flaggers have to be *accurate*, but also *fast*

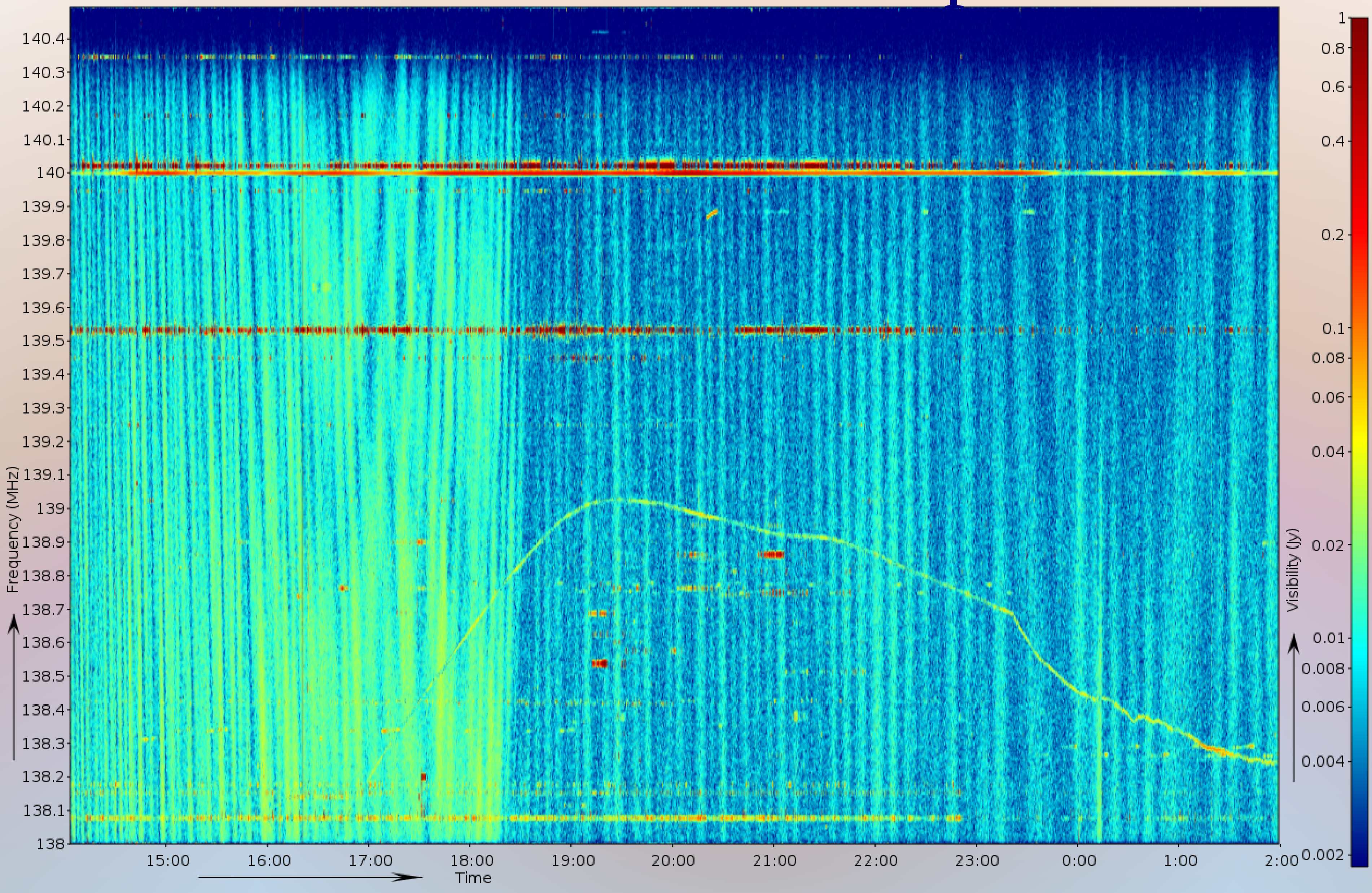


MAD flagger (comparable to Pyflag, Miriad's flagger, AIPS flagger)

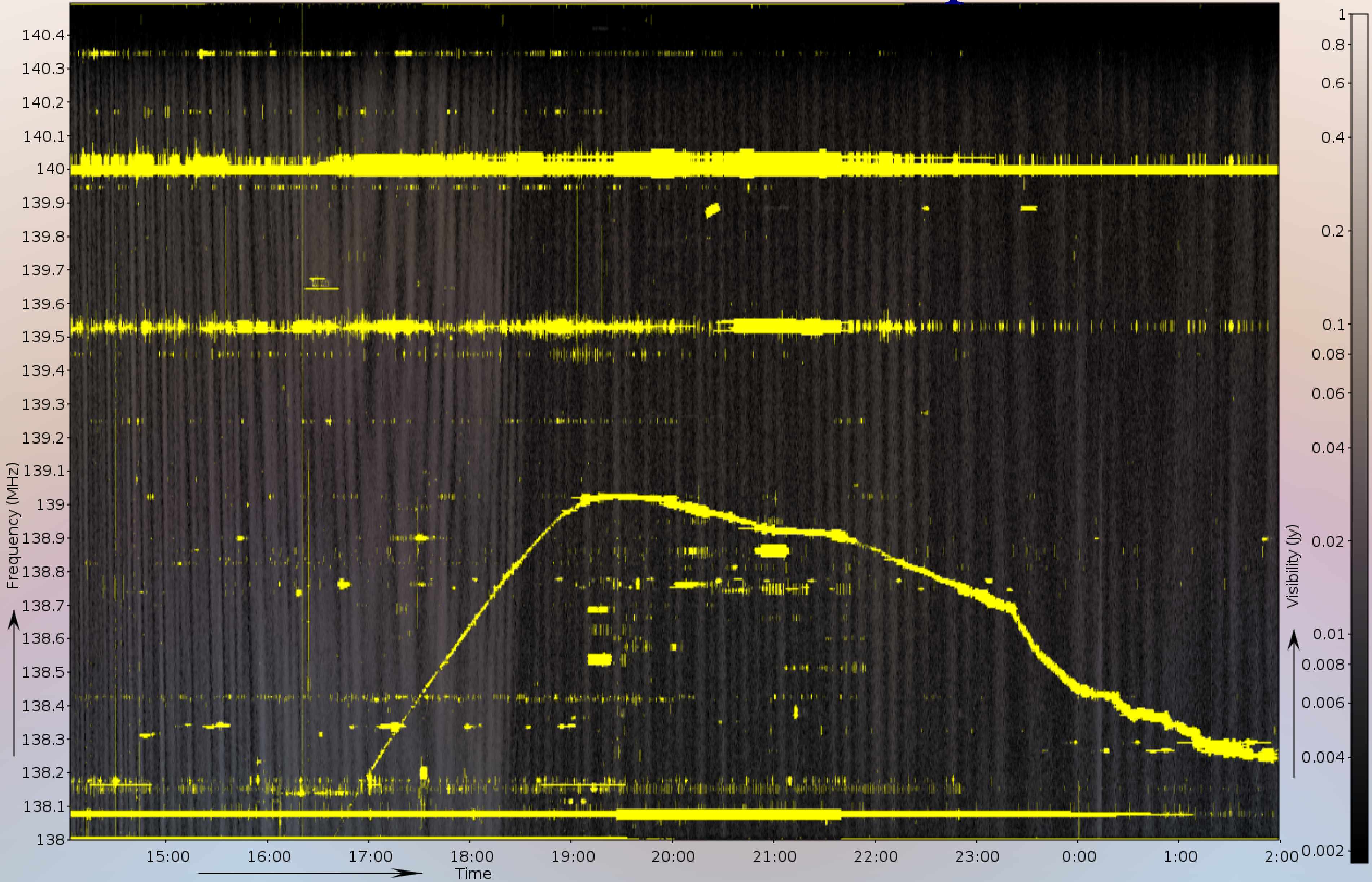


AOFlagger

WSRT data example



WSRT data example



Thresholding vs. AOFlagger

MWA 3 min observation with 32 tiles

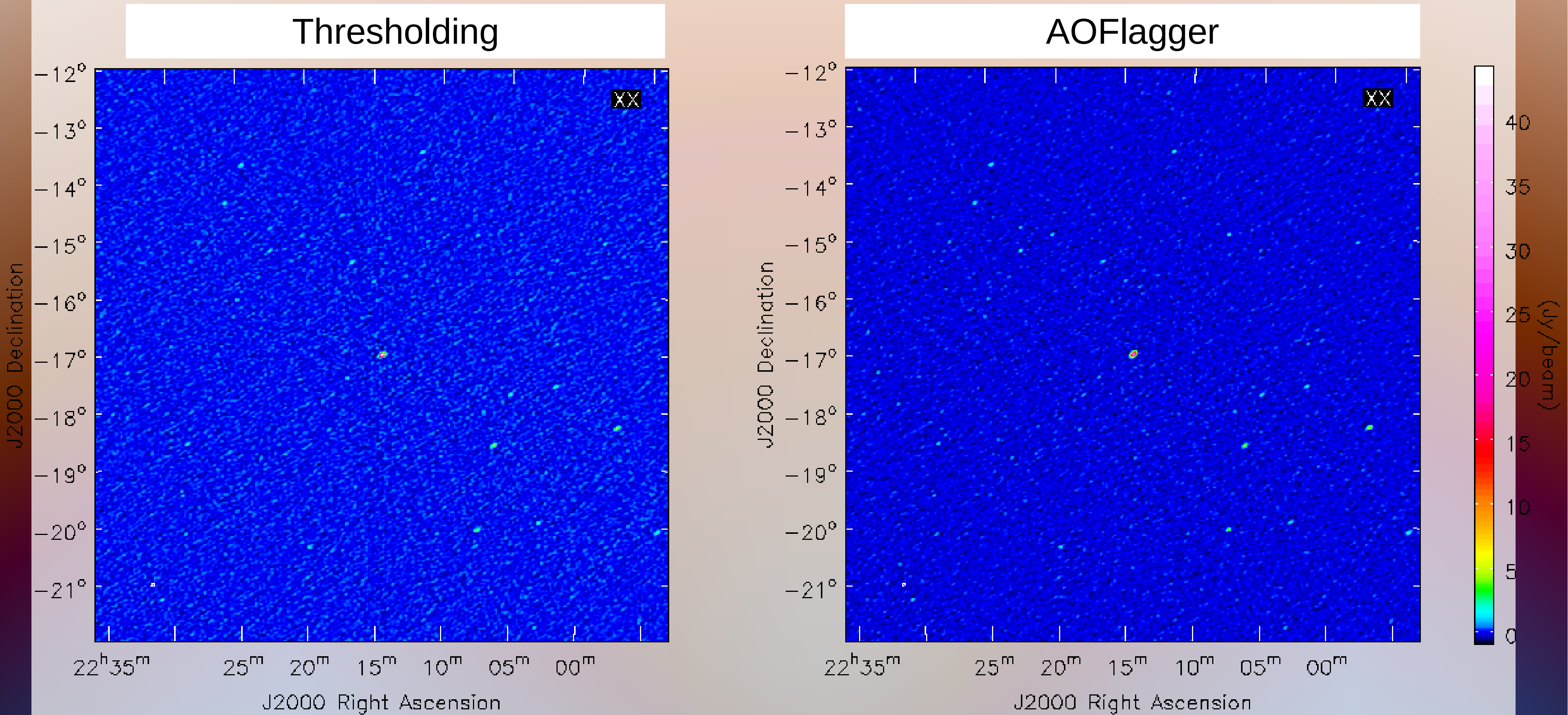


Image credit: Natasha Hurley-Walker (MWA data)

More about AOFlagger

- (Almost) same algorithm can be used for many telescopes
  - Software has been successfully used for: LOFAR (Offringa et al 2012), MWA (Offringa et al. 2015), WSRT, JVLA, GMRT, ATCA, Parkes, Arecibo, and BIGHORNS
- I don't know if it is used for ALMA...
- For Miriad users:
  Miriad has an implementation of AOFlagger
- SumThreshold algorithm available in E-Merlin “SERPent” pipeline (Peck & Fenech, 2013)

RFI excision for LOFAR

- LOFAR's case:
  - Fully automated detection, only a few % lost data
  - Only small residuals, do not affect image quality
- Why such good results?
  - LOFAR has very high time/freq resolutions
  - Design has accounted for interference
  - High accuracy of algorithms
- Some transmitters do remain problematic (e.g., DAB, FM, wind turbines)
- Tweaking still required for special cases

Analysing RFI

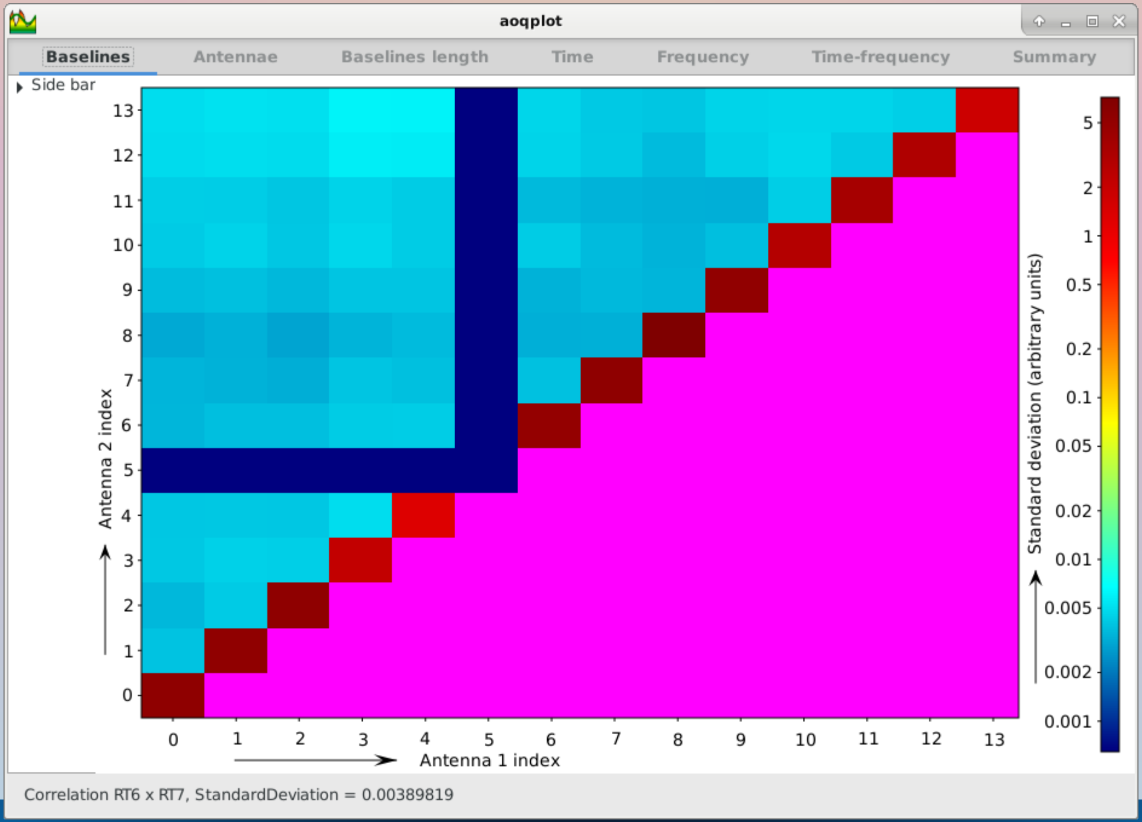
(Demo: open `rfigui` in other window)

- Open set, goto RT1 x RT2.
- Execute strategy
- Edit strategy: change flagged polarizations, change sumthreshold sensitivity
- Save strategy
- Execute '`aoflagger`' on cmdline.

Further analyses

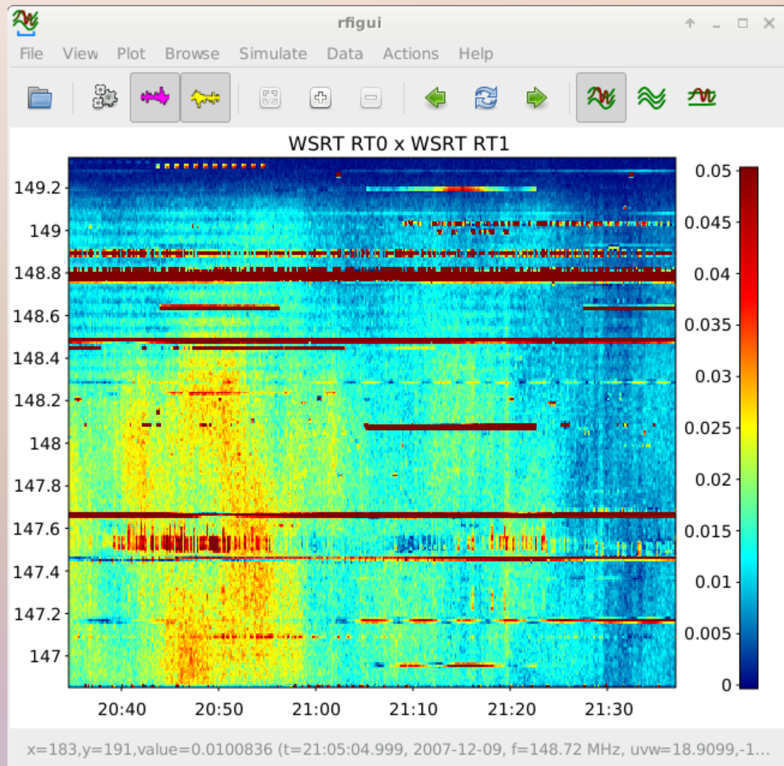
(Demo: open `aoqplot` in other window)

- casaplotms is slow for very big files
- aoqplot can give a quick overview

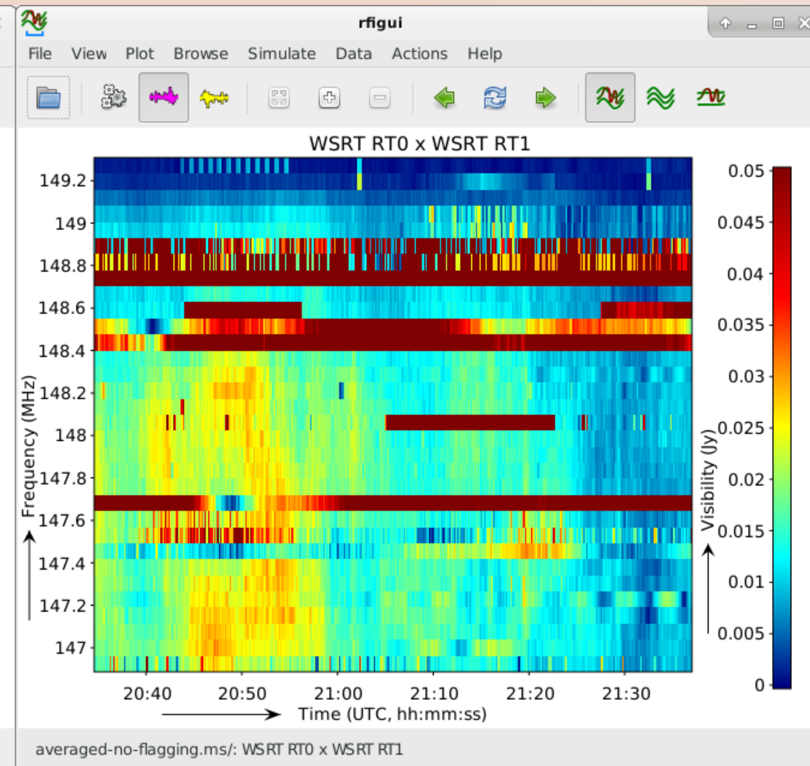


- Always flag (first) at highest possible resolution:

Highest resolution:



Averaged without RFI detection:



- Flagging is incremental: don't reset flags!
  (e.g. `taql update obs.ms set FLAG=false`)
  Correlator might have set flags. These will be lost. To undo flagging, use backup (column).

Averaging & smearing

- Data size can be reduced by averaging data in time and/or frequency direction

- Only average *after* RFI detection

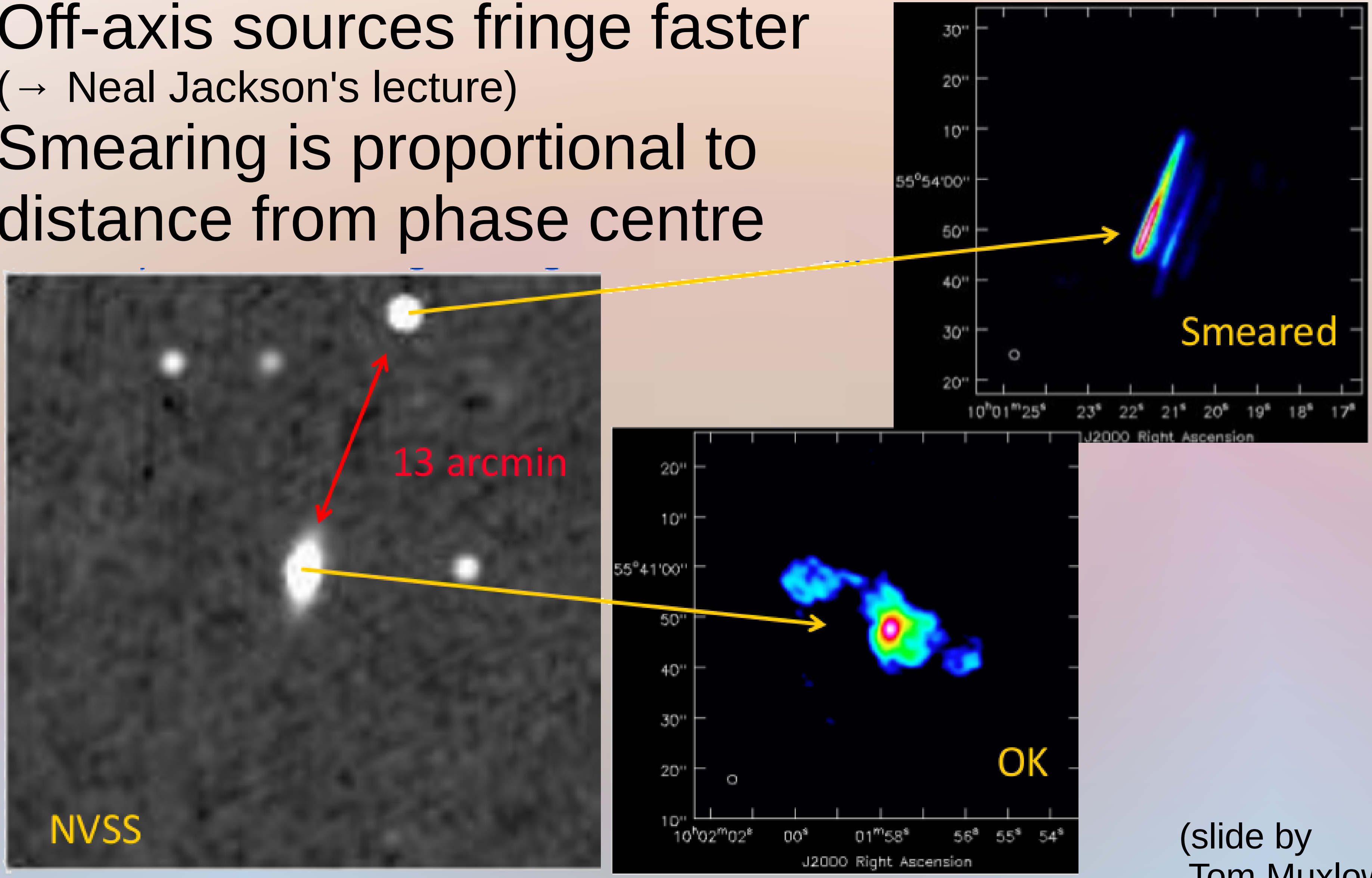
- Over-averaging causes *smearing*
  - *Time-smearing*: in tangential direction
  - *Frequency-smearing*: in radial direction
- Calibration might also constrain averaging factor
  → Next talk by George Heald

Bandwidth smearing

Off-axis sources fringe faster

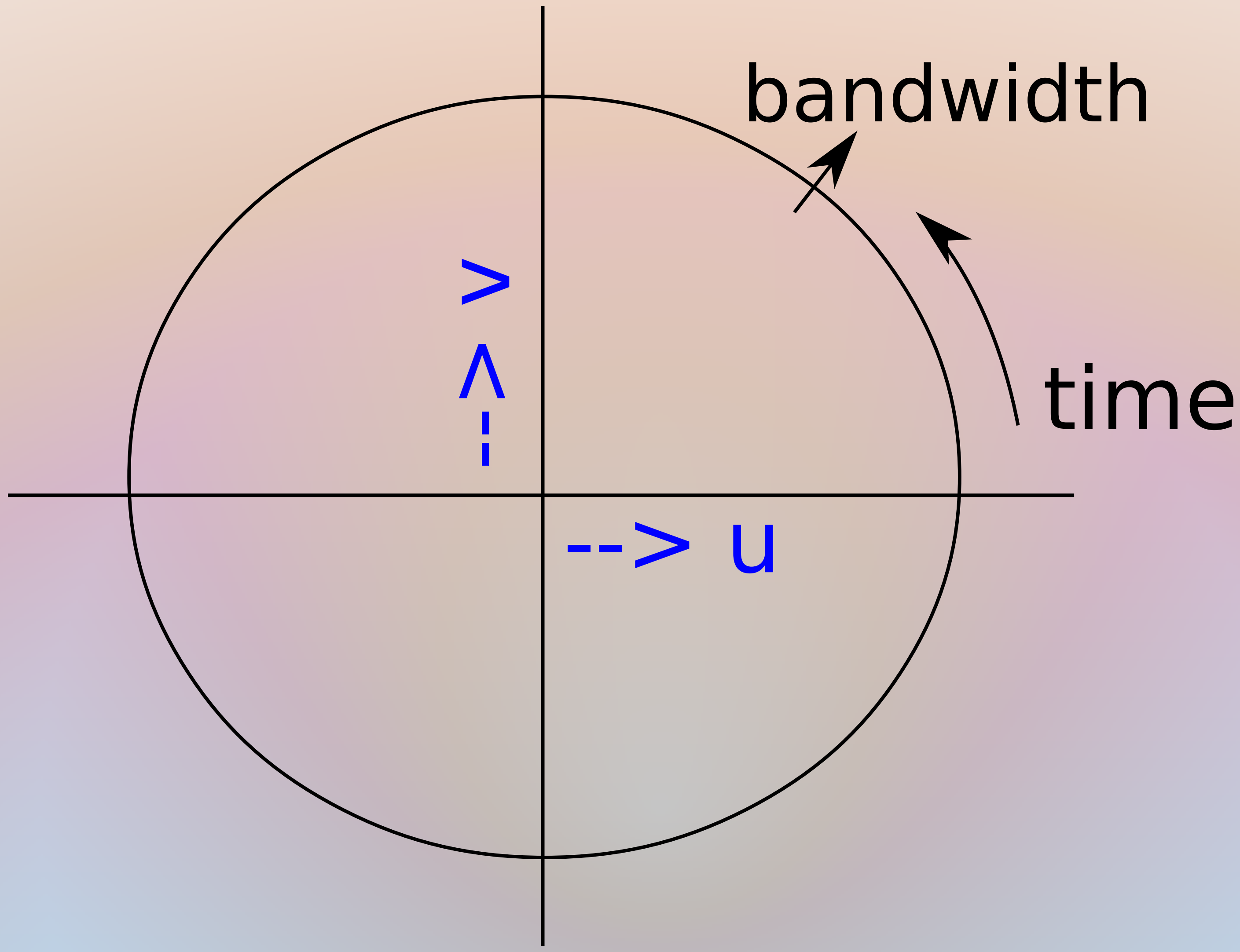
(→ Neal Jackson's lecture)

Smearing is proportional to distance from phase centre



(slide by Tom Muxlow)

Averaging in uv-space



Smearing

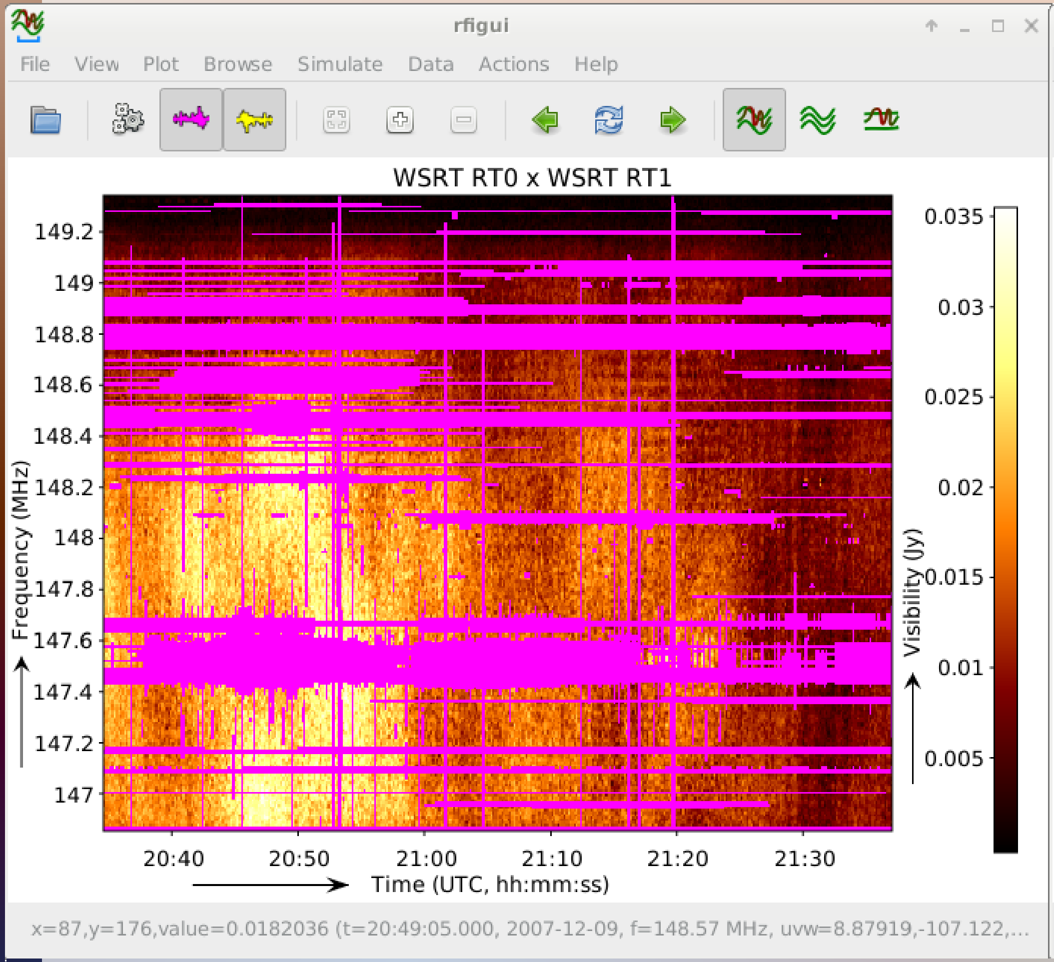
- General rule: phase turn along time / frequency should be sampled << 1/4th of a turn.
- Example with 1" resolution (e.g. LOFAR international baseline) and 1 deg off-axis source:
  - Source is 3600 resolution elements away
  - Phase turns ~3600 times in 6 hours (or over observing frequency)
  - Need ~14000 samples in 6 hours
  - Time res $\Delta t < \sim 2$ s ($\Delta\nu < \sim 10$ kHz @ 150 MHz).

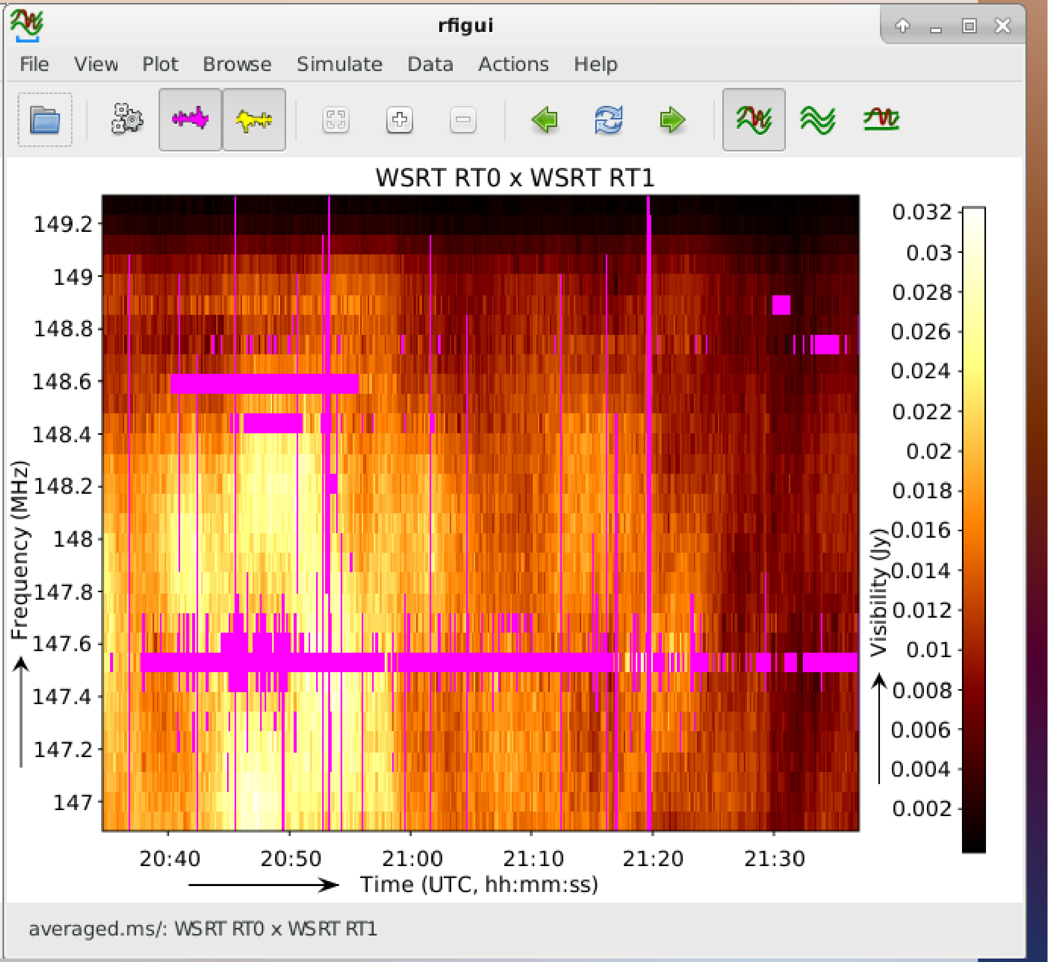
Data averaging with CASA

- (Demo: casa split)
- Example: (from casapy shell)

```
inp split
vis='3C196_spw5_sub1.MS' (input)
outputvis='averaged.MS'
width=8                  (Average over 8 channels)
timebin='60s'   (Average over 60 s)
go
```

Original resolution: After averaging:





Averaging DATA

- Processing data can be very time expensive, but almost all steps scale linear with nr. of visibilities.

- Work on averaged data (and/or subset) while experimenting with settings

```
anoko@DOP348:~/ERIS2015$ du 3C196_spw5_sub1.MS/ -sh
998M    3C196_spw5_sub1.MS/
anoko@DOP348:~/ERIS2015$ du averaged.ms/ -sh
45M     averaged.ms/
anoko@DOP348:~/ERIS2015$ 
```

NDPPP: Averaging LOFAR data

- Almost all telescopes have existing sets of scripts to do preprocessing… Use them!
- '`split`' task does not work well on LOFAR data (see LOFAR cookbook for details)
- Instead, a specialized LOFAR pipeline was made to perform several steps at once
- NDPPP: "New Default Pre-processing Pipeline"
- Can run aoflagger and perform averaging at once (as well as several other things)
- See LOFAR Cookbook for detailed info
- (MWA has a similar pipeline called '`cotter`').

Averaging DATA

- Processing data can be very expensive, but almost all steps scale linear with nr. of visibilities.
- While experimenting with settings, work on averaged data

Summary

- First step in data processing is
  data inspection
- Second step is data flagging

...or isn't it?

Summary

- First step in data processing is
  data inspection
- ~~Second step is data flagging~~
- Second step is BACKUP YOUR DATA
- Third step is data flagging and RFI detection
- Calibration, imaging, … to be discussed!

Summary

- I've shown:
  - Data inspection (with e.g. CASA casaplotms, rfigui and aoqplot)
  - Flagging data manually (with taql)
  - Automated RFI detection (with the AOFlagger)
  - Data averaging (with CASA split or NDPPP)
  - Issues with insufficient resolution (smearing, bad RFI detection)
- Good luck!