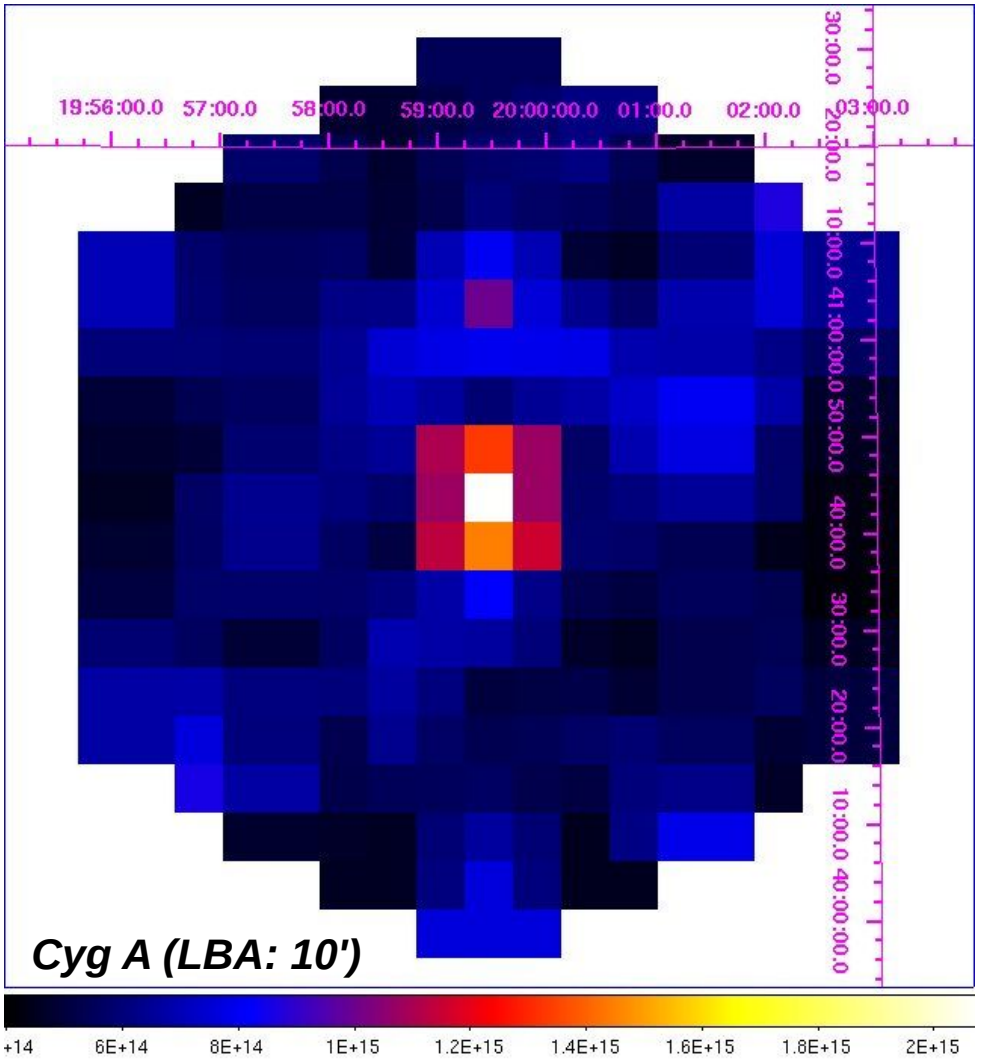
LOFAR DATA SCHOOL 2016

ASTRON

Universiteit Leiden

Tied-Array Imaging (II) , with contributions from:

- **RRL group**
- **Scintillation (R. Fallows)**
- **Pulsar Working Group**
- **Radio Observatory**



Outline

- **Tools**
- **Calibration (Cyg A imaging)**
- **Beams**
- **Scientific examples**
  - * **total power spectroscopy**
  - * **scintillation**
  - * **transients (e.g. pulsars)**

LOFAR Tied-Array Imaging

A) *Incoherent* addition of stations → station voltages added w/o delays

→ spectral resolution : identical to interferometry
→ spatial resolution : station beam (FWHM ~ few degrees)

B) *Coherent* addition of stations → station voltages added w. delays *(single clock)*

→ spectral resolution : identical to interferometry
→ spatial resolution : tied-array beam (TAB)
- 22 CS (LBA: 10' , HBA: 3' , HGH: 2')
- 6 CS (LBA: 1 deg , HBA: 20' , HGH: 15')

Data output: HDF5 format (*.h5 = tab_header , *.raw = tab_data[t , f])

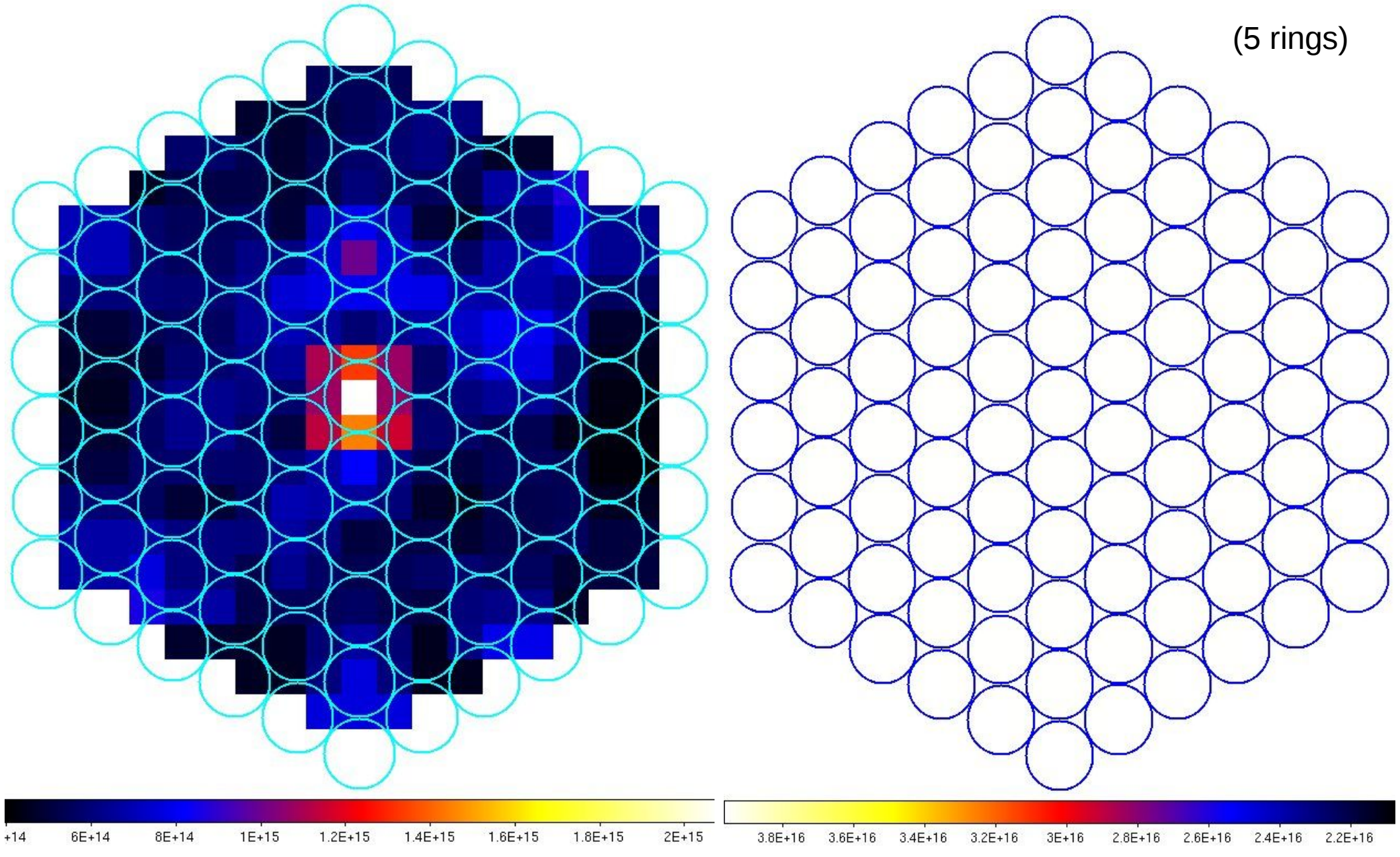
Phase information lost in addition, so why ?

→ *Total power measurements (large spatial scales)*
→ *High time resolution (<< 1s sampling)*

note: complex voltage data dumps are possible, but not discussed here...

LOFAR Tied-Array Imaging: Covering large areas

*** example 'Rings' (specify: TAB spacing and number of rings)**



Tied-Array Imaging: Beams

1) **Tile (HBA,HGH) / Dipole (LBA) beam**

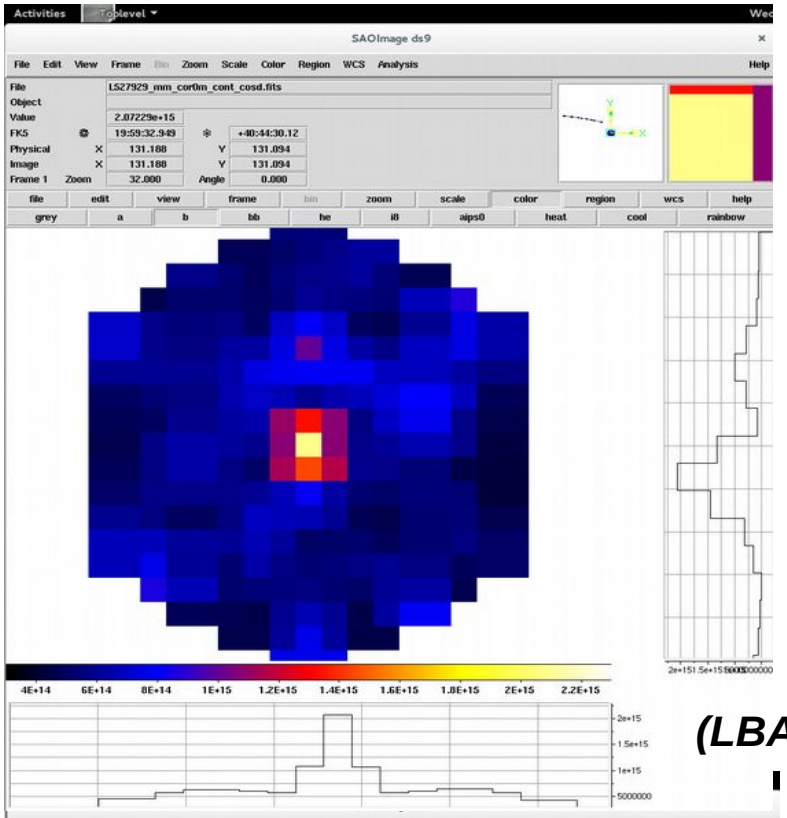
   → **tile beam (about 20 degrees)**
   → **dipole beam (“all sky”)**

2) **Station beam**

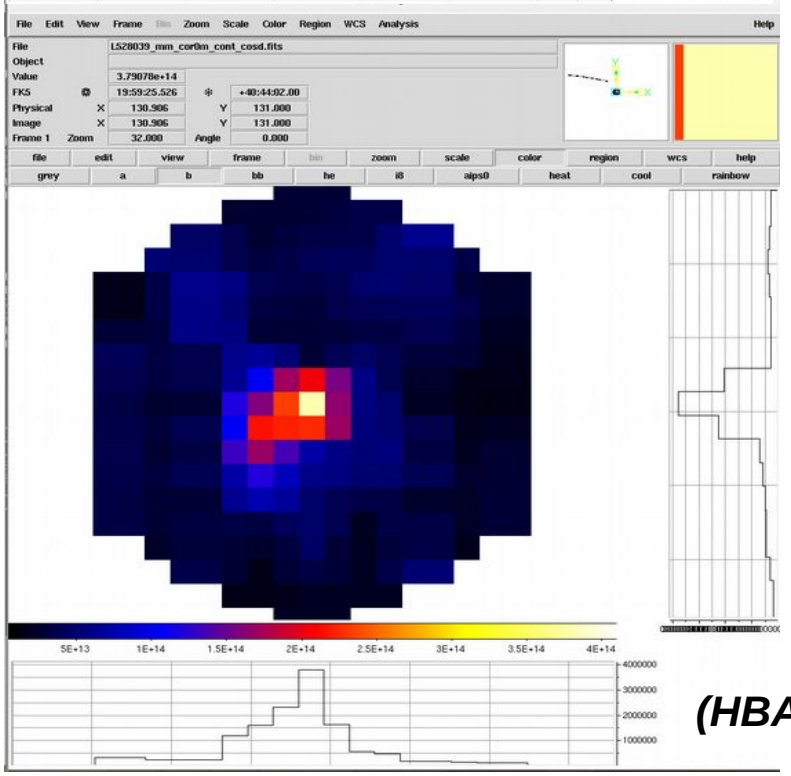
   → **few degrees (see LOFAR website)**

3) **Tied-array (synthesized) beam (TAB)**

   → **depends on #stations included**



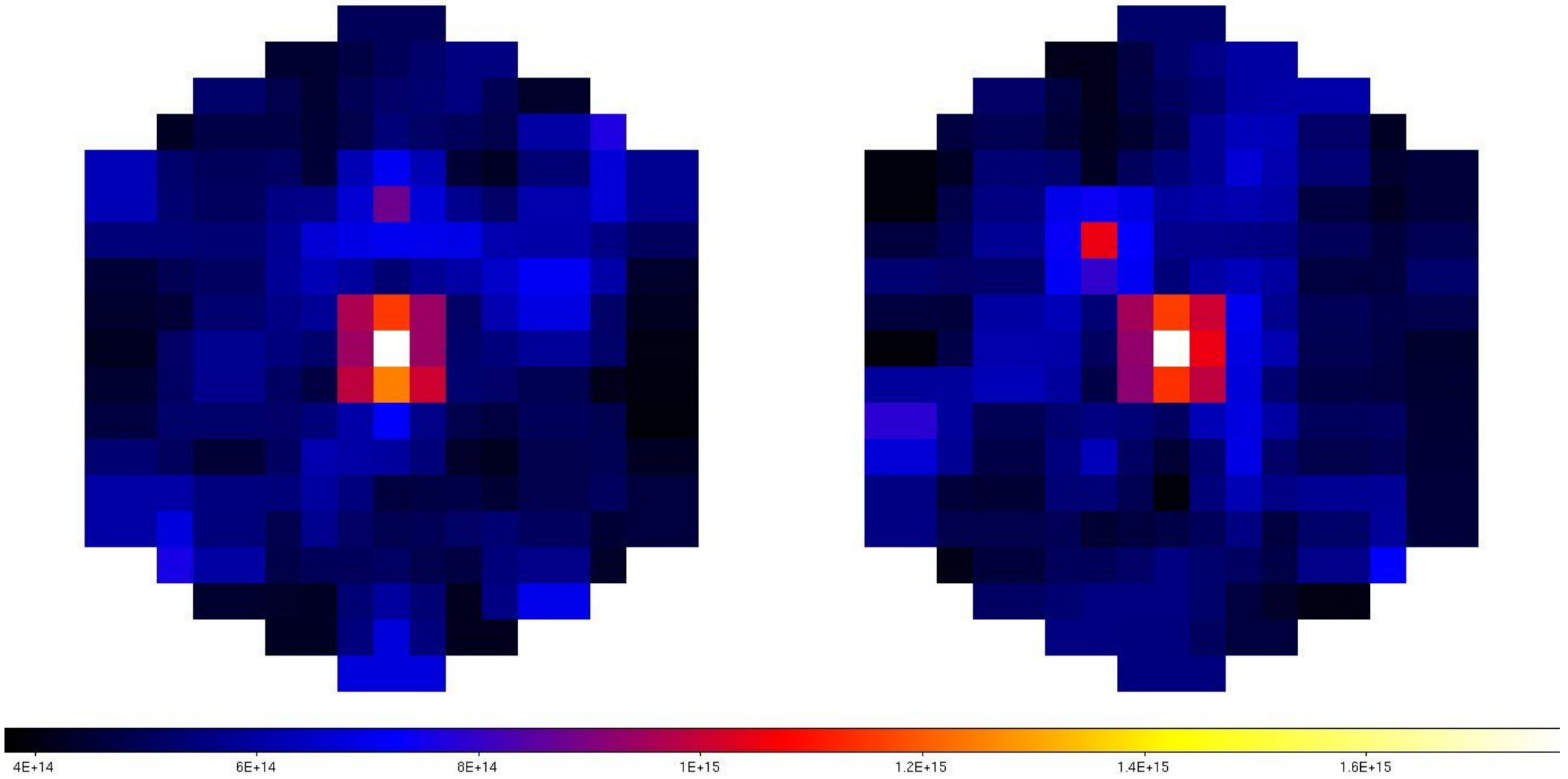
(LBA)



(HBA)

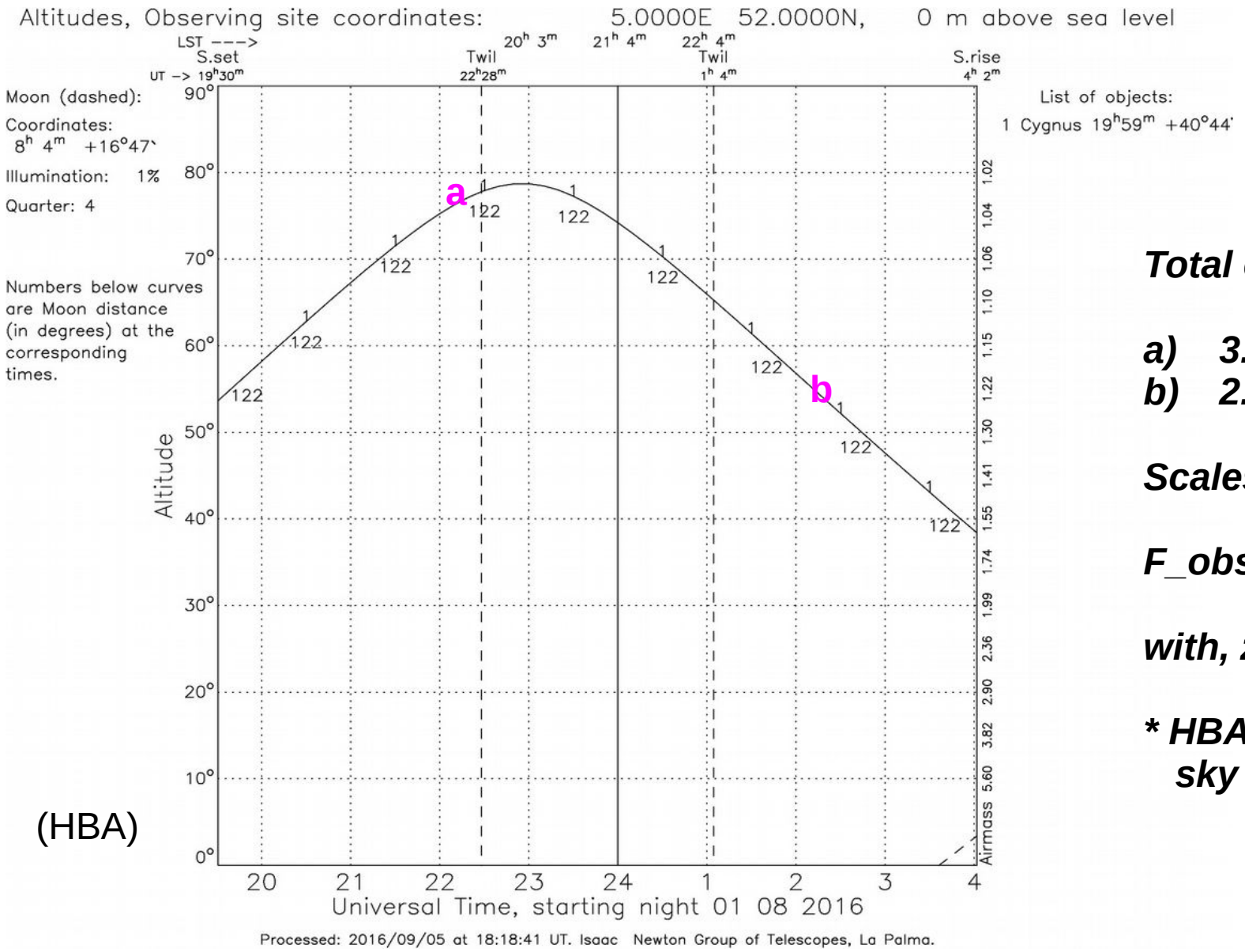
Tied-Array Imaging: TAB beam rotation

(LBA: tracking Cyg A - sidelobes rotate)



LOFAR Tied-Array Imaging: Flux scales

Elevation dependent total flux (due to array projection, i.e. system gain)



(HBA)

Total observed flux

a) 3.8
b) 2.4

Scales roughly as:

F_obsv = F_intr * cos(z)

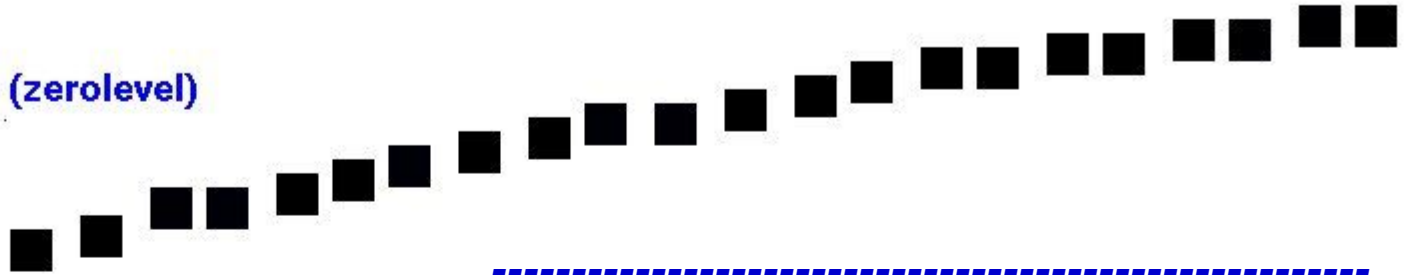
with, z = zenith angle

**** HBA total signal is sky dominated***

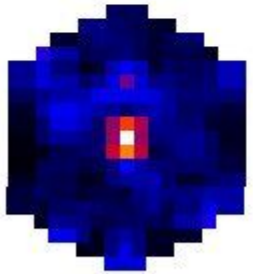
LOFAR Tied-Array Imaging: Calibration

Calibration of TA data is similar to 'single dish' calibration

OFF TABs (zerolevel)



Flux Calibrator



Target

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1. Calibrate system noise via OFF TAB

- System noise (mostly) additive

- True zero does not exist, at low Frequencies (use MW model)

2. Set flux scale via Cal (multiplicative)

- Requires bright calibrators

** [1,2] time dependent, or alternatively perform time normalization first.*

LOFAR Tied-Array Imaging

Tools: Reduction / Analysis of tied-array data ***(incomplete summary)***

1) RRL group (ask JBRO if interested in details)

- **dedicated python scripts: convert HDF5 to MS and apply LOFAR software**
- **dedicated python/IDL scripts: analysis**

2) Radio observatory / Scintillation (R. Fallows; ASTRON)

- **DAL (data access library)**

  http://www.lofar.org/wiki/doku.php?id=public:user_software:dal

- **Dynamic spectrum toolkit**

  http://www.lofar.org/wiki/doku.php?id=public:user_software:dynspec

3) Pulsar Working group

- **LOFAR BF pulsar scripts (V. Kondratiev; ASTRON)**

  https://github.com/vkond/LOFAR-BF-pulsar-scripts

LOFAR Tied-Array Imaging: Science

1) **Radio recombination lines (RRL)**

   - **Total power imaging / spectroscopy**
   - **Detect and model RRLs to determine physical conditions of the CNM**

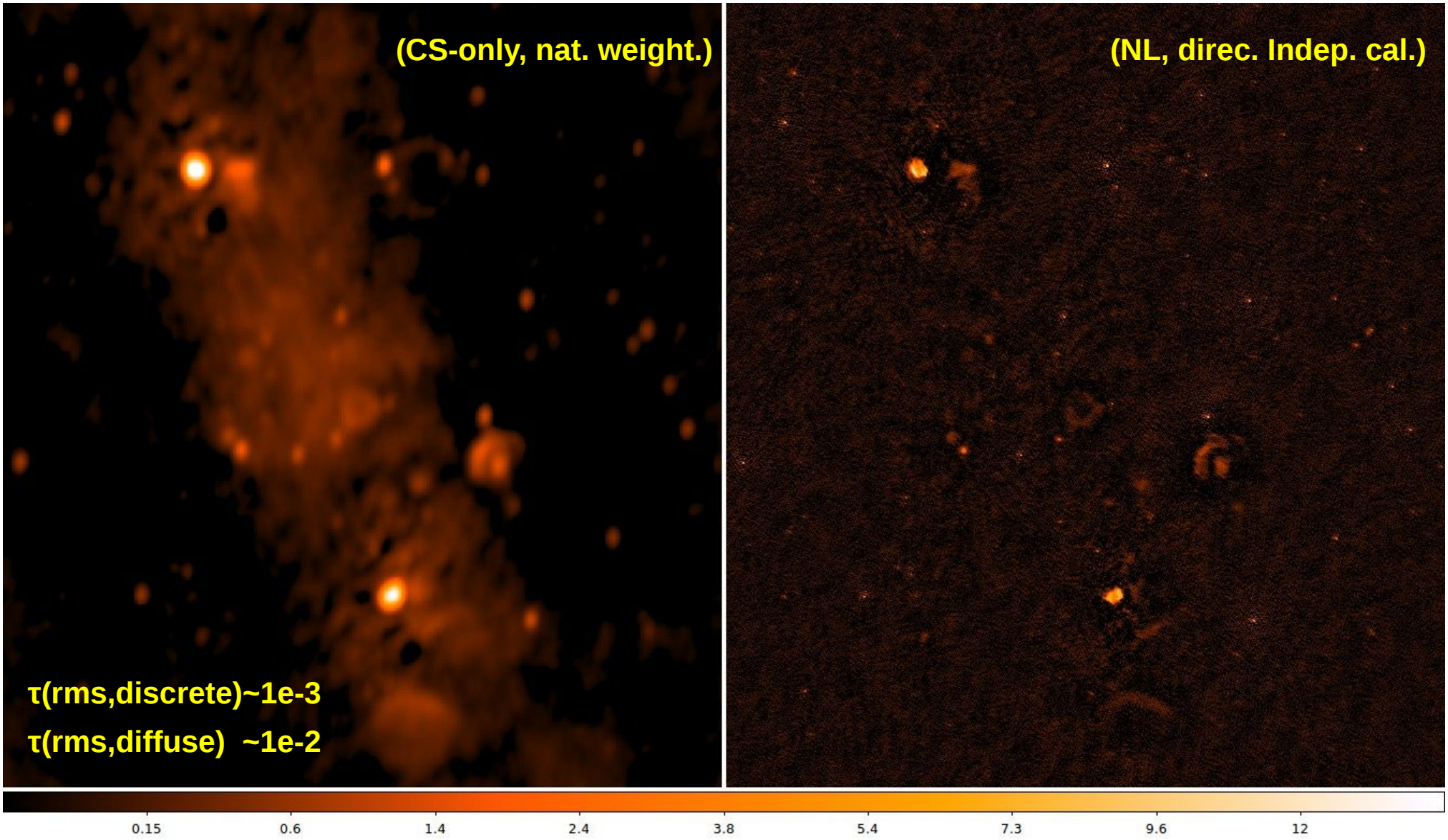
2) **Scintillation**

   - **Study dynamic spectra for signal propagation in turbulent media**
   - **Model properties of the ionosphere and the interplanetary medium**

3) **Transients and Pulsars**

   - **Find new transient phenomena (e.g. pulsars, FRB's, gravitational waves)**
   - **Study pulse profiles (pulsars models, gravity, (inter-)galatic medium).**

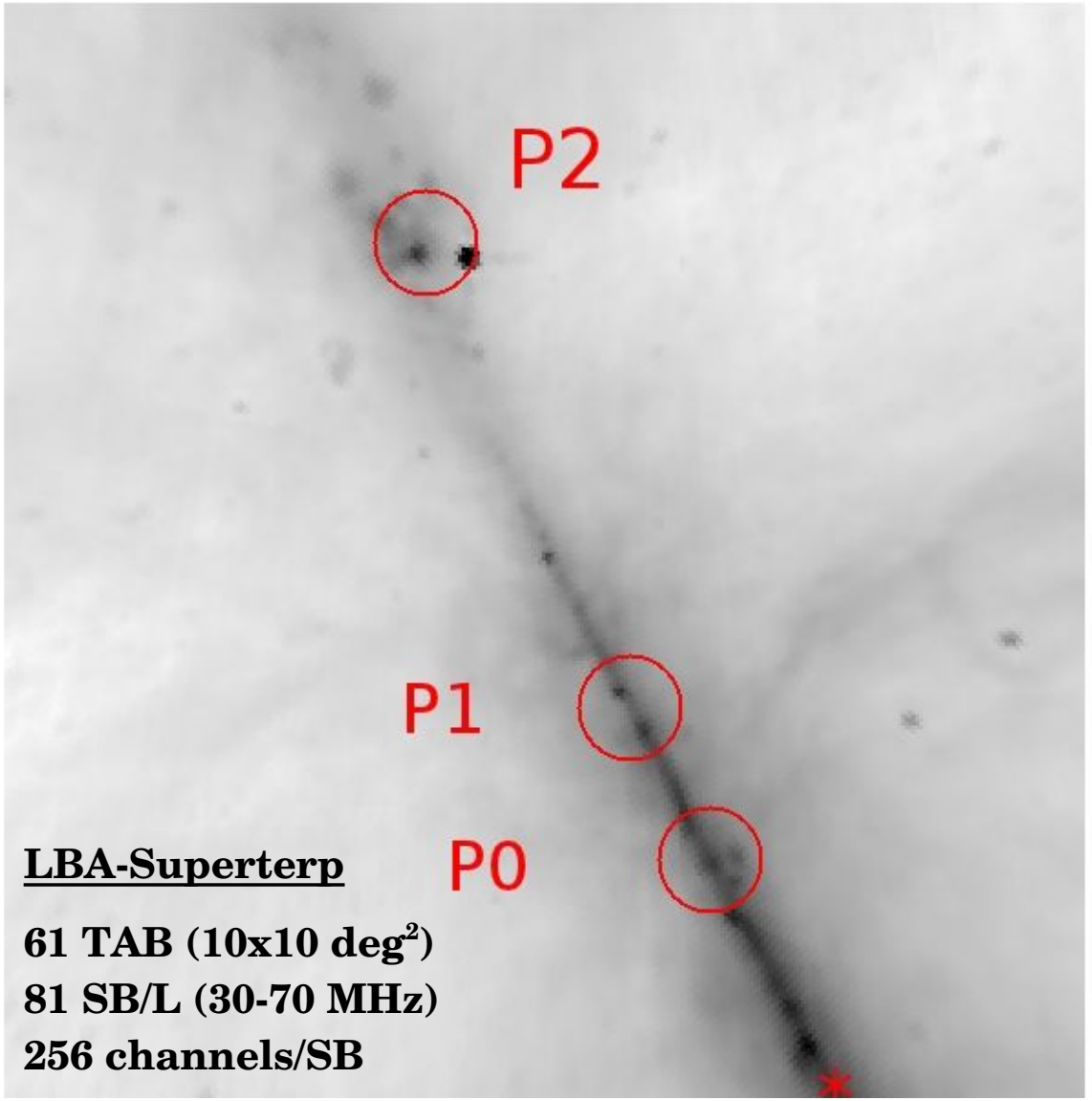
RRL surveys: Why we need total power



* CRRL basic quantity is optical depth, diffuse MW provides natural screen
  - only about 10-20% continuum recovered in interferometric HBA
  - continuum scale (MW < 10 λ) is very different from gas scale (~arcmin)

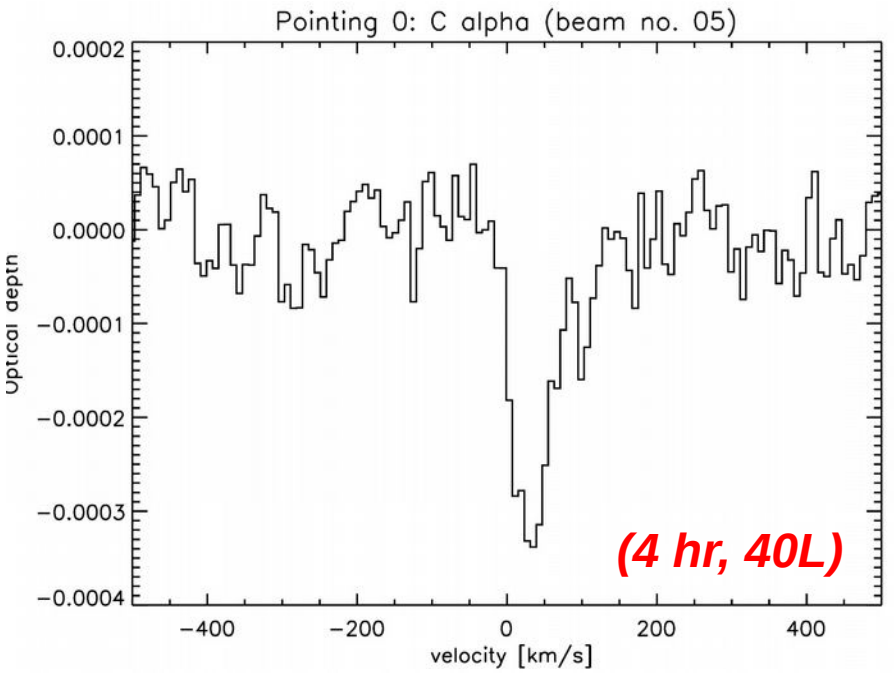
Galactic TA CRRL Survey: (BG results – LC 0 , 1)

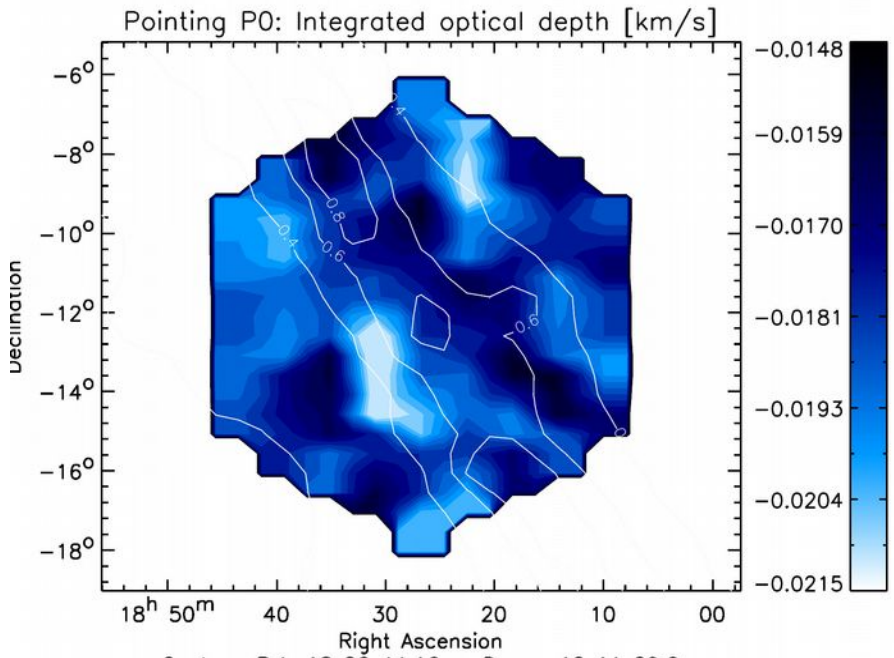
Haslam+1982 (408 MHz) map



LBA-Superterp

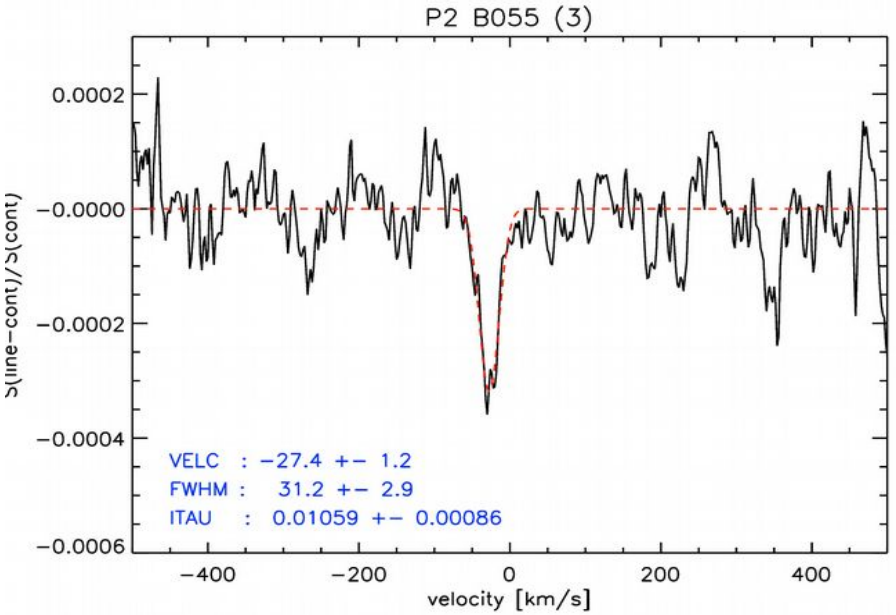
61 TAB (10x10 deg^2)
81 SB/L (30-70 MHz)
256 channels/SB

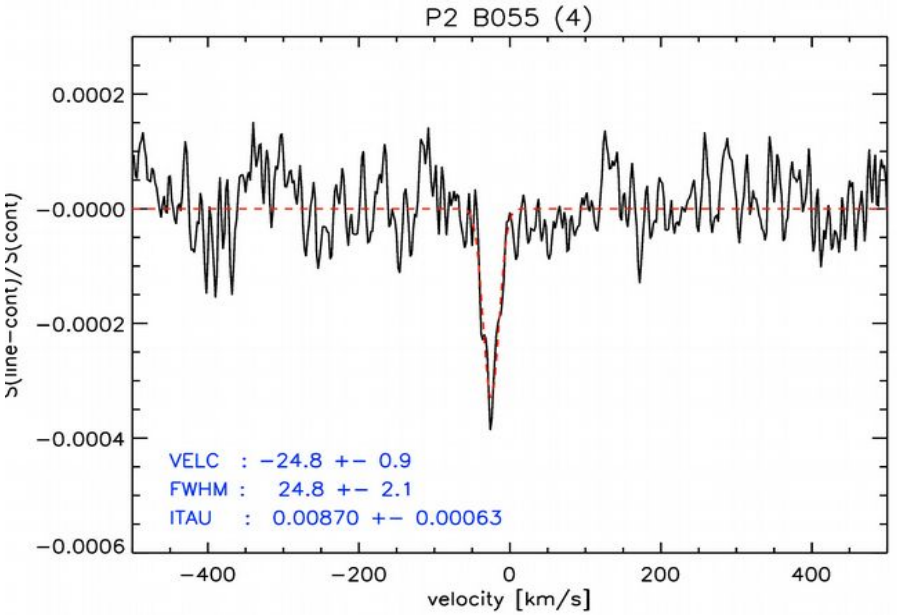


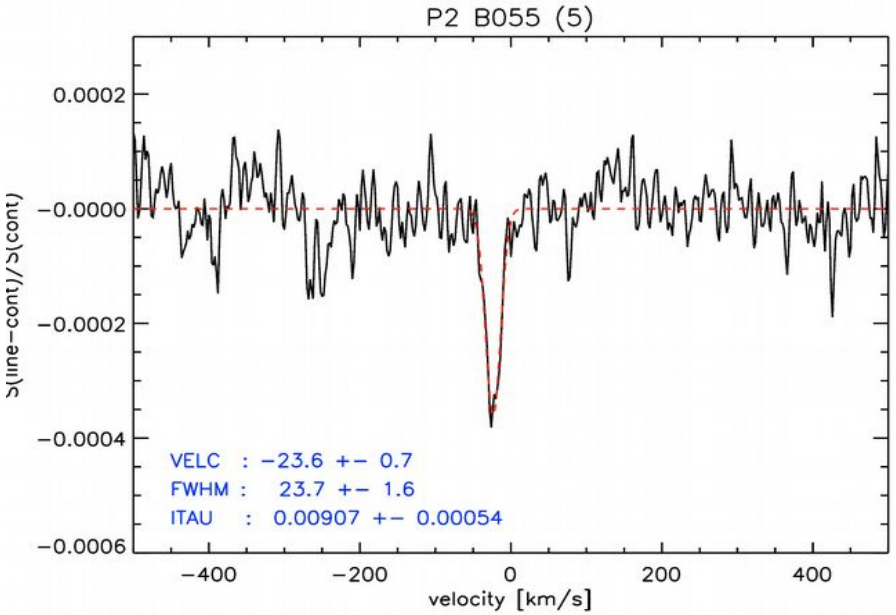


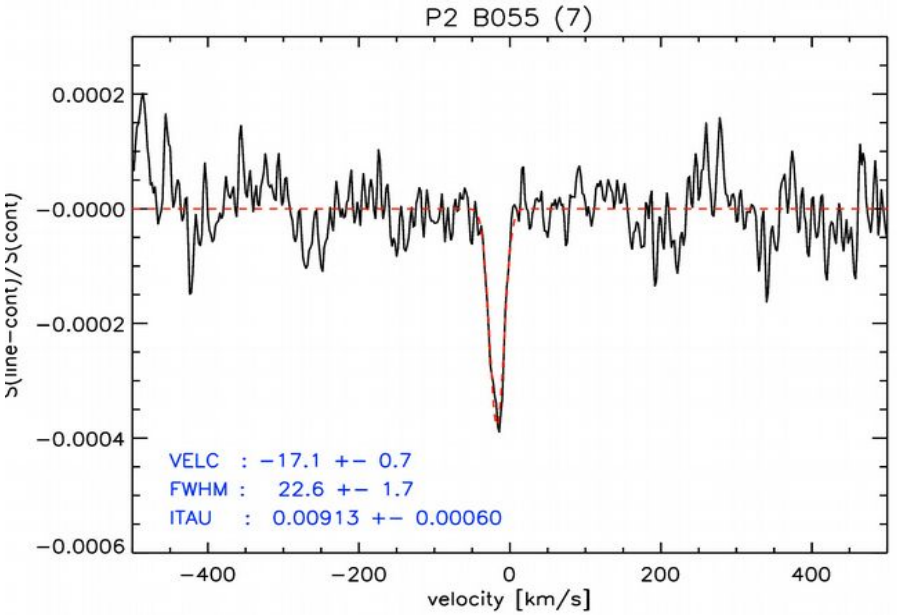
LBA TA CRRL: BG Stability , Quality & Instrument noise

* **Results from 4 observing runs: Instrumental noise level 'constant'**





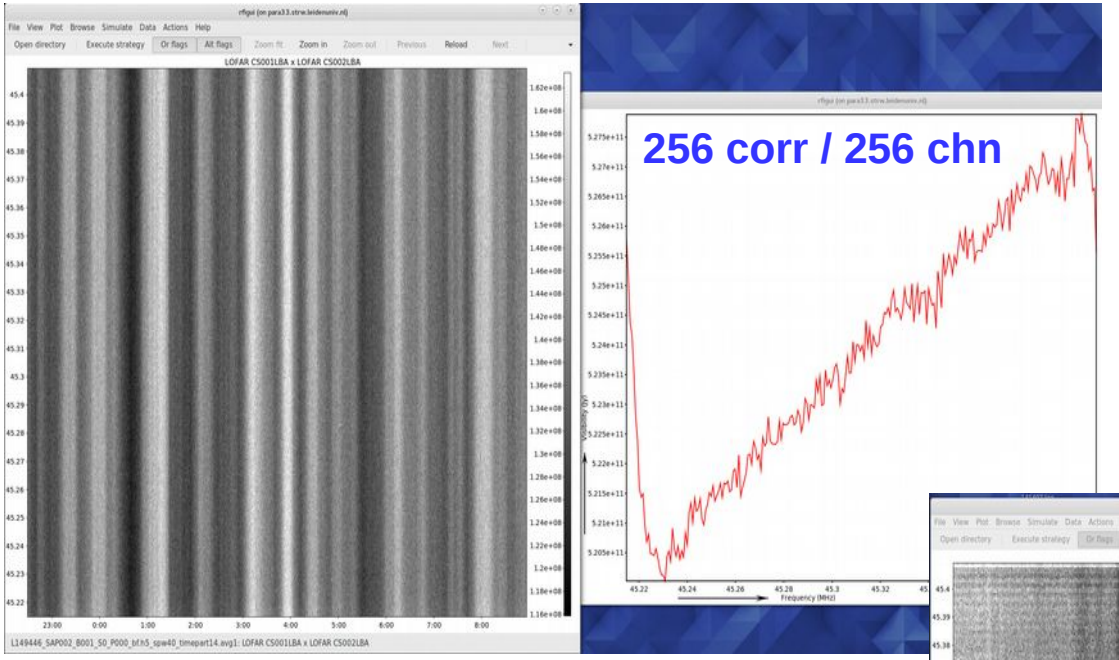




Correlator Issue I: #channels vs. bandpass corrections

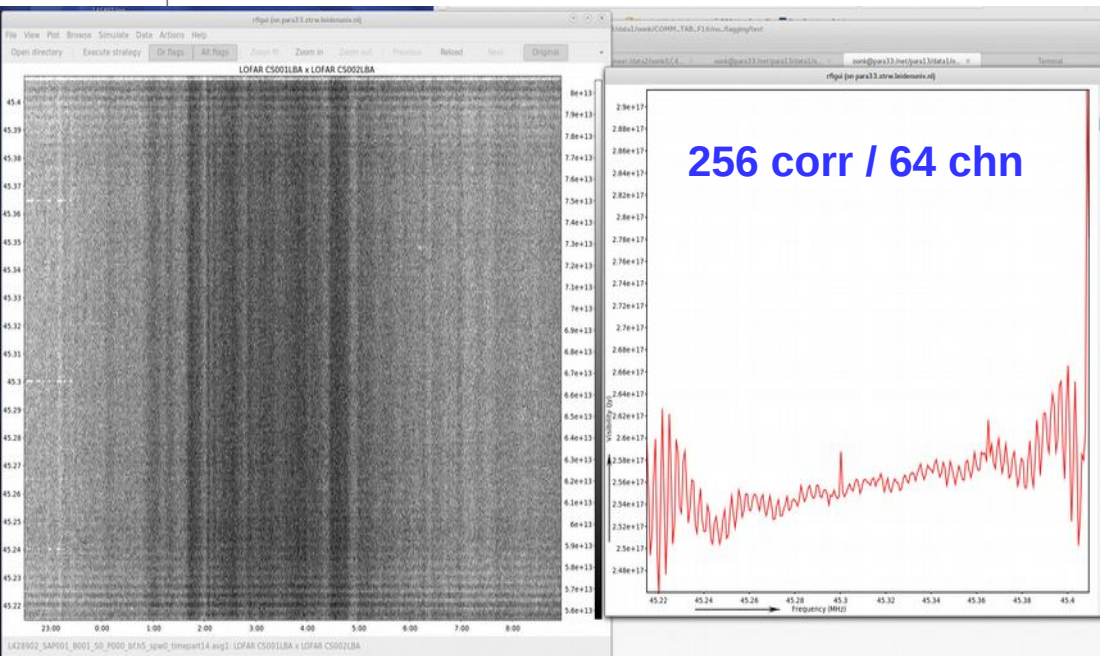
Bandpass: (now solved, do corrections at the observed channel resolution)

Project 1 (LBA 256chn):



Cycle 5: Cobalt (bad bandpass)
τ(rms,chn) > 1e-2
systemic noise (bps)
can not detect RRL

↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓

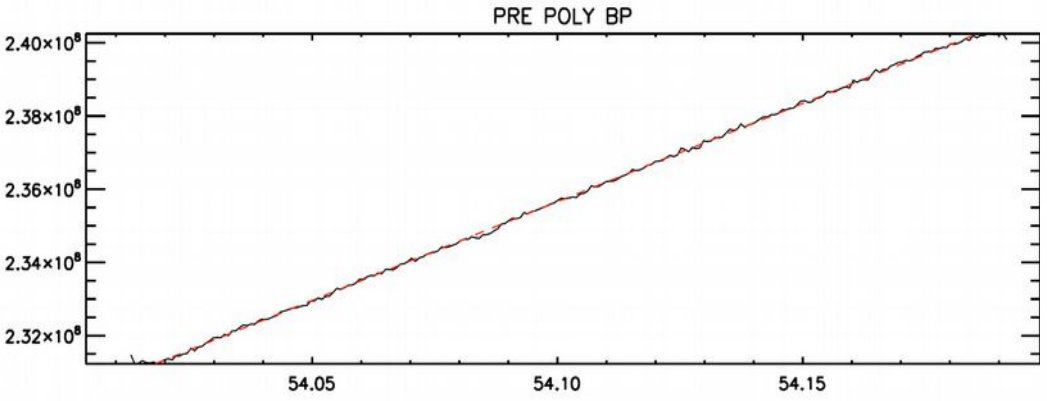


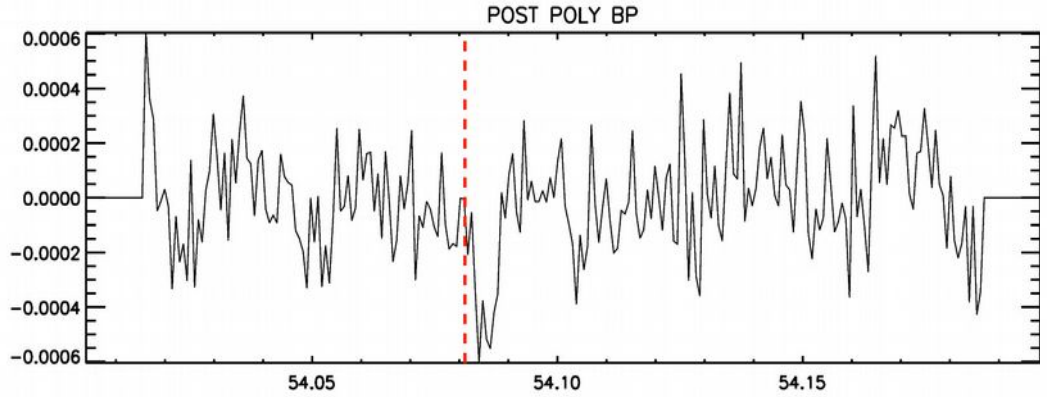
↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑

Cycle 1: Bluegene (good data)
τ(rms,chn) ~ 1e-3
gaussian noise
RRL easily detected

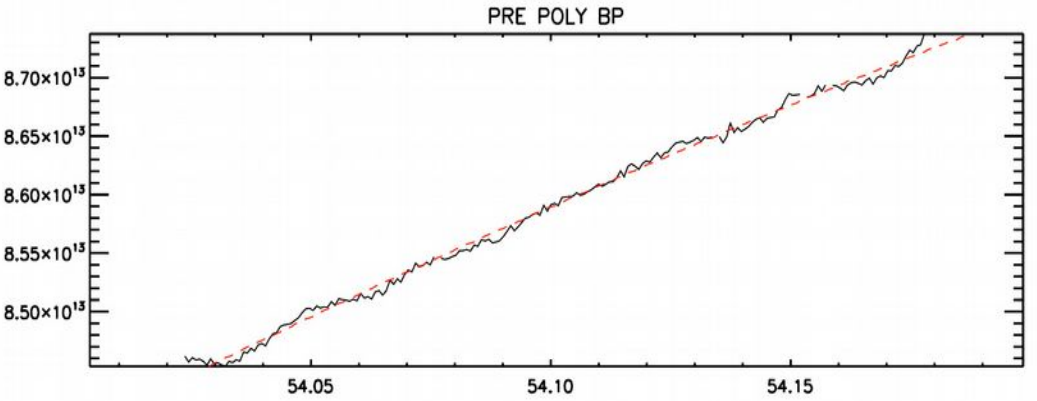
Correlator Issue II: Residual bandpass has PPF ripple

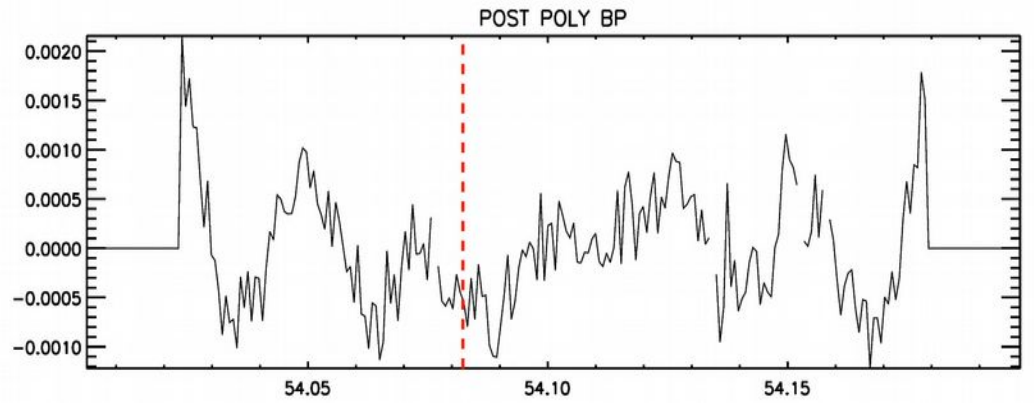
BG: Flagging & Averaging only





C: Flagging, Averaging, 256chn corr



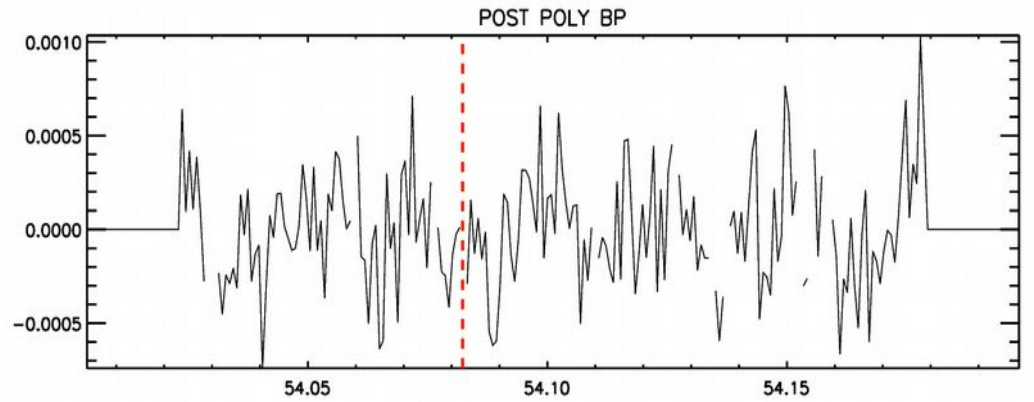


Cobalt Bandpass ('off') corrected =>

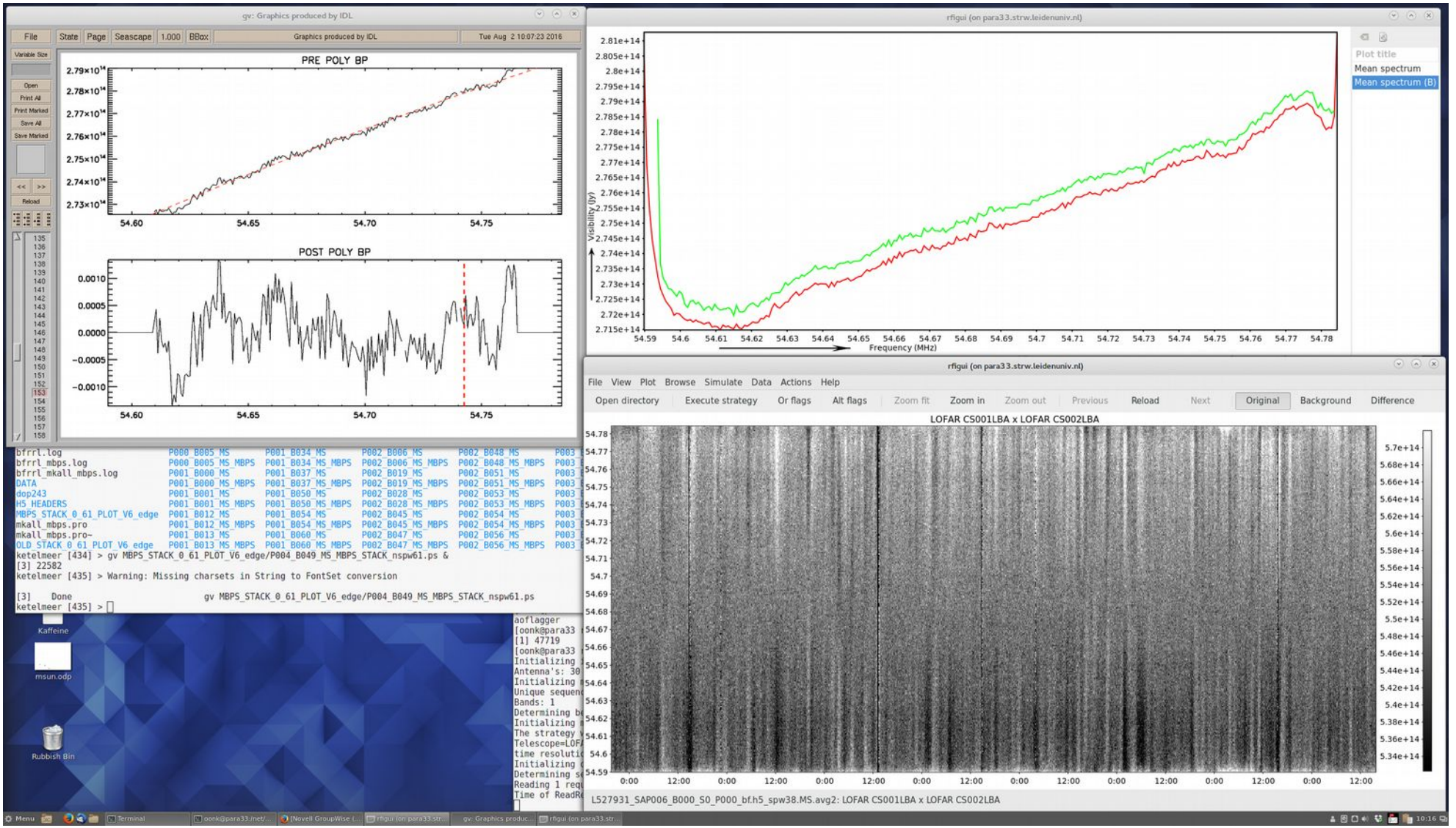
- spectral rms factor ~2 worse

- bandpass adds sqrt(2) noise

" ONGOING INVESTIGATION "



Correlator Issue III: Time dependent, frequency gradients

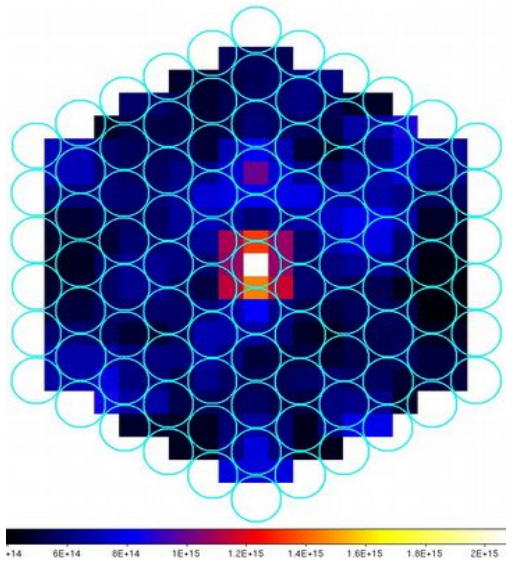


*** Bottom-right shows dynamic spectra (signal in freq vs time) for a single subband:**

- signal has frequency gradient (bandpass) but its fluctuates rapidly in time

- likely instrumental (cycle 6) as this was not seen cycles 0,1 for LOFAR

Conclusions:



1. Tied-Array mode for LOFAR is used for,

- ***total power imaging / spectroscopy***
- ***high time resolution***
- ***… your science***

2. Absolute flux calibration of TA data is possible,

- ***high-cadence (or simultaneous) flux and off obsv.***
- ***apriori MW model or multiple calibrators***

3. Some issues remain in the current data,

- ***residual ppf waves in the bandpass***
- ***time dependent, frequency gradients***

LOFAR