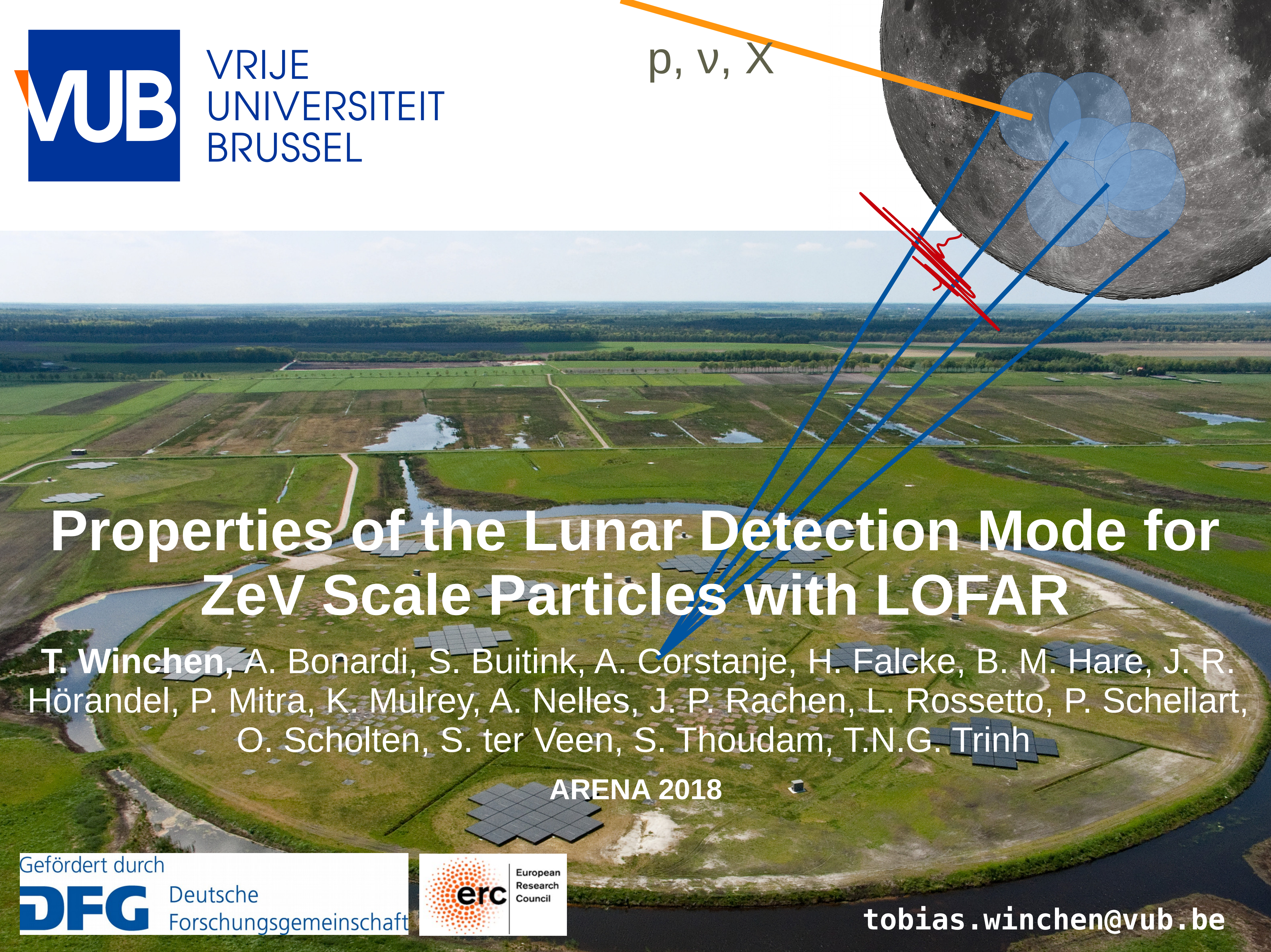
VRIJE UNIVERSITEIT BRUSSEL



Properties of the Lunar Detection Mode for ZeV Scale Particles with LOFAR

T. Winchen, A. Bonardi, S. Buitink, A. Corstanje, H. Falcke, B. M. Hare, J. R. Hörandel, P. Mitra, K. Mulrey, A. Nelles, J. P. Rachen, L. Rossetto, P. Schellart, O. Scholten, S. ter Veen, S. Thoudam, T.N.G. Trinh

ARENA 2018

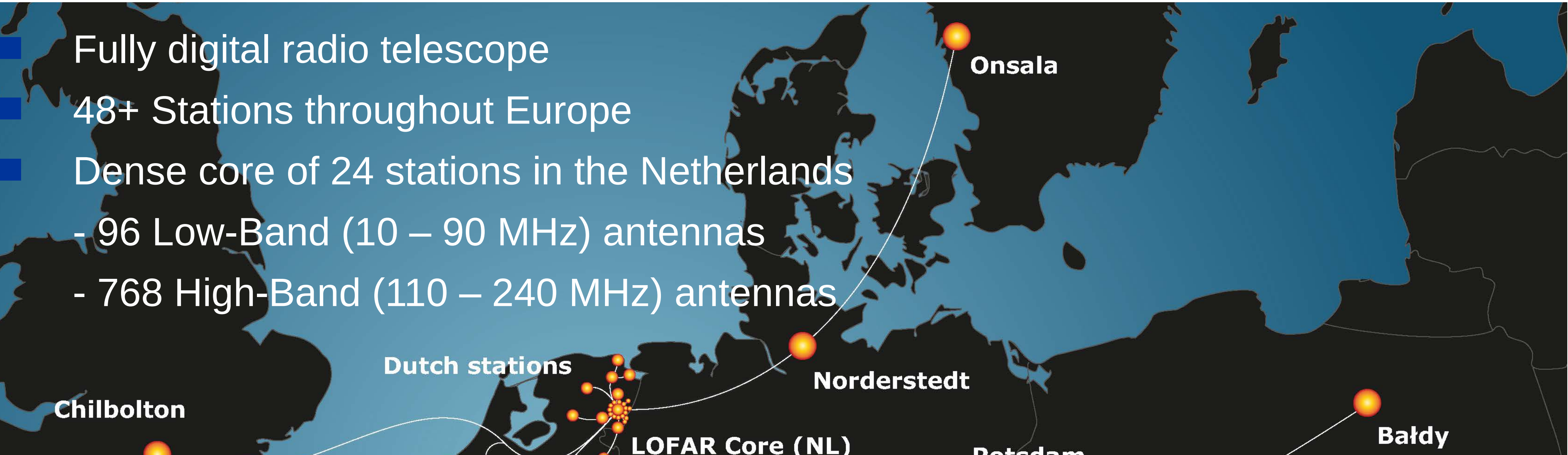
Gefördert durch DFG Deutsche Forschungsgemeinschaft

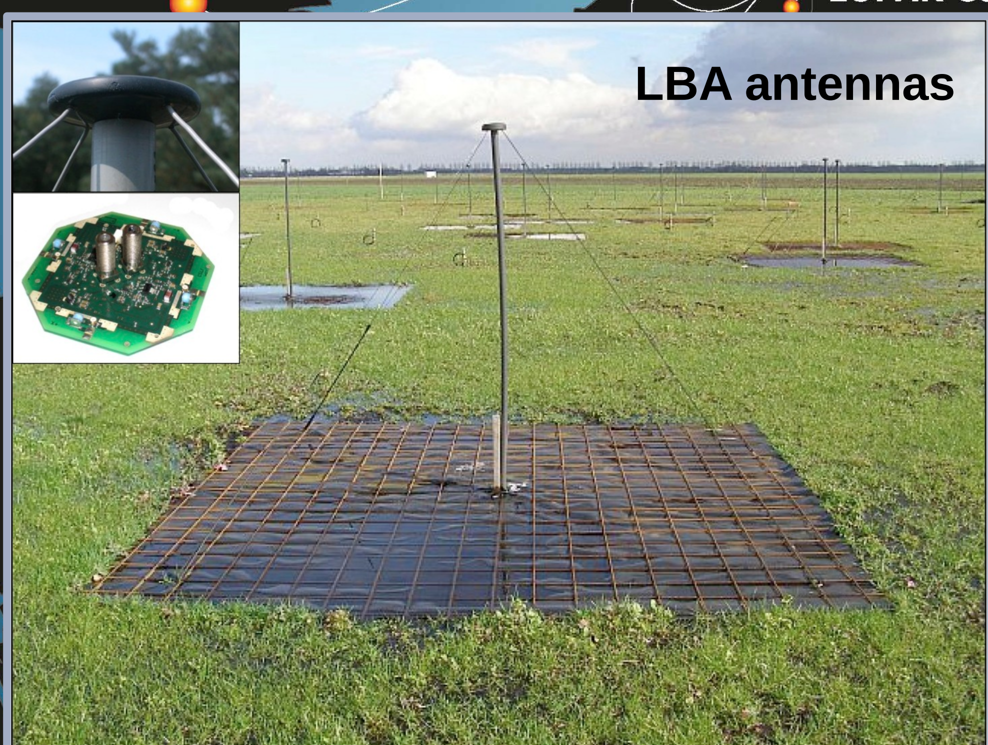
erc European Research Council

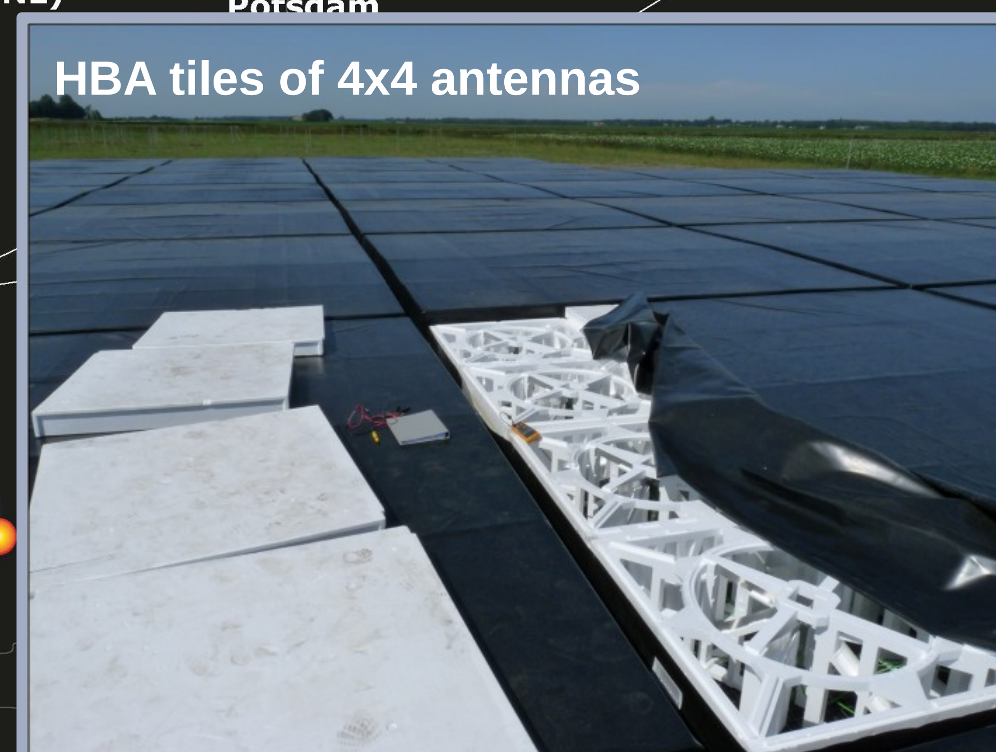
tobias.winchen@vub.be

The LOw Frequency ARray

- Fully digital radio telescope
- 48+ Stations throughout Europe
- Dense core of 24 stations in the Netherlands
- - 96 Low-Band (10 – 90 MHz) antennas
- - 768 High-Band (110 – 240 MHz) antennas





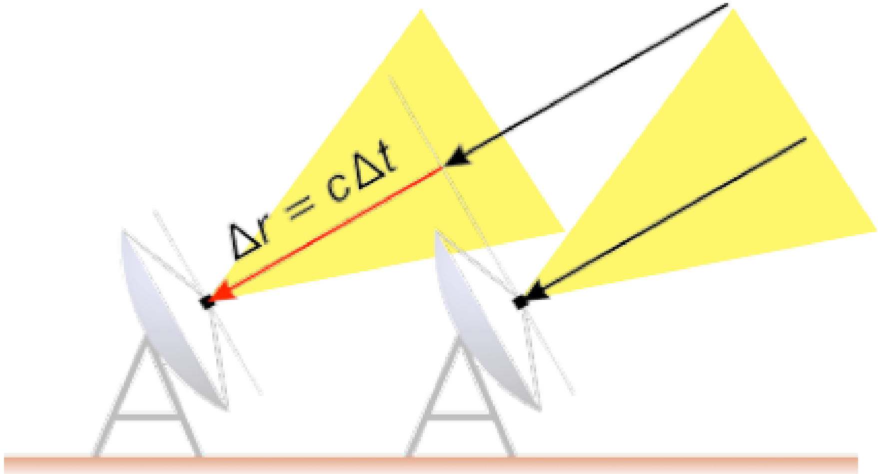


A Fully Digital Radio Telescope

Conventional radio telescope:

Mechanically point (few) directional antennas into observing direction + combine signals

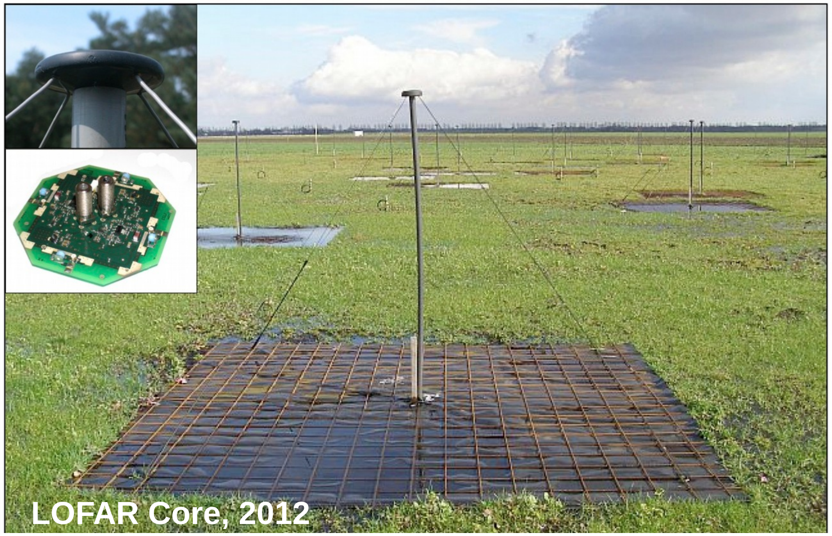
Observe only one direction at a time

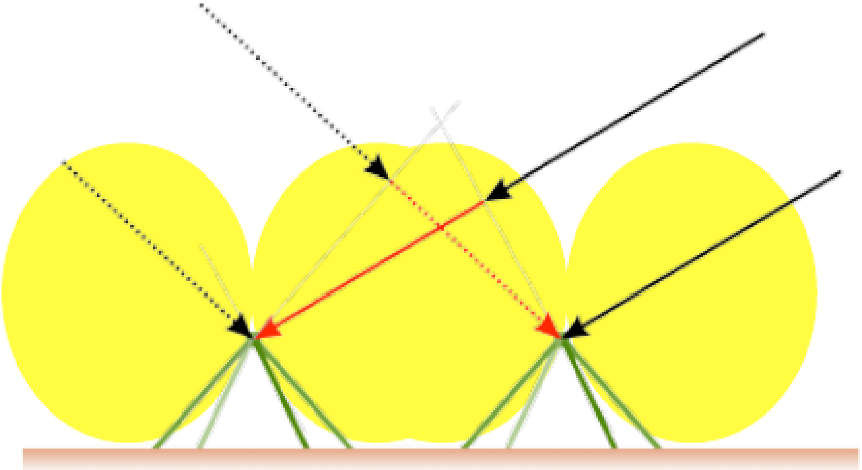


Digital radio telescope:

Many omni-directional antennas digitally combine signals according to direction

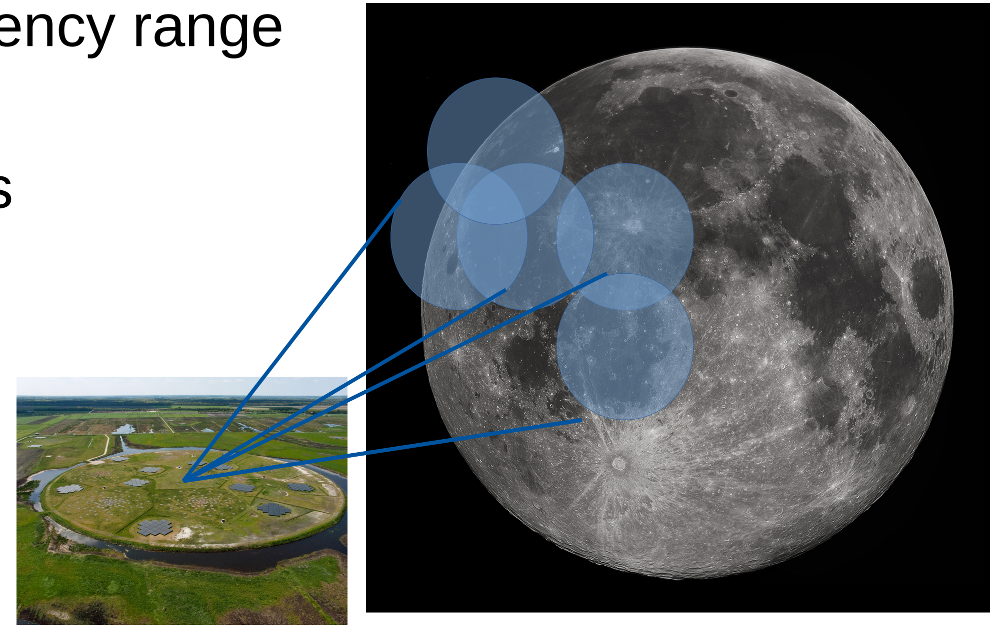
Observe multiple directions simultaneously

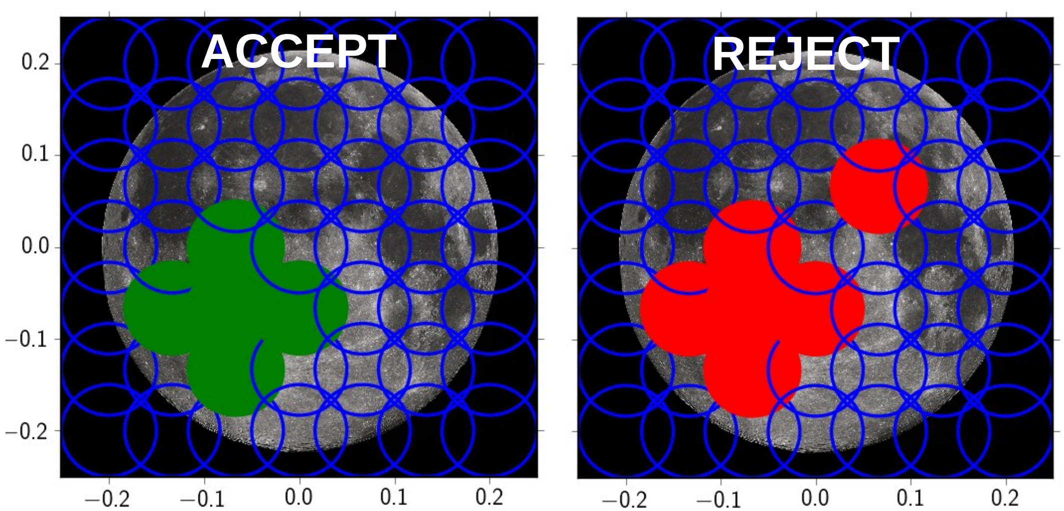




Observation Strategy

- HBA Antennas have optimal frequency range
- Form multiple beams on the Moon
- Search for ns pulses in time-series
- Anti coincidence to suppress RFI
- Analyze Faraday rotation and dispersion to validate lunar origin



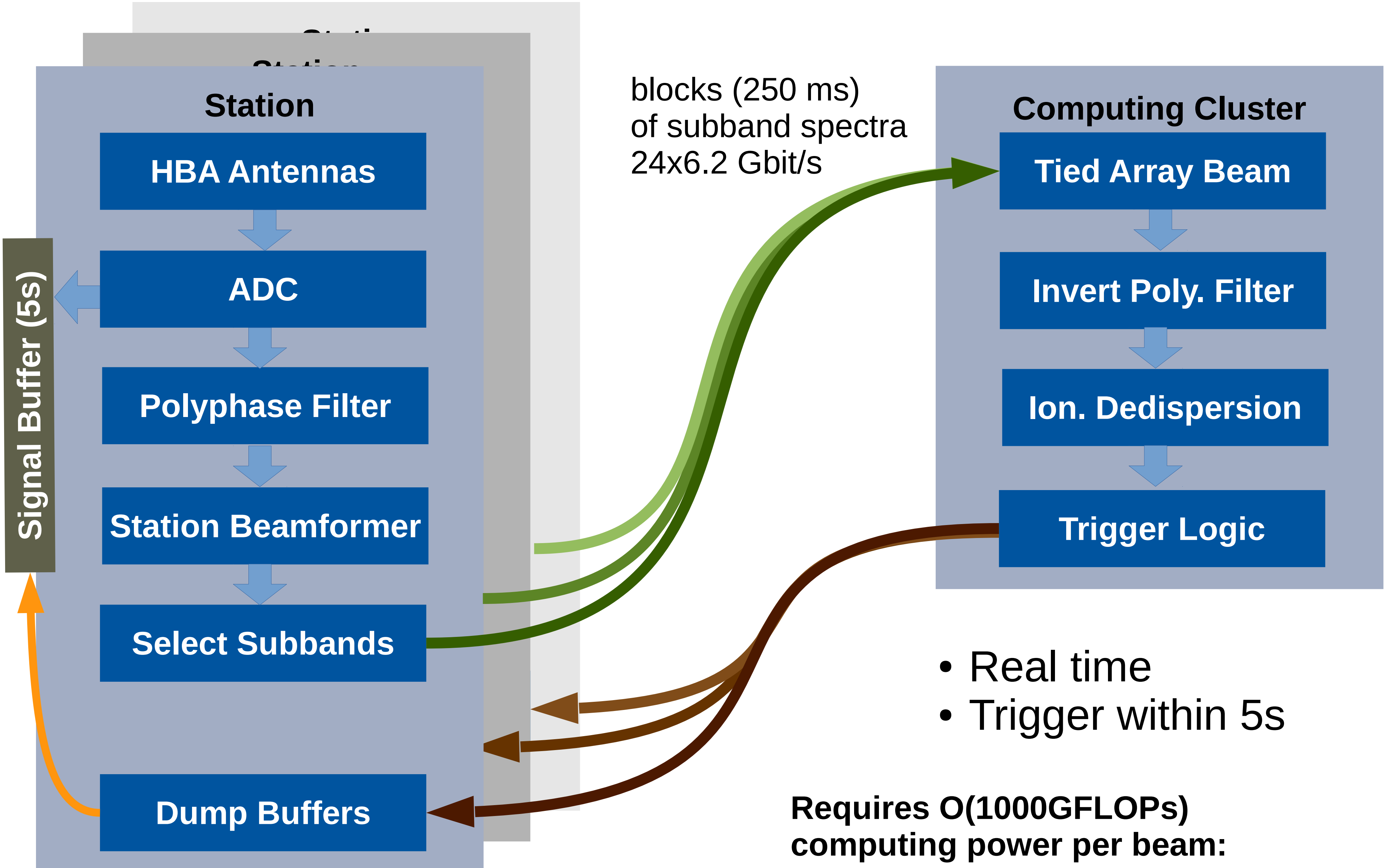


Challenge:

LOFAR designed to integrate flux, user access only to processed signal

- Reconstruct ns time series from processed signal for trigger
- Use buffered traces for analysis

Online Data Analysis



- Real time
- Trigger within 5s

Requires O(1000GFLOPs) computing power per beam: Beyond standard LOFAR capabilities

DRAGNET Cluster

- Designed for Pulsar searches with LOFAR
  (J. Hessels et al., Amsterdam)
- 23 worker nodes:
  - 16 CPU cores (2x Xeon E5-2630v3 (2014))
  - 128 GiB ram
  - 4x TitanX GPU
  - 56 Gbit/s Infiniband connection to LOFAR

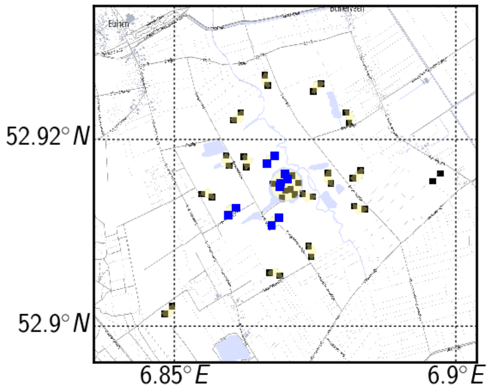
= 92 High-End GPUs + CPUs ; 0.5 PetaFLOP/s

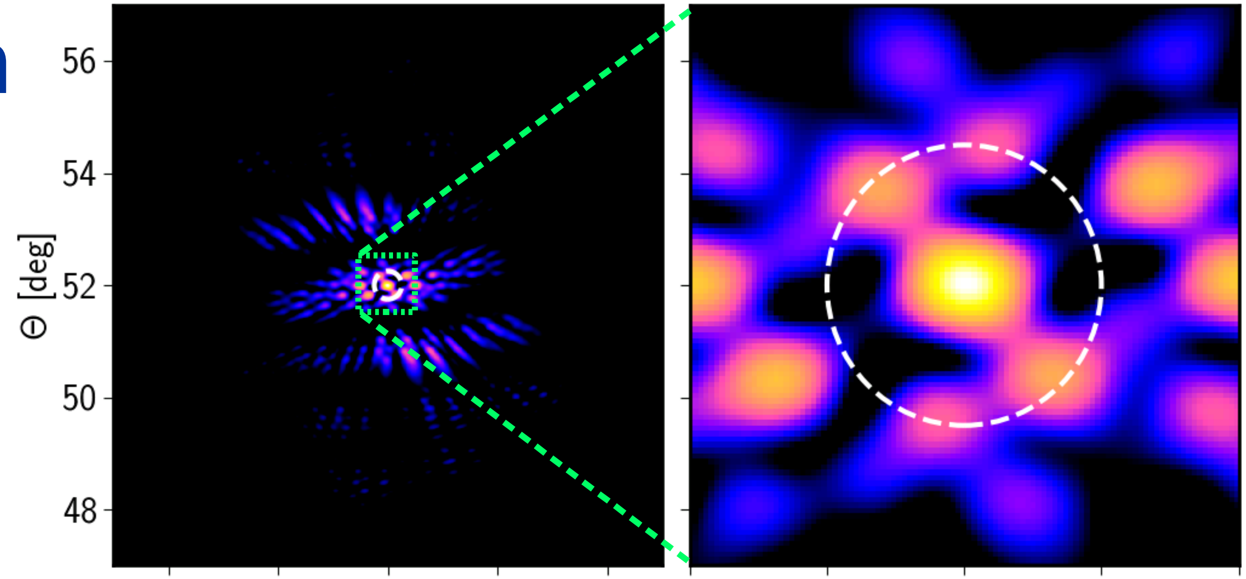
+ Performance of prototype implementation allows full coverage of moon

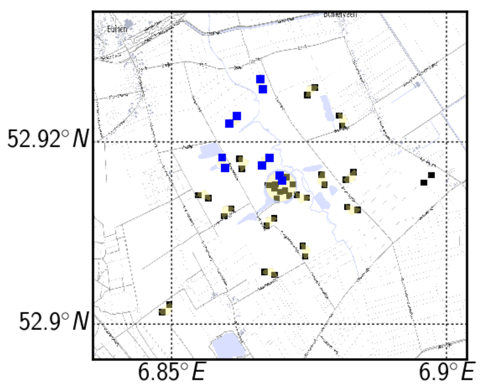
- Bandwidth limited to processing data of 5 / 24 stations

  → Implications on Beamshape + Performance

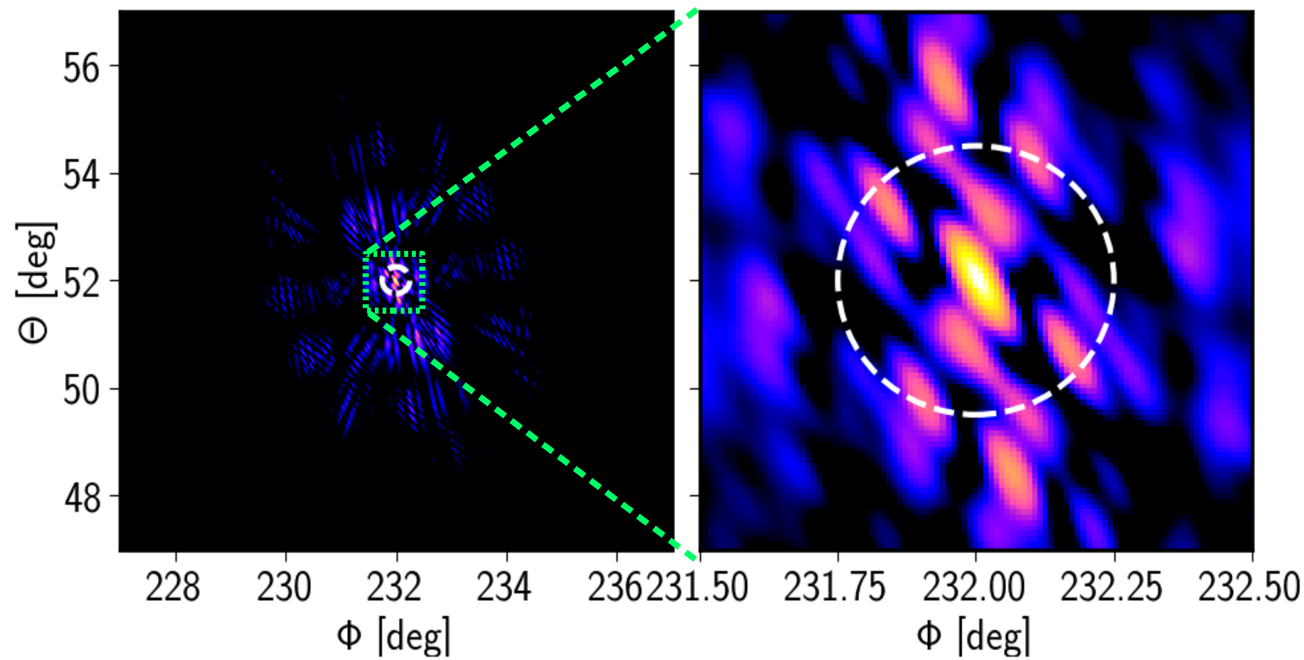
Station Selection



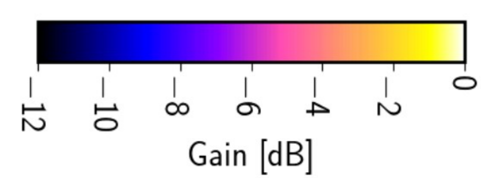




Less strong sidelobes off-moon

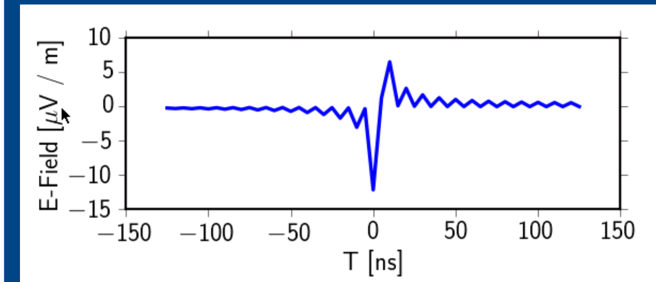


- Strong suppression beyond 3 deg from moon
- Complex side-lobes on moon



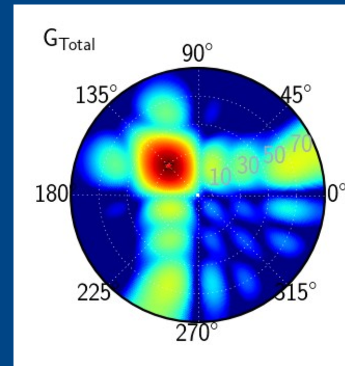
Full Simulation

1. Simulate Physical Detector

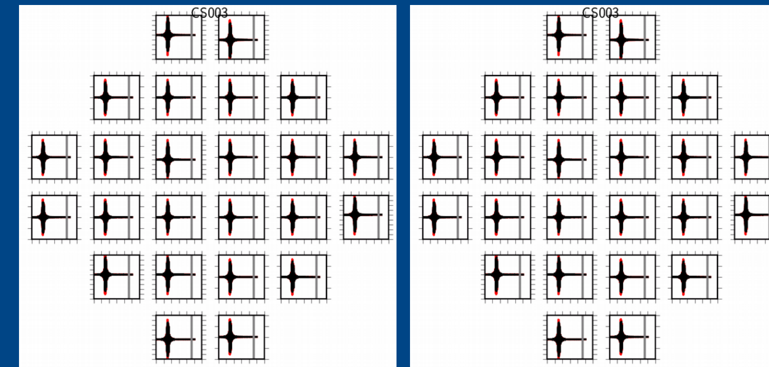


Dispersion

*



=



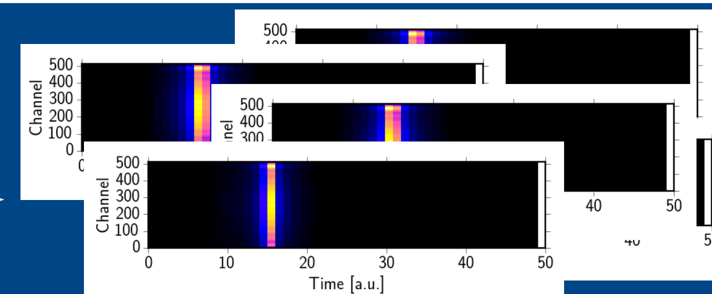
E-Field Pulse

Fold with tile gain-pattern

Voltage in Stations

2. Simulate Pre-Processing

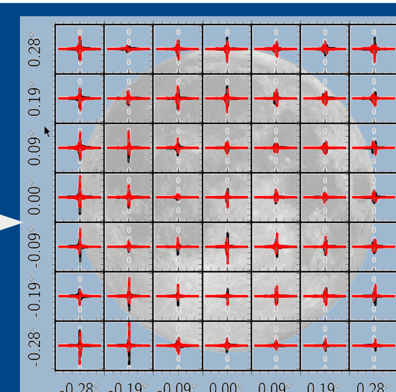
Voltage in Stations → PPF → *Other Filters* →



Station Beams

3. Online Analysis

Station Beam → PPF Inversion → De Dispersion →

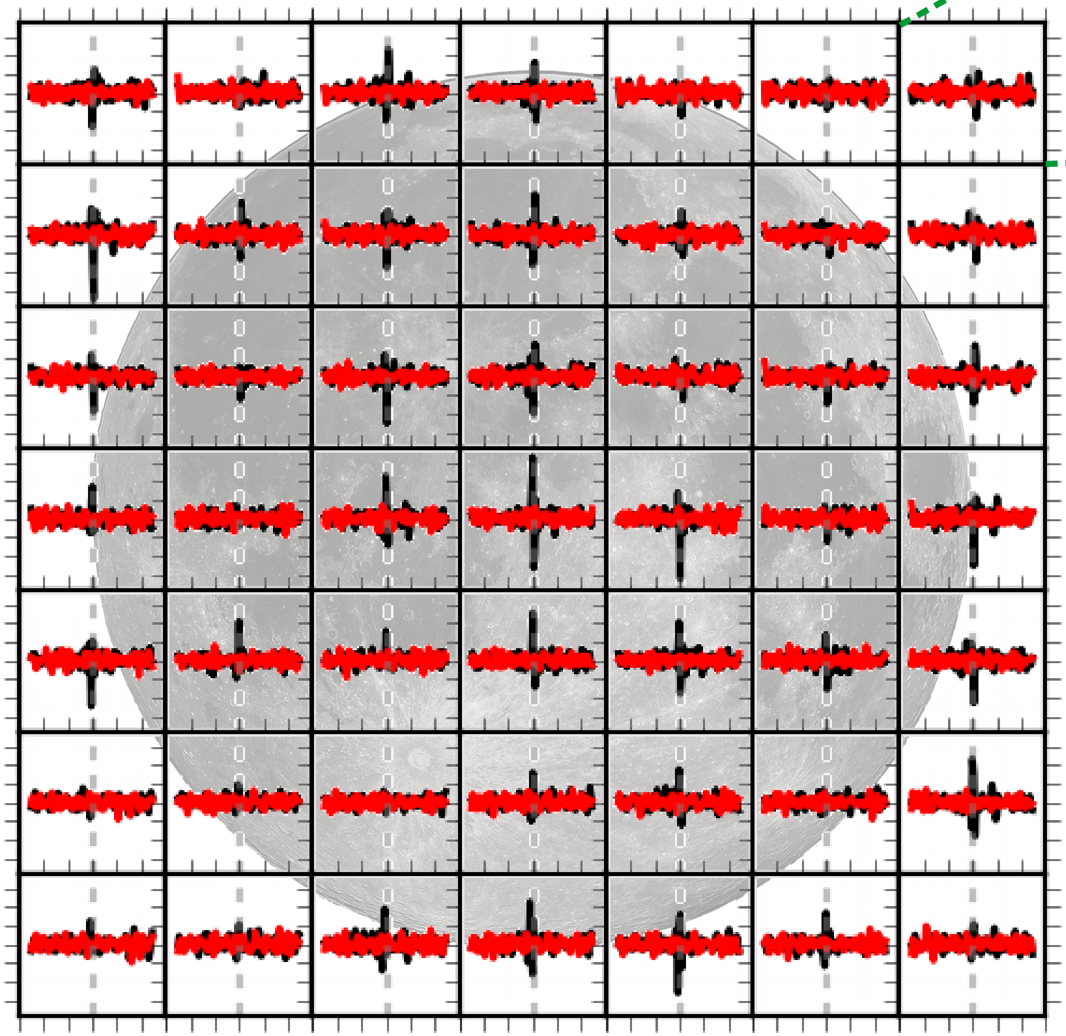


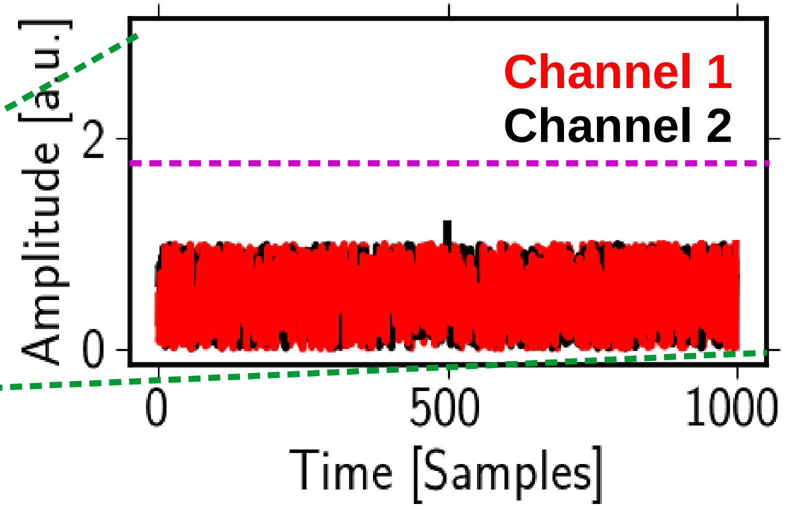
→ Trigger

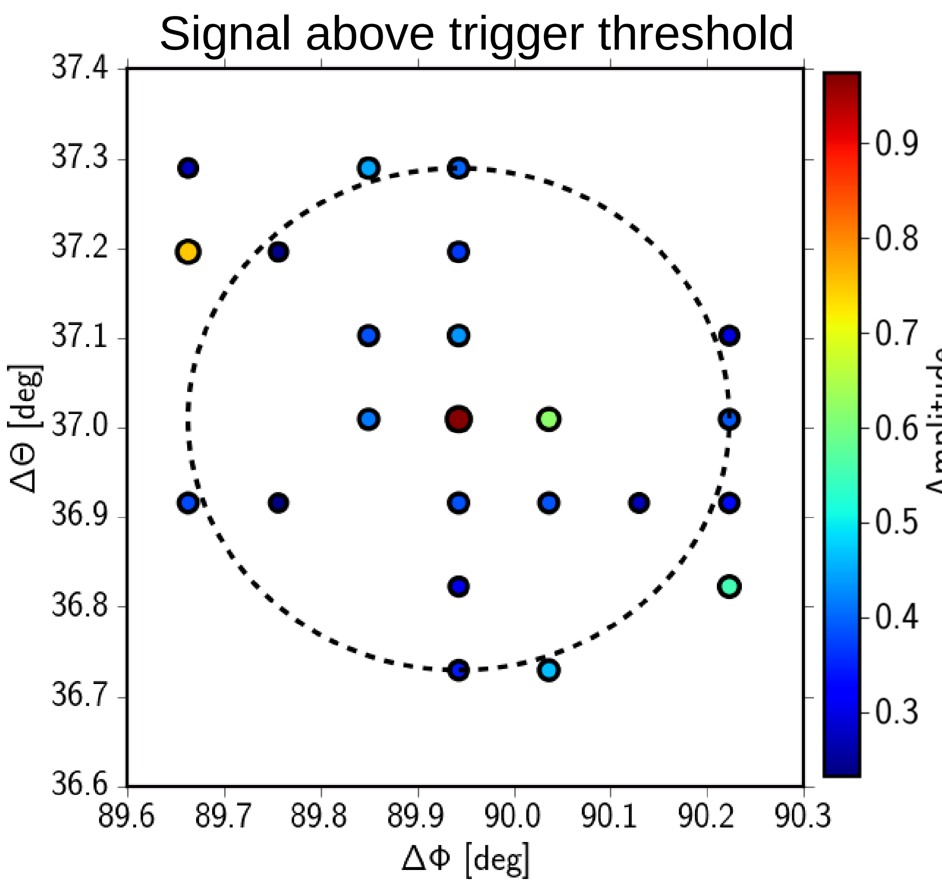
Analysis Beams on Moon

Simulated Pulse from Moon Center

Signal trace in 49 Analysis Beams
at different point on moon



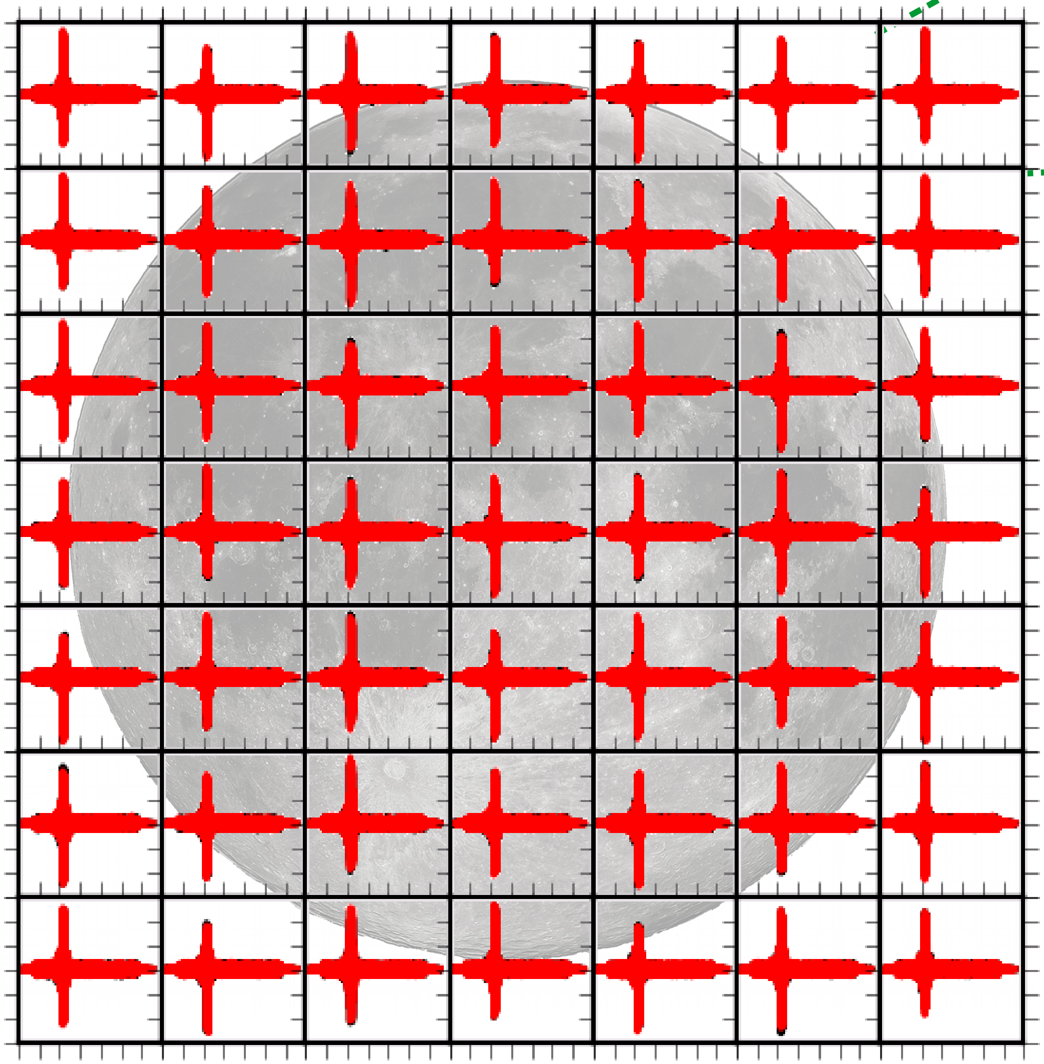


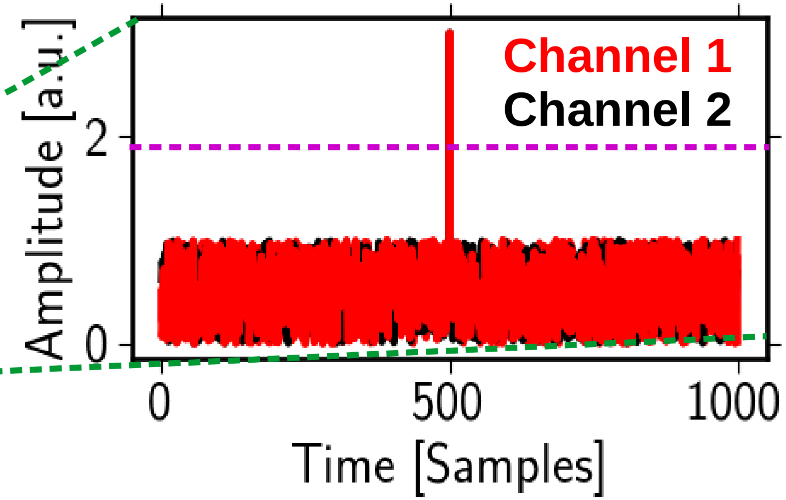


→ **Pulse Visible in several beams**

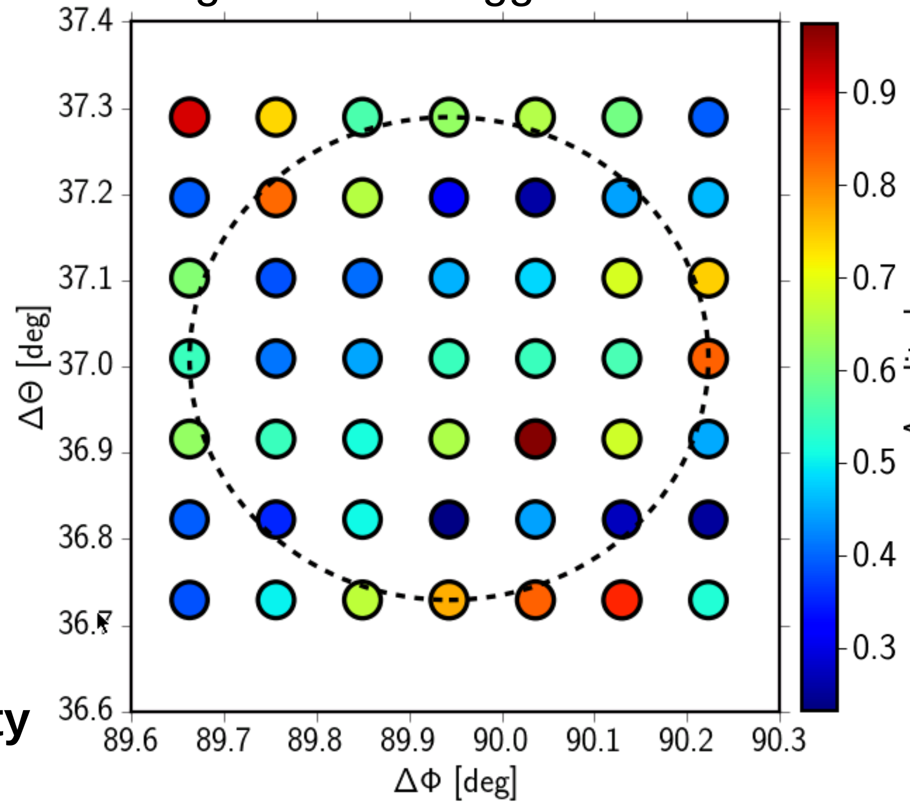
Simulated Pulse from Horizon (RFI)

Signal trace in 49 Analysis Beams
at different point on moon





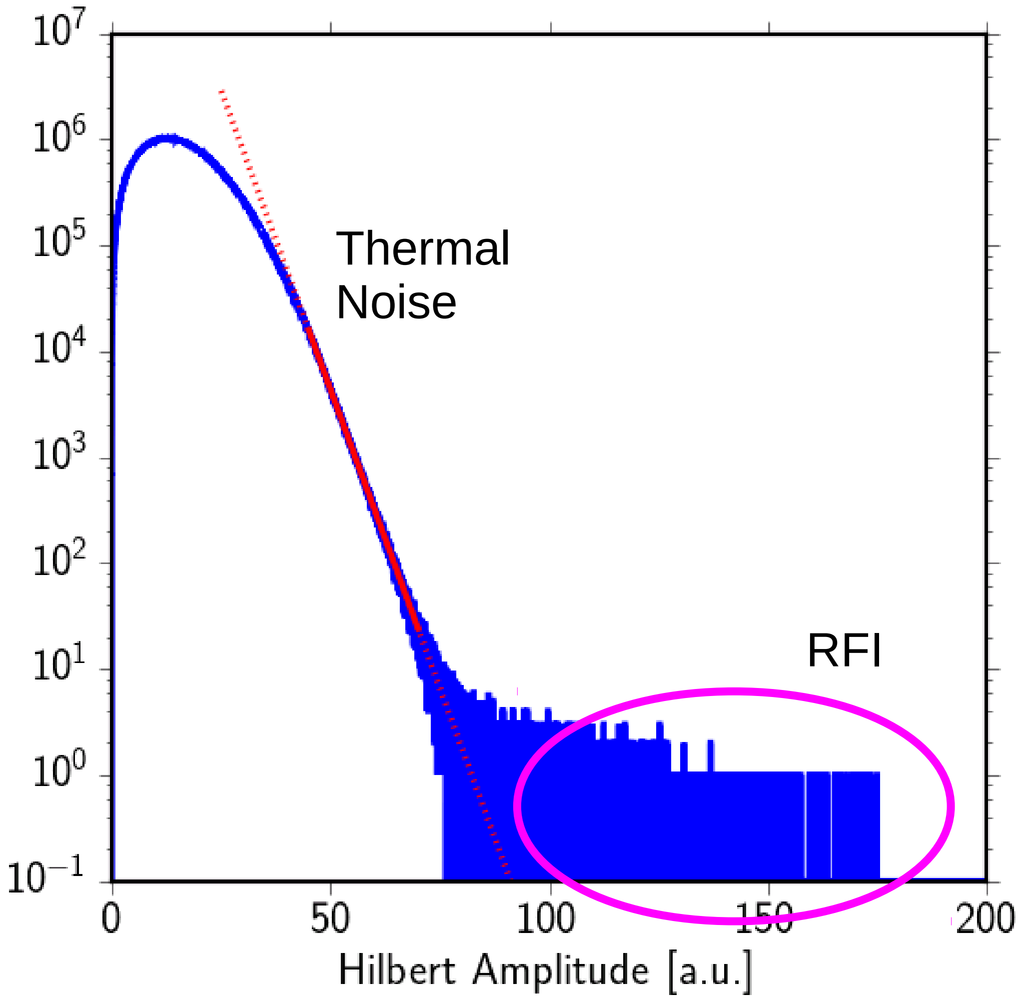
Signal above trigger threshold

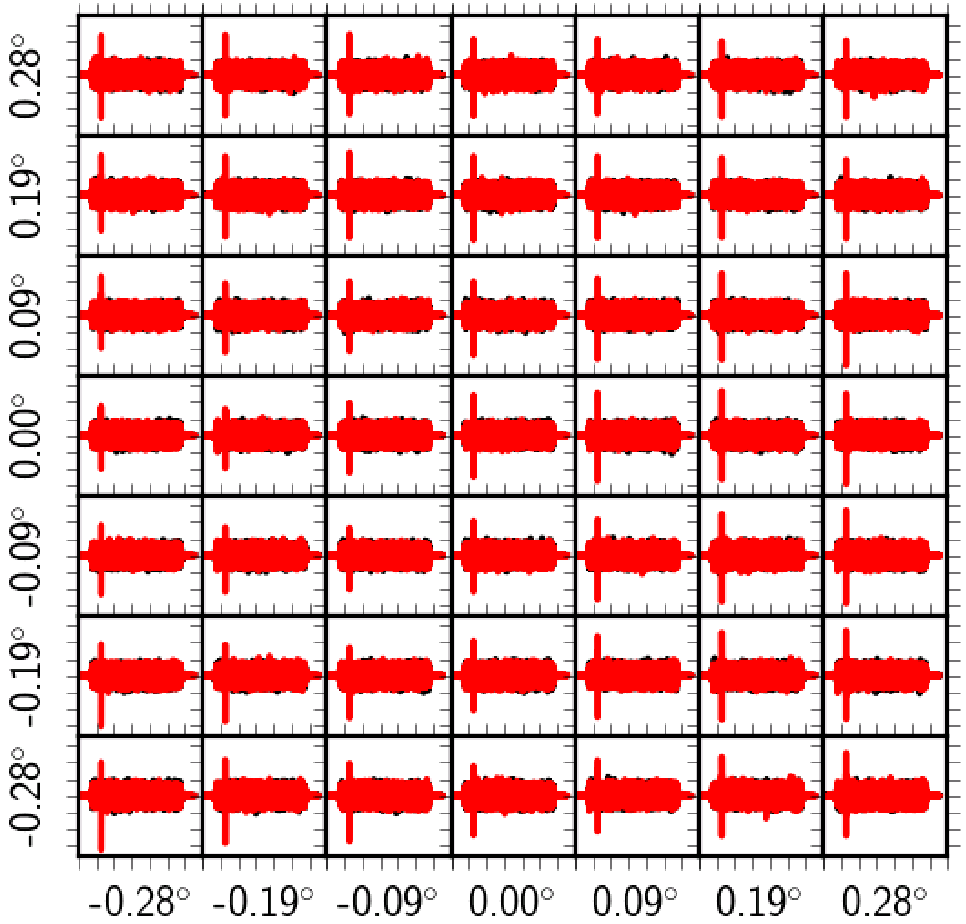


→ **RFI Visible in all beams with similar intensity**

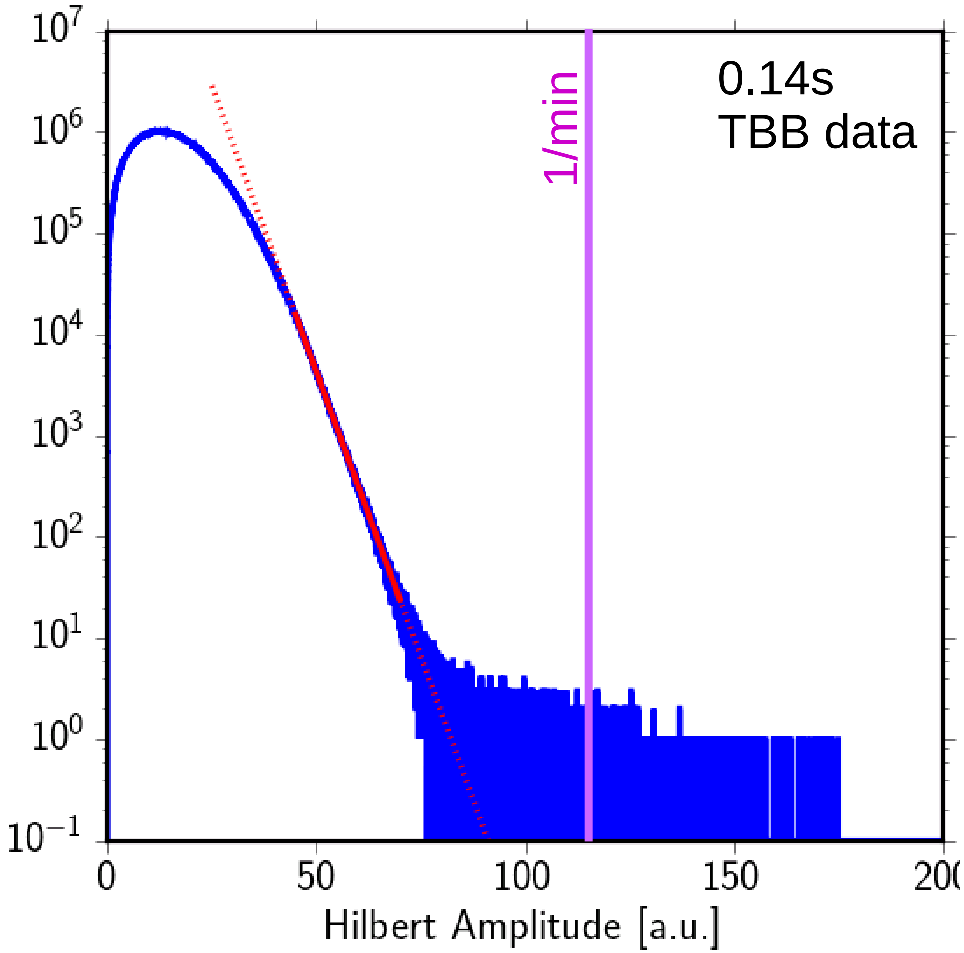
RFI visible in Data

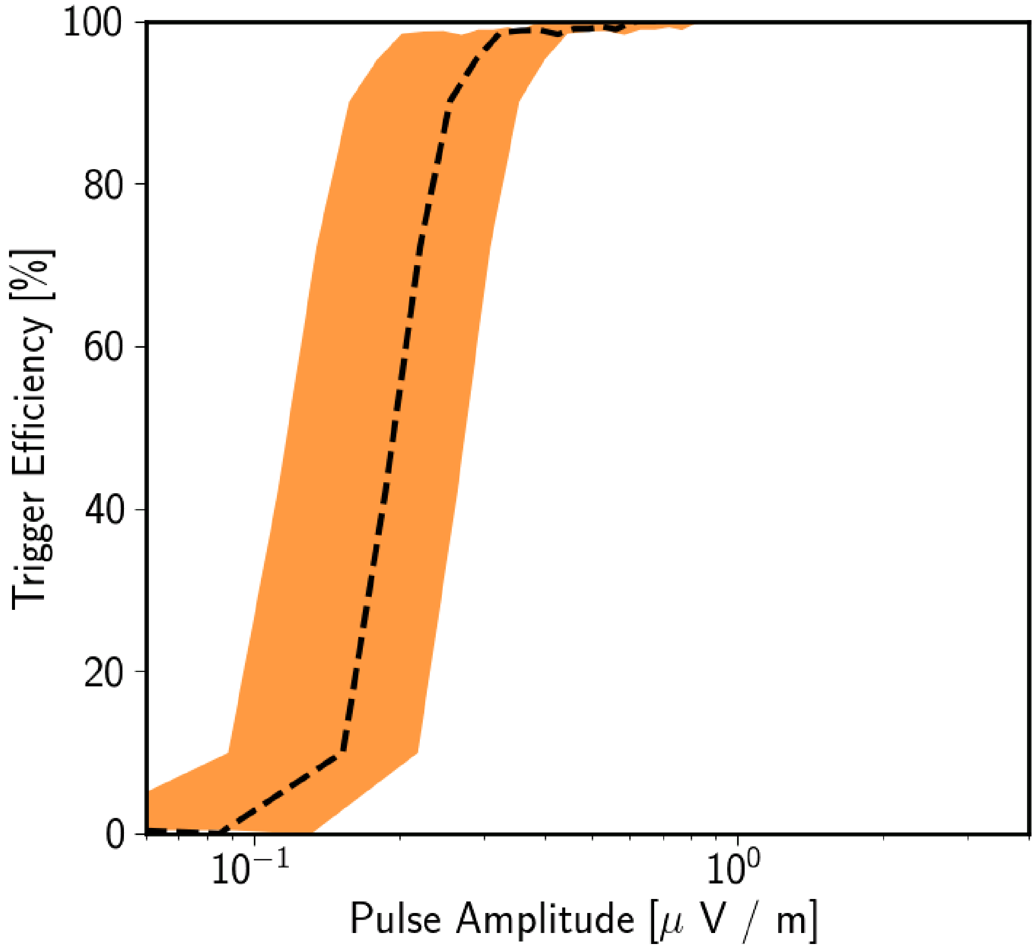
- 0.14s of TBB Data (not on Moon)
- Processed by Analysis/Simulation pipeline





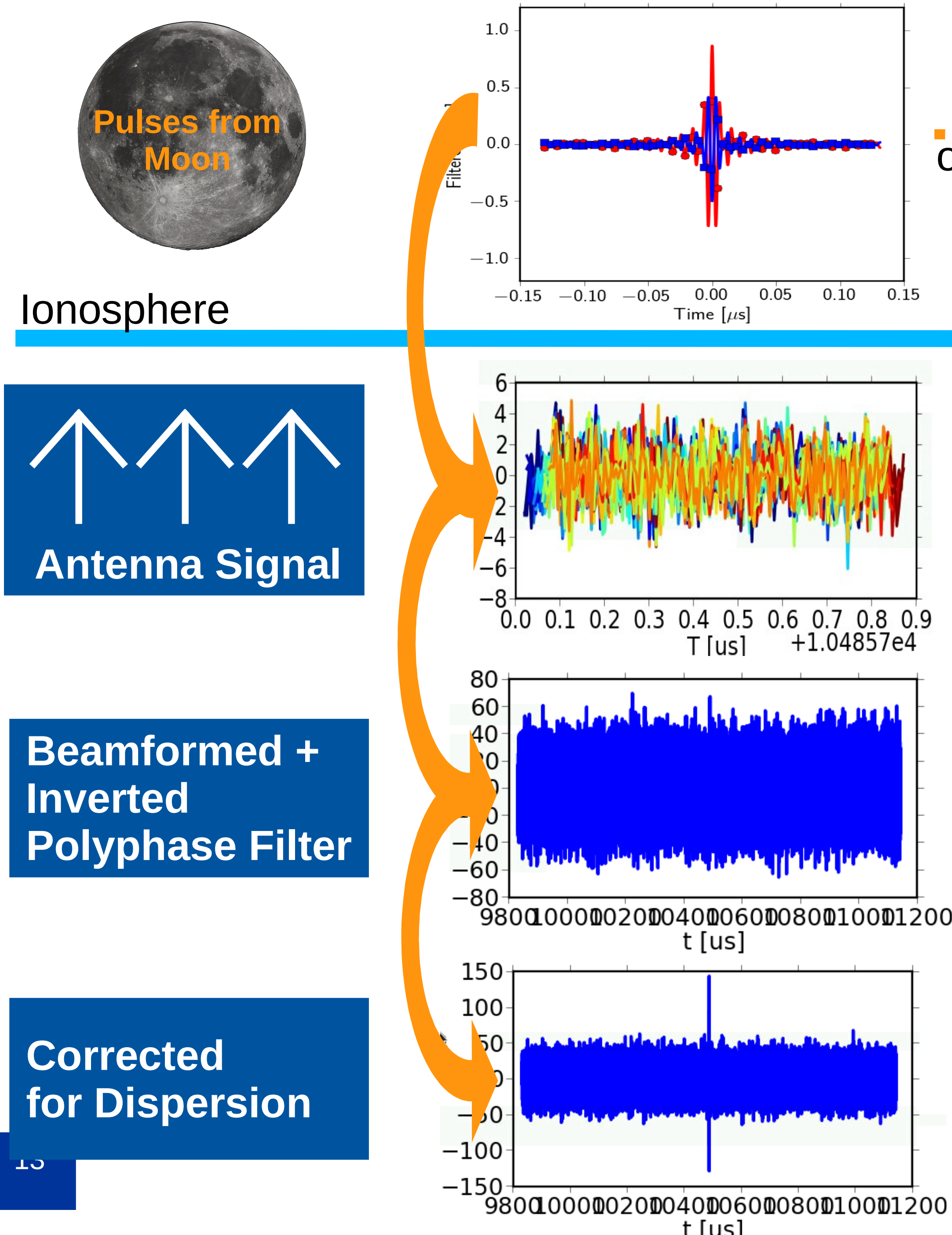
Threshold Trigger

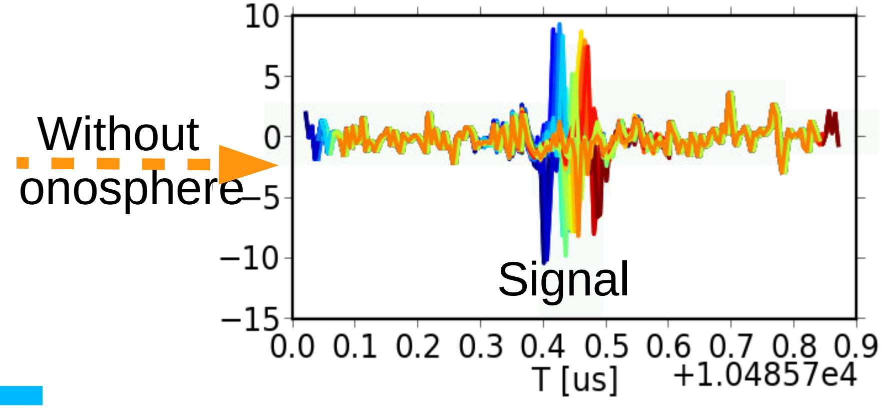




Limit trigger rate to 1/min to reduce data transfer

Ionospheric Dedispersion





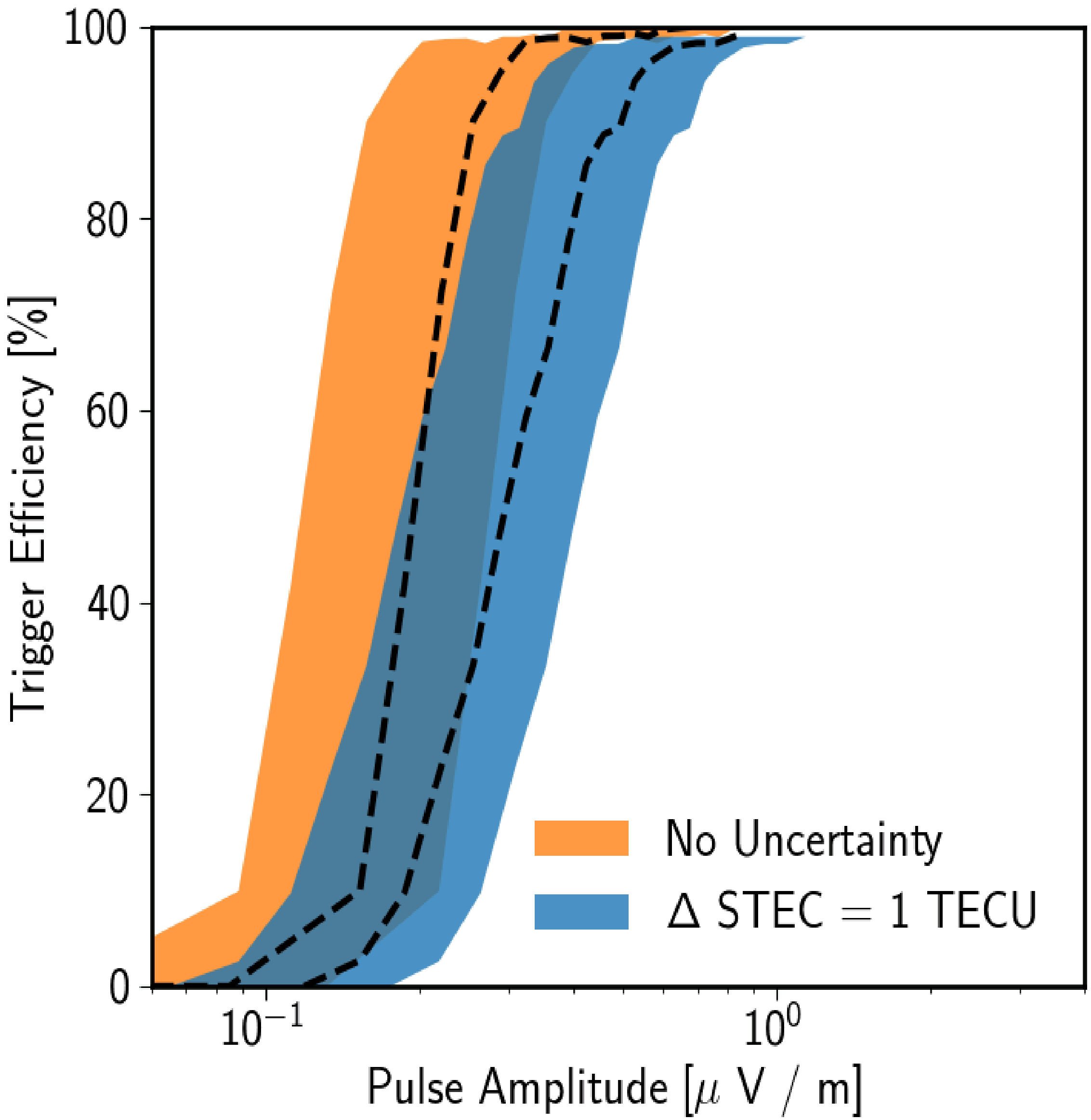
- EM Pulse from Moon pass through Ionosphere
- Frequency dependent dispersion
- Dispersion depends on electron content of ionosphere (STEC)

$$\Delta t(\nu) = 1.34 \frac{STEC}{\mathrm{TECU}} \left(\frac{\nu}{\mathrm{Hz}}\right)^{-2} \mathrm{s}$$

1 TECU = 10^{16} electrons / m^2

- STEC not known exactly → Test as many STEC-Values as possible

DeDispersion – STEC Accuracy

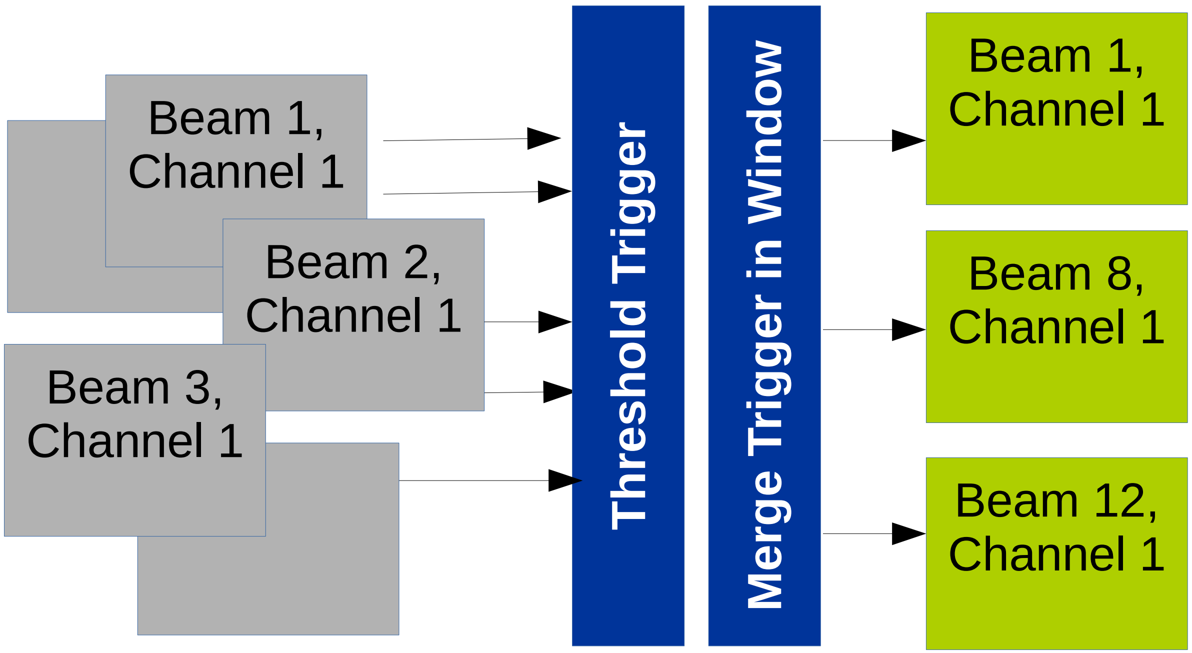


- Simulated STEC varies distributed around 20 TECU with spread 1 TECU
- Always corrected for 20 TECU

- 1 TECU uncertainty on Ionosphere corresponds to roughly factor 2 in E-Field threshold for 100% efficient reconstruction
- The minimum detectable field is not affected that significantly

- **We probably can know the STEC better than 1 TECU (~0.1 TECU reported by Zelle et al, 2015.)**

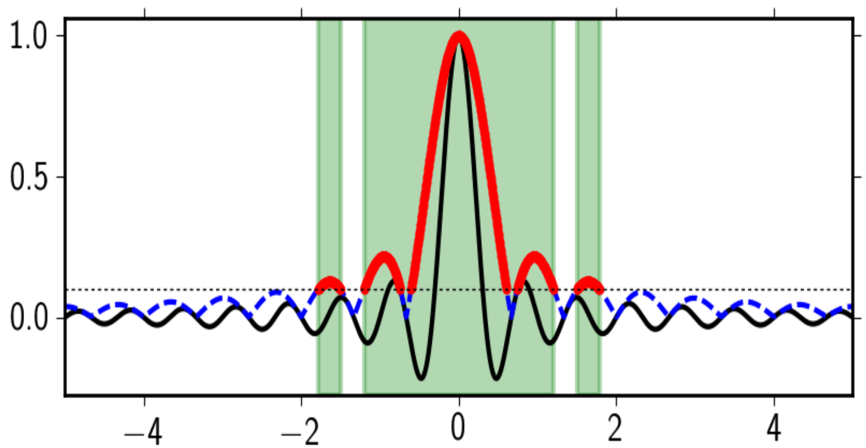
RFI Suppression: (‘Anti - Coincidence’)

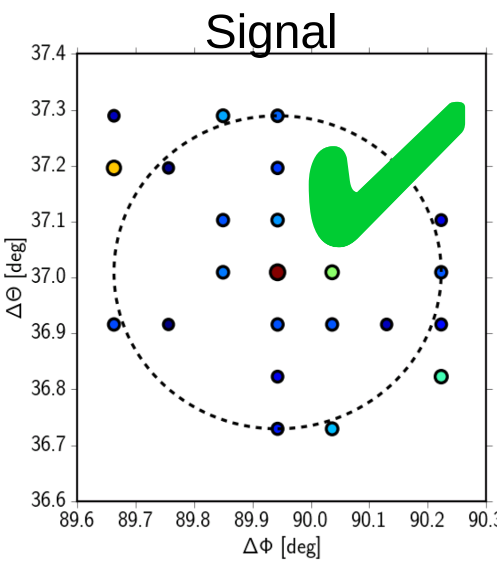


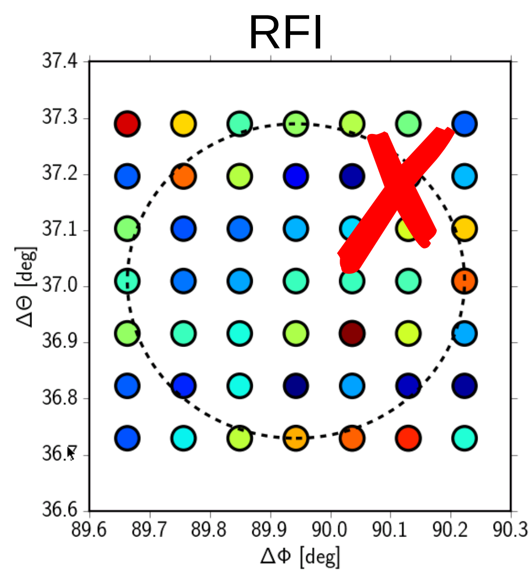
Anti Coincidence Trigger

Number of Beams above Threshold

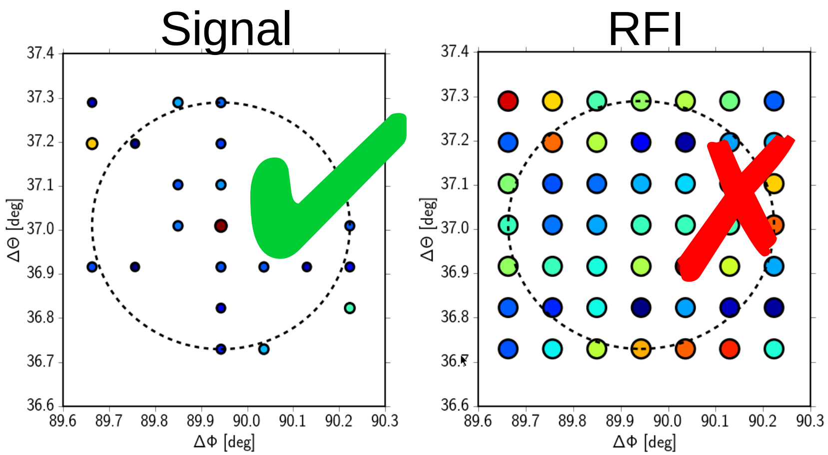
Amplitudes above Threshold

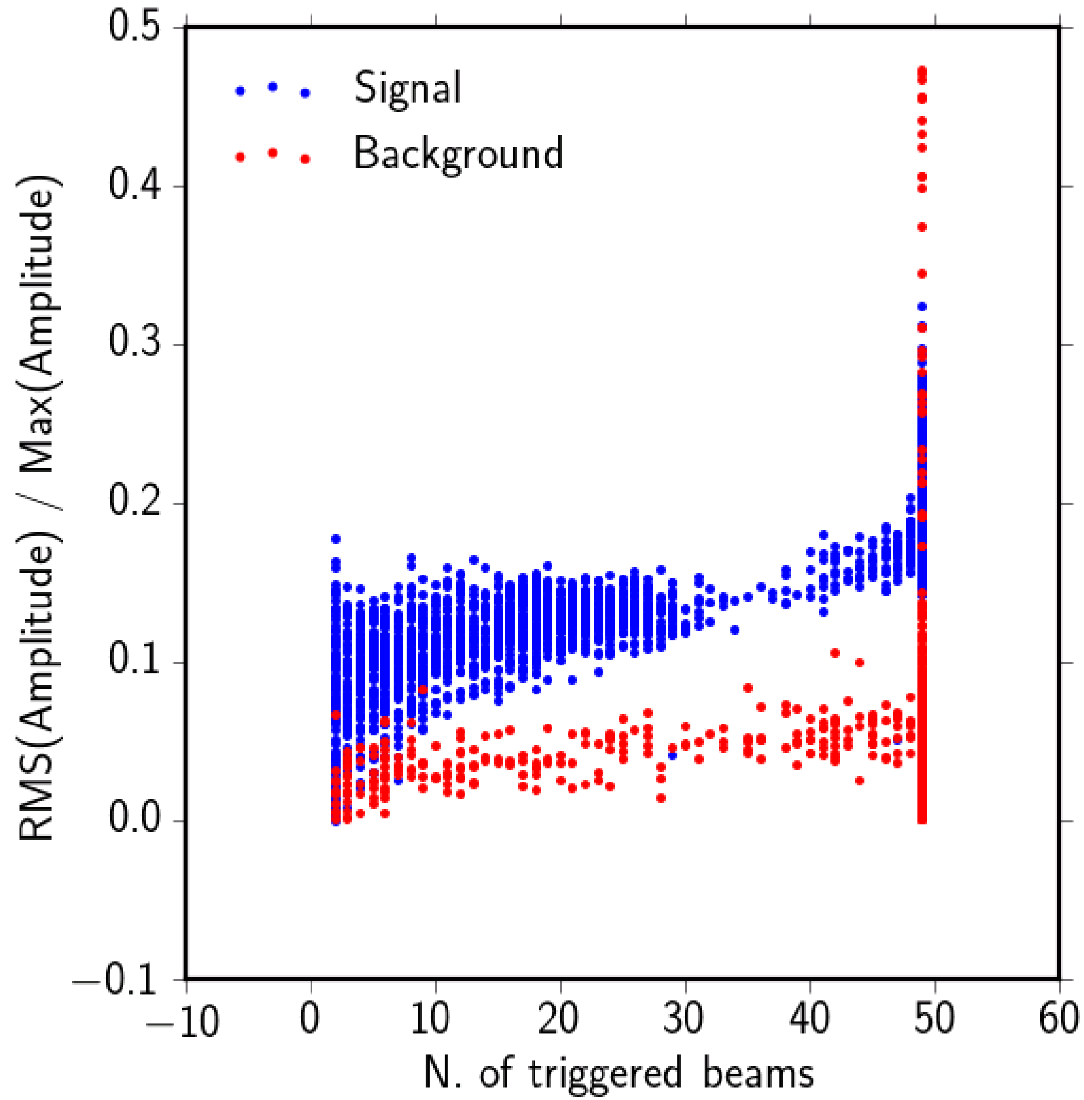






RFI Suppression: ('Anti - Coincidence')





Signal:

Pulse from random* position on Moon
+ 20 +/- 1 TECU DeDispersion
+ TBB background (no RFI)

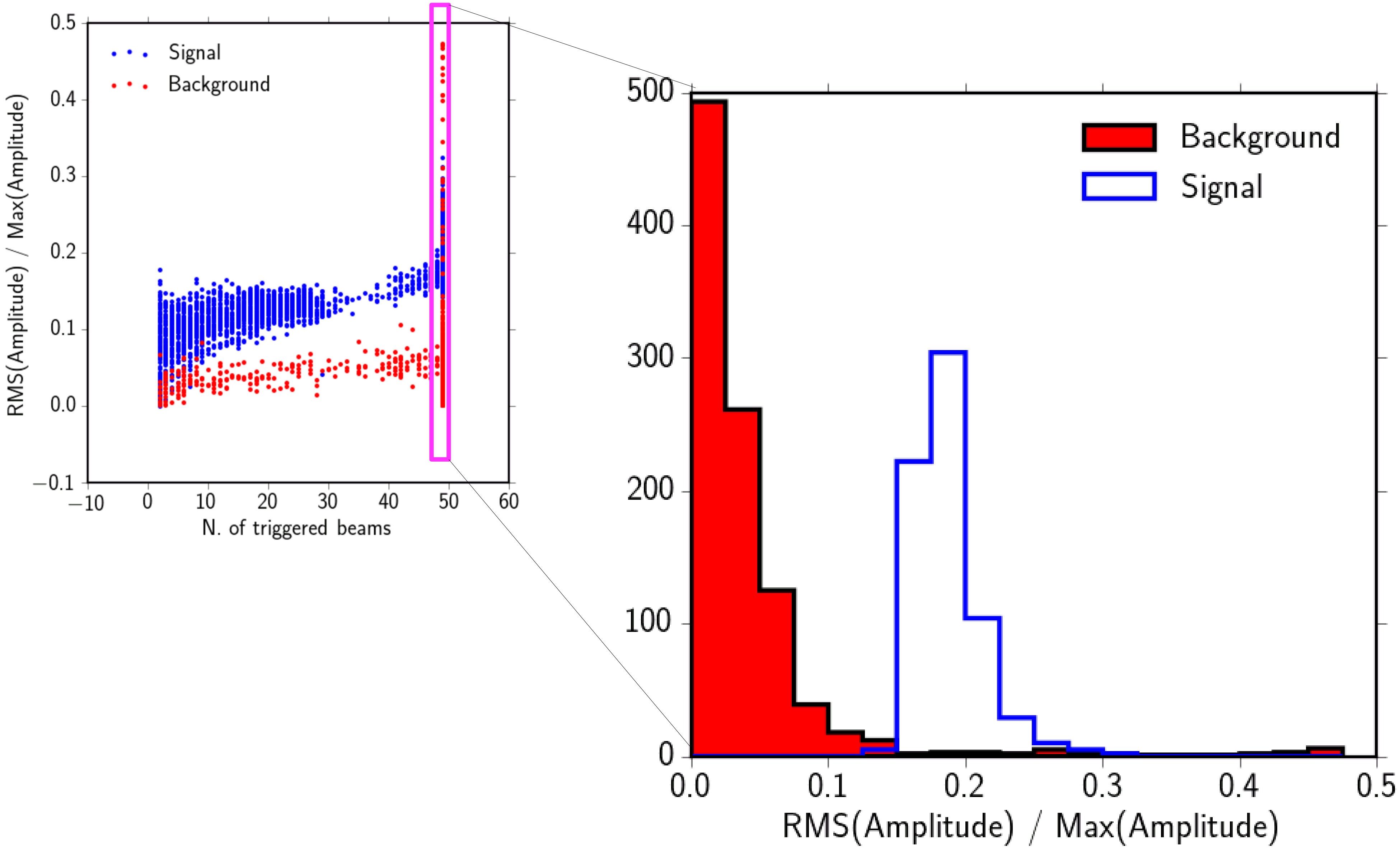
Background:

Strong pulse from horizon
+ DeDispersion 20 TECU
+ TBB background (no RFI)

Strong signals might trigger all beams

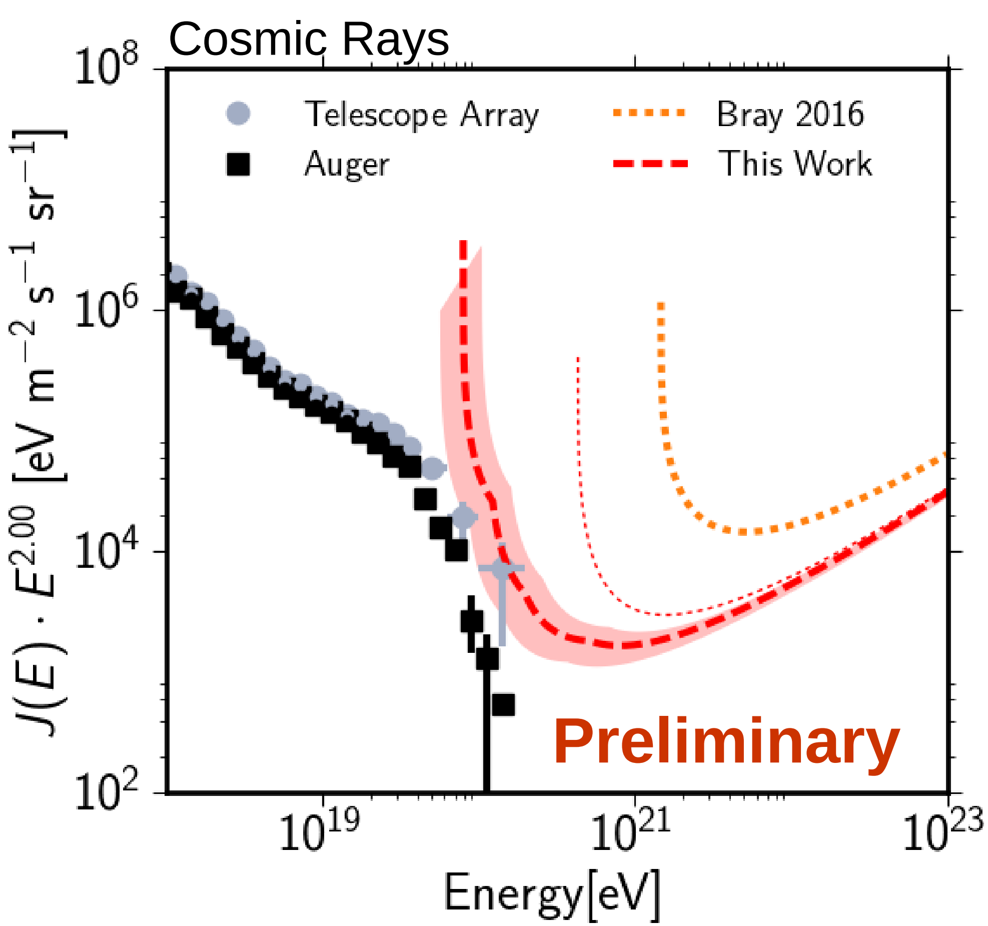
* isotropically in solid angle covered by Moon – pdf of possible impact angles not included!

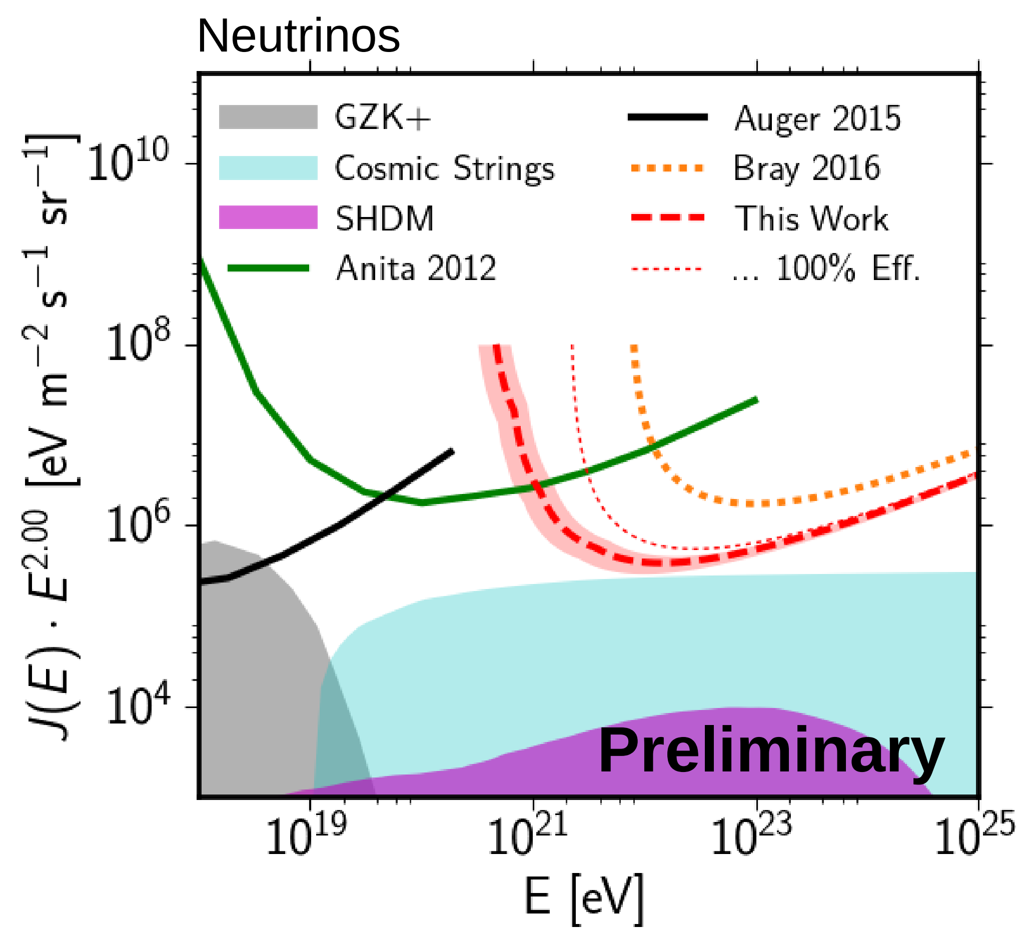
Trigger in Every Beam



Good signal / background separation for strong signals
→ Anti-coincidence does not limit energy range!

Expected Sensitivity (200h)





Difference to previous values (Bray 2016):

- 5 instead of 24 stations
- Increased bandwidth
- Reduced trigger threshold
- Full detector simulation instead of semi analytical parametrization

Caution: Still relies on semi-analytical model for pulse escape from moon

Conclusions

VRIJE UNIVERSITEIT BRUSSEL

- Search Cosmic Particles on ZeV scale via Lunar-Askaryan-Effect with LOFAR (and SKA in future)
  - Full Simulation of Process + Prototype Implementation
    - Analysis + Simulation software ready:

      PPF Inversion, Dedispersion, Beamforming, Filter
    - Preliminary design choices for station selections, etc.
    - Design of trigger + sensitivity calculation (In progress)
  - Coincidence trigger imposes no upper limit on detectable pulses
  - Including regime with low efficiency reduces energy threshold for limits

- Outlook
  - Implementation of Online System in progress
  - First commissioning data (1 min) taken (analysis ongoing)
  - Further commissioning runs + integration of software in LOFAR systems in Summer 2018
  - Proposal for observation runs 2018/2019 (LOFAR cycle 11+)

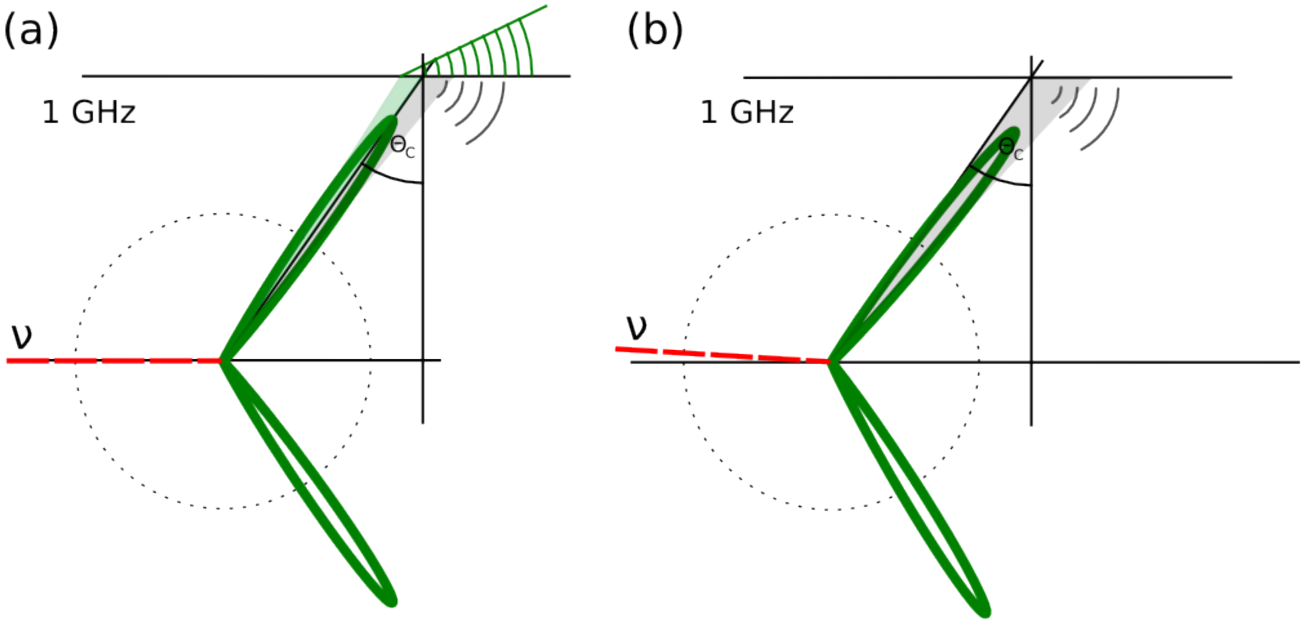
Gefördert durch DFG Deutsche Forschungsgemeinschaft

erc European Research Council

tobias.winchen@vub.be

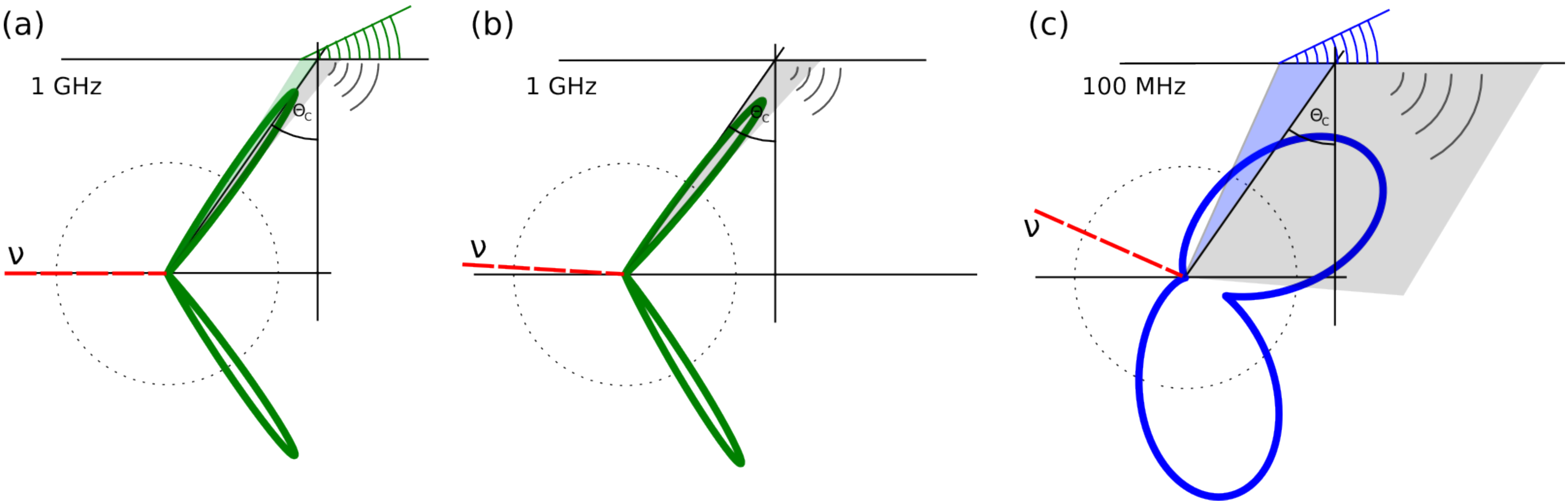
Backup

Pulse Reflected at High Frequencies



- Radiation emitted in Cherenkov cone
- Cherenkov angle == Angle of total reflection
- Upgoing shower required / rely on surface roughness

Pulse Escapes at Low Frequencies



- Cherenkov cone is broader at low frequencies
- Also downgoing showers detectable
- Optimum in 100 - 200 MHz range (Scholten et al. 2006)

Inversion of Polyphase Filter

- Filter to decompose signal into subbands
- FFT signal is smeared out over neighboring frequencies
- Efficient filtering with PPF

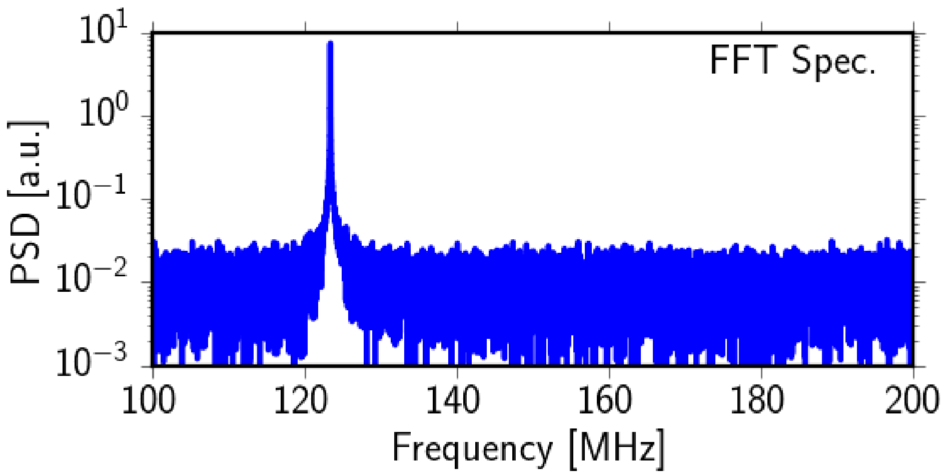
  + avoids frequency smearing

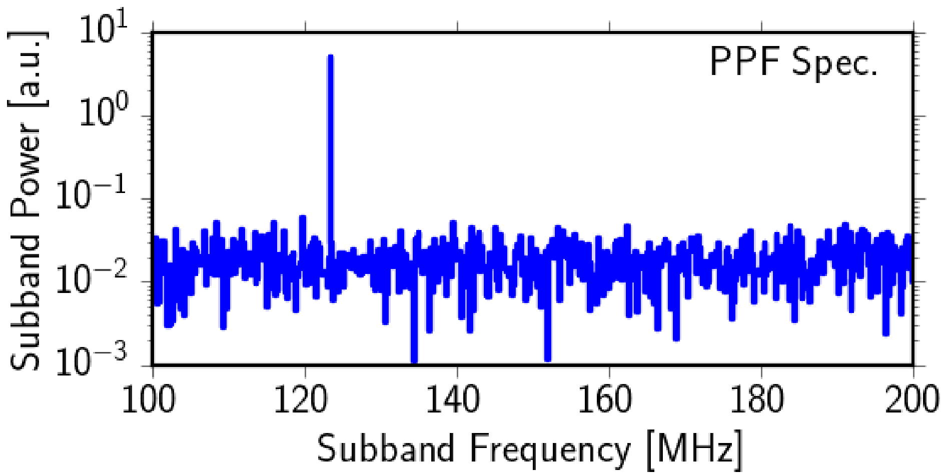
  - Reduces time resolution

  from 5 ns to ~5 us
- Inversion with small error possible,

  but computationally intensive:

  O(1000) GFLOP / s / beam
- As much computing power as possible needed for dedispersion + trigger

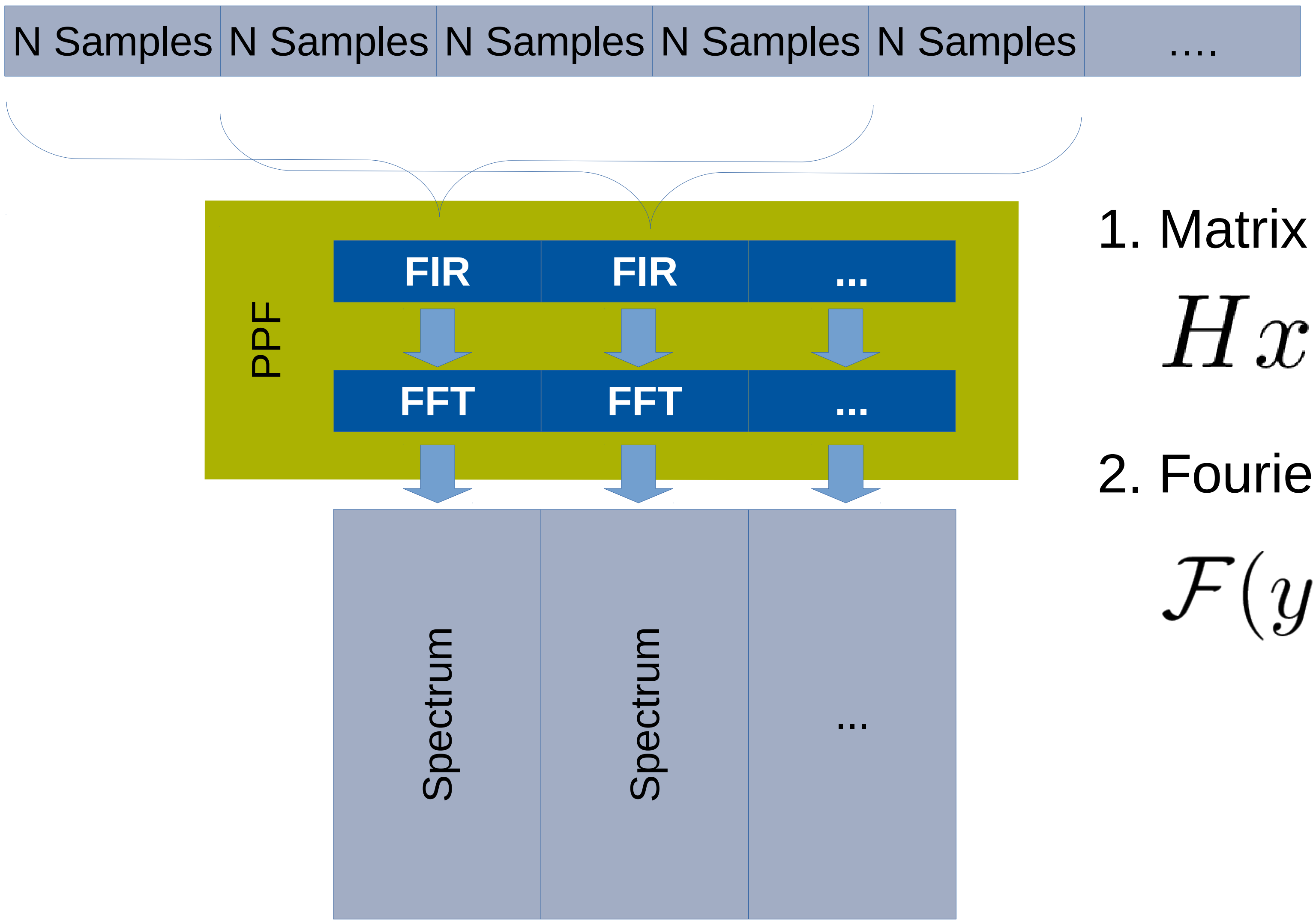




Not available on regular system, requires additional computing power

- Use DRAGNET, CPU/GPU cluster for pulsar searches

Polyphase Filter



1. Matrix product

$$Hx = y$$

2. Fourier transformation

$$\mathcal{F}(y) = \tilde{y}$$

Inverse Polyphase Filter (PPF^{-1})

$$\mathcal{F}^{-1}(\tilde{y}) = y$$

- Direct inversion of FIR filter

$$H^{-1} y = \hat{x}$$

Inverse does not exists as H is not square

- Approximate inverse

$$Gy \approx \hat{x} \qquad GH \approx I$$

Supposed to be numerically unstable / produces artifacts (spikes)

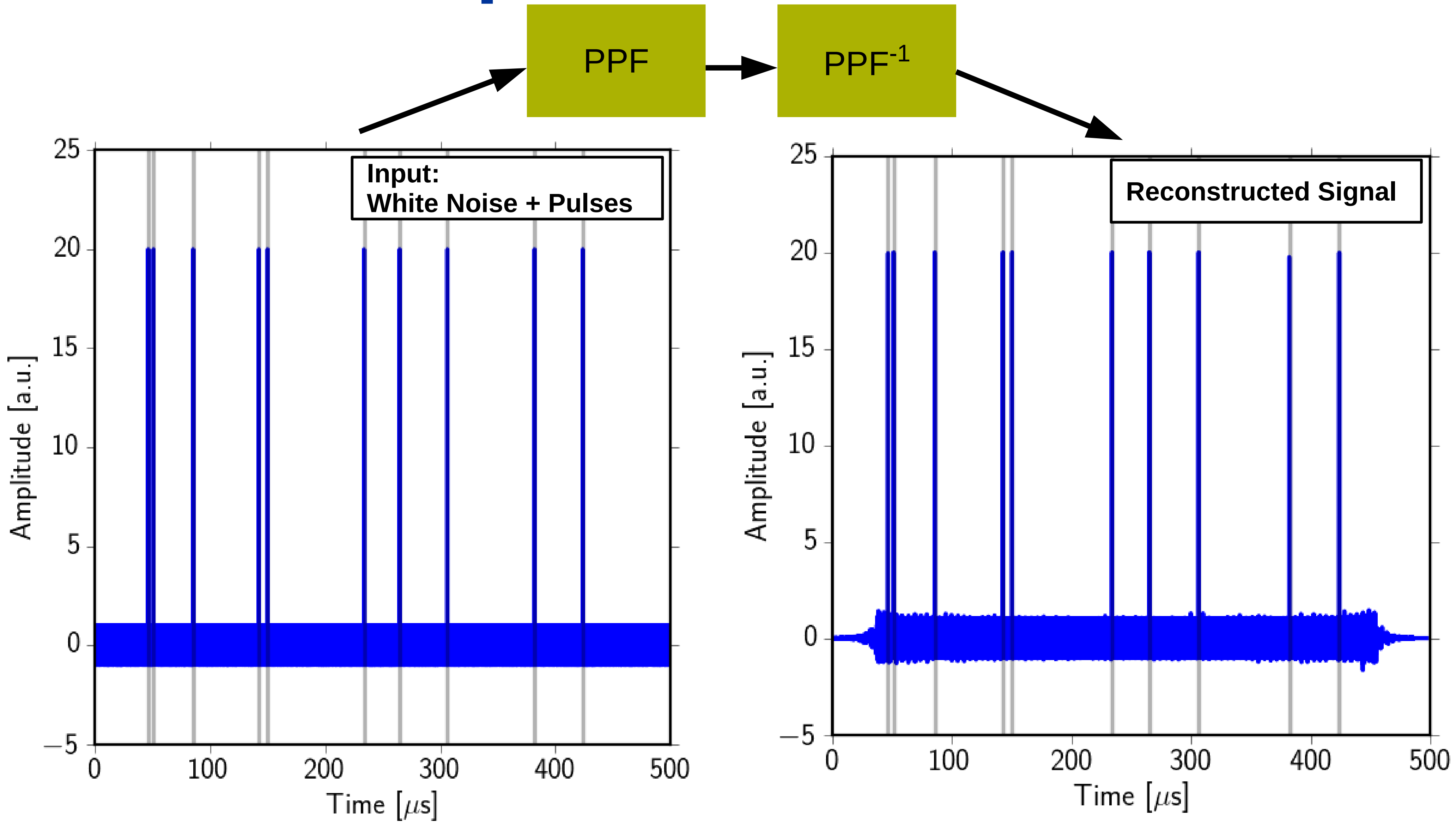
- Robust approach: Solve linear system

$$H\hat{x} = y$$

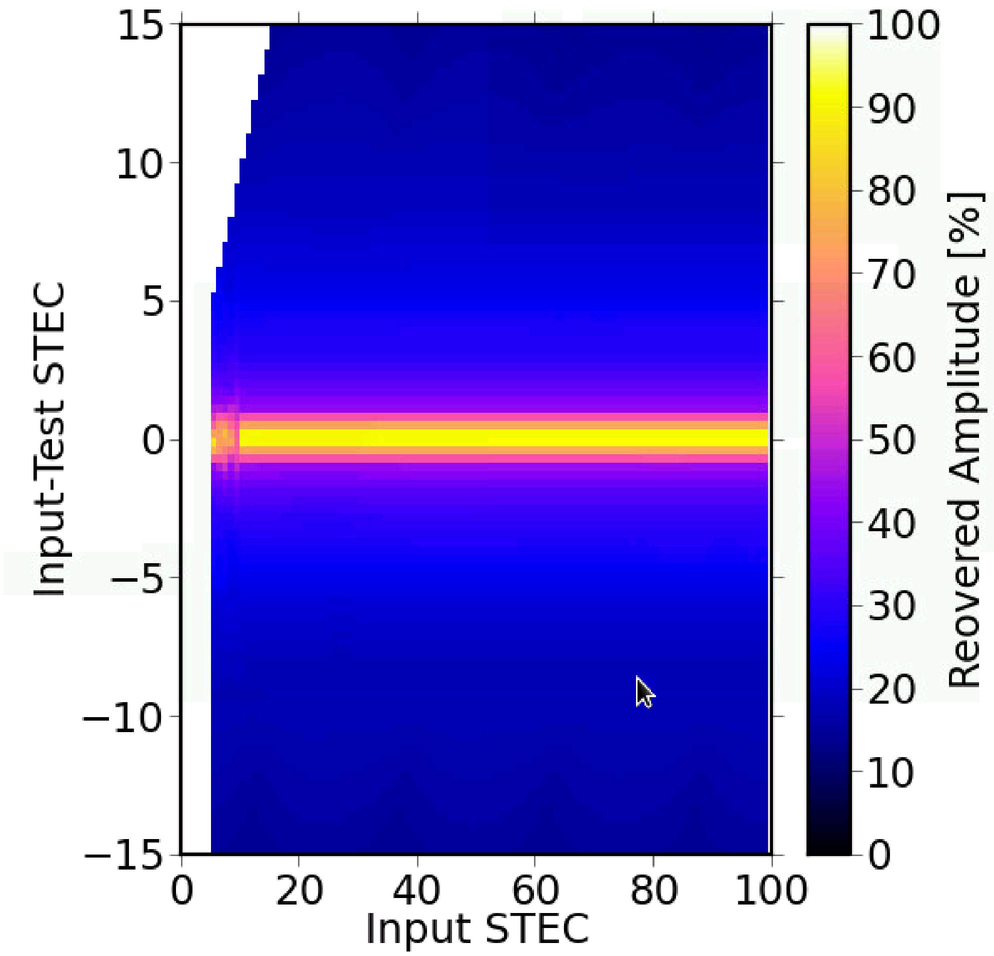
using iterative least squares (LSMR)

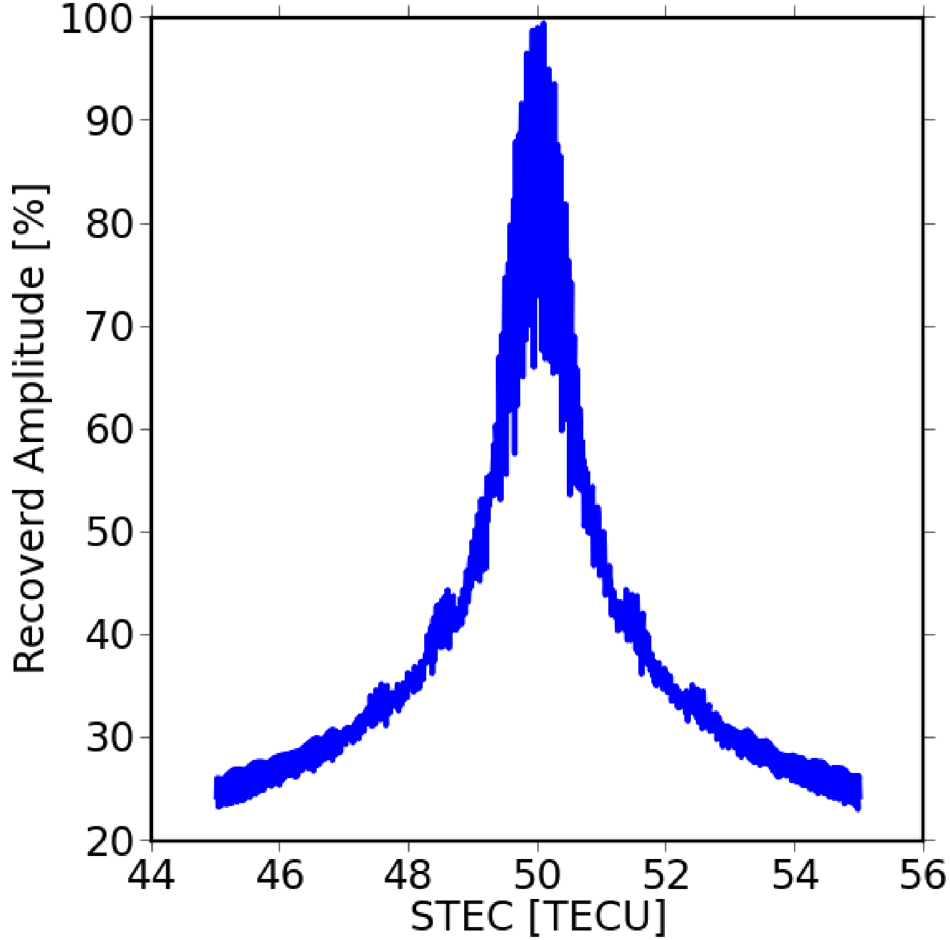
$$\min_{\hat{x}} \|H\hat{x} - y\|$$

PPF^{-1} Example



Dedispersion





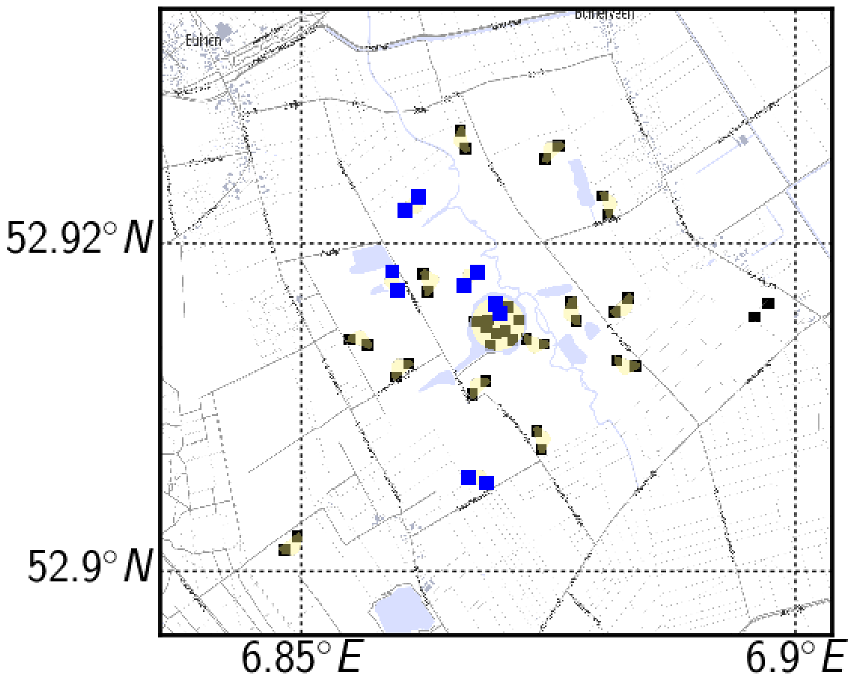
Recovery of 99% of amplitude possible
PPF results in 30% fluctuations with small TEC values → need to scan multiple TEC values

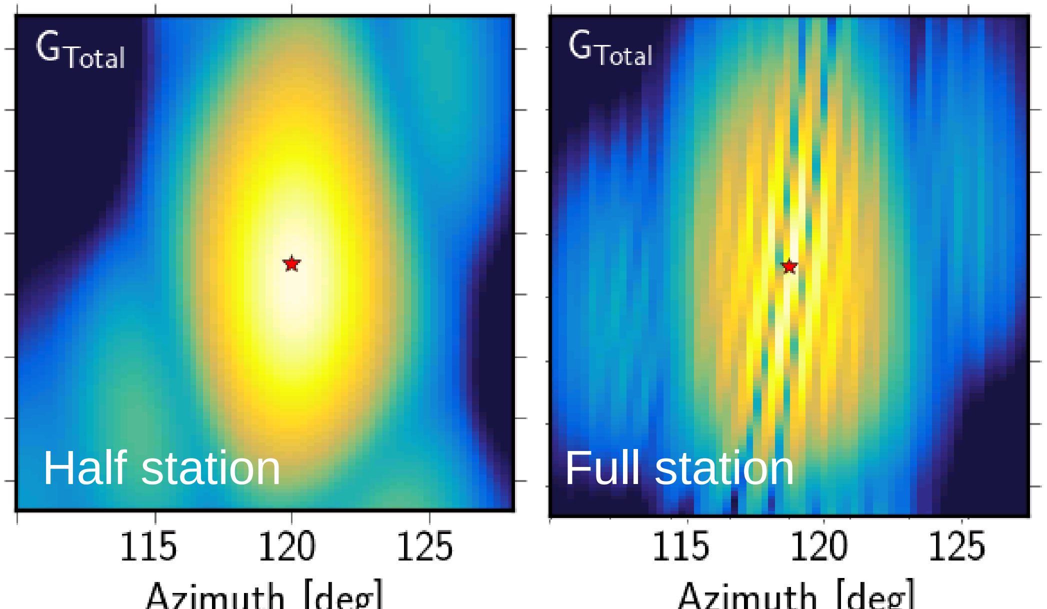
Preliminary Station Selection

- Available bandwidth to DRAGNET limited to

  ~ 5 stations

- Choose FULL stations as grating lobes have only weak influence on analysis beams

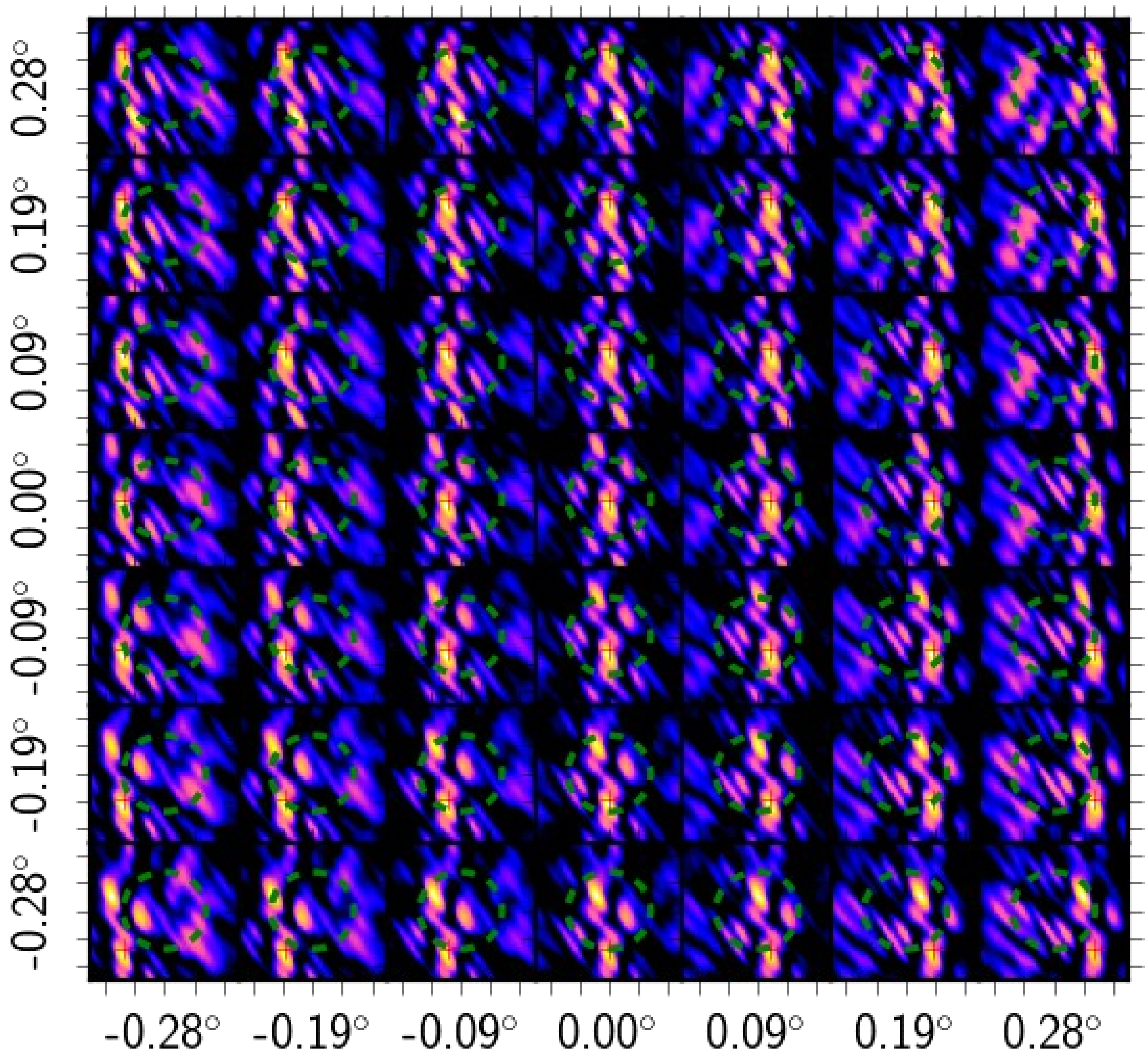




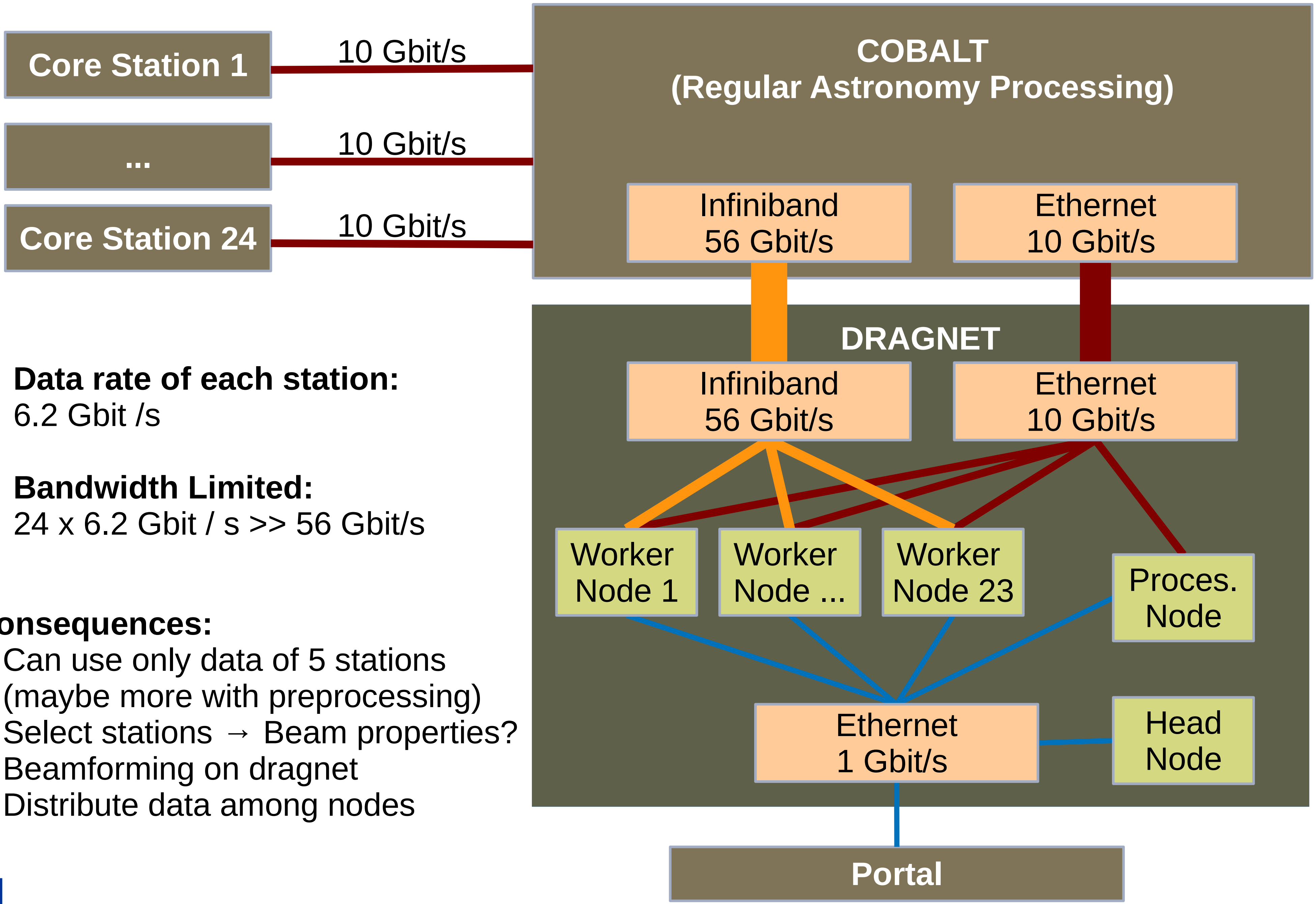
Preliminary set:

CS003, CS013, CS030, CS031, CS301

Analysis Beams



LOFAR Network

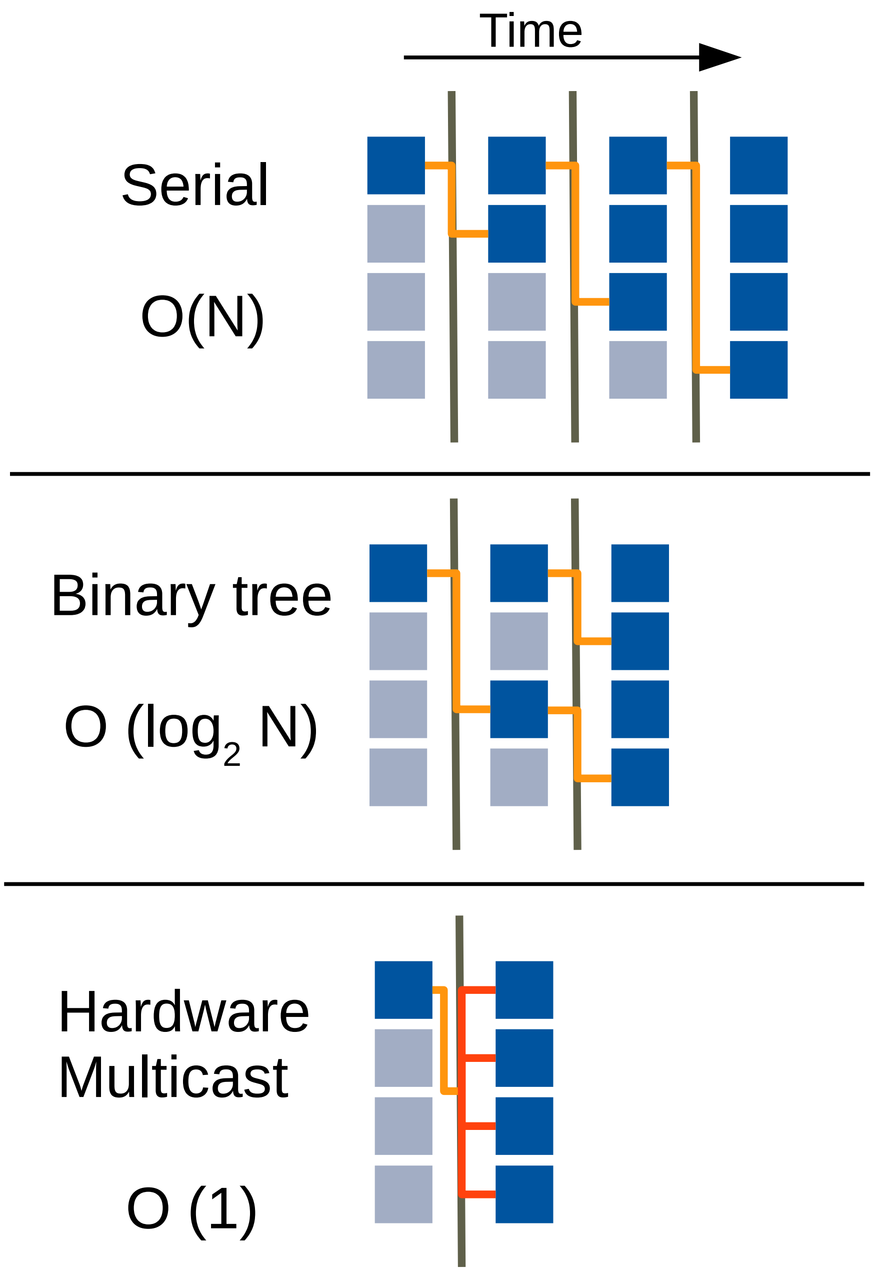


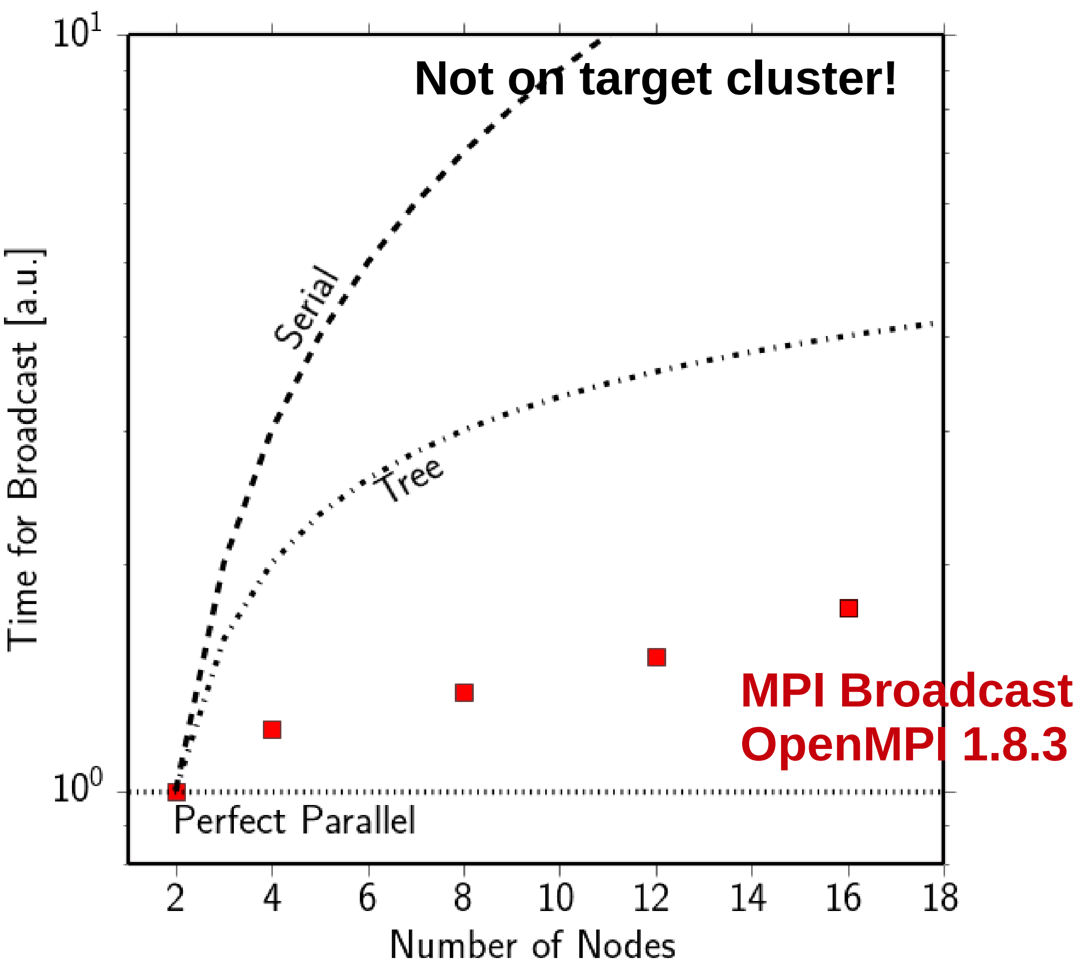
Data rate of each station:
6.2 Gbit /s

Bandwidth Limited:
24 x 6.2 Gbit / s >> 56 Gbit/s

Consequences:
- Can use only data of 5 stations (maybe more with preprocessing)
- Select stations → Beam properties?
- Beamforming on dragnet
- Distribute data among nodes

Online System: Data Broadcast

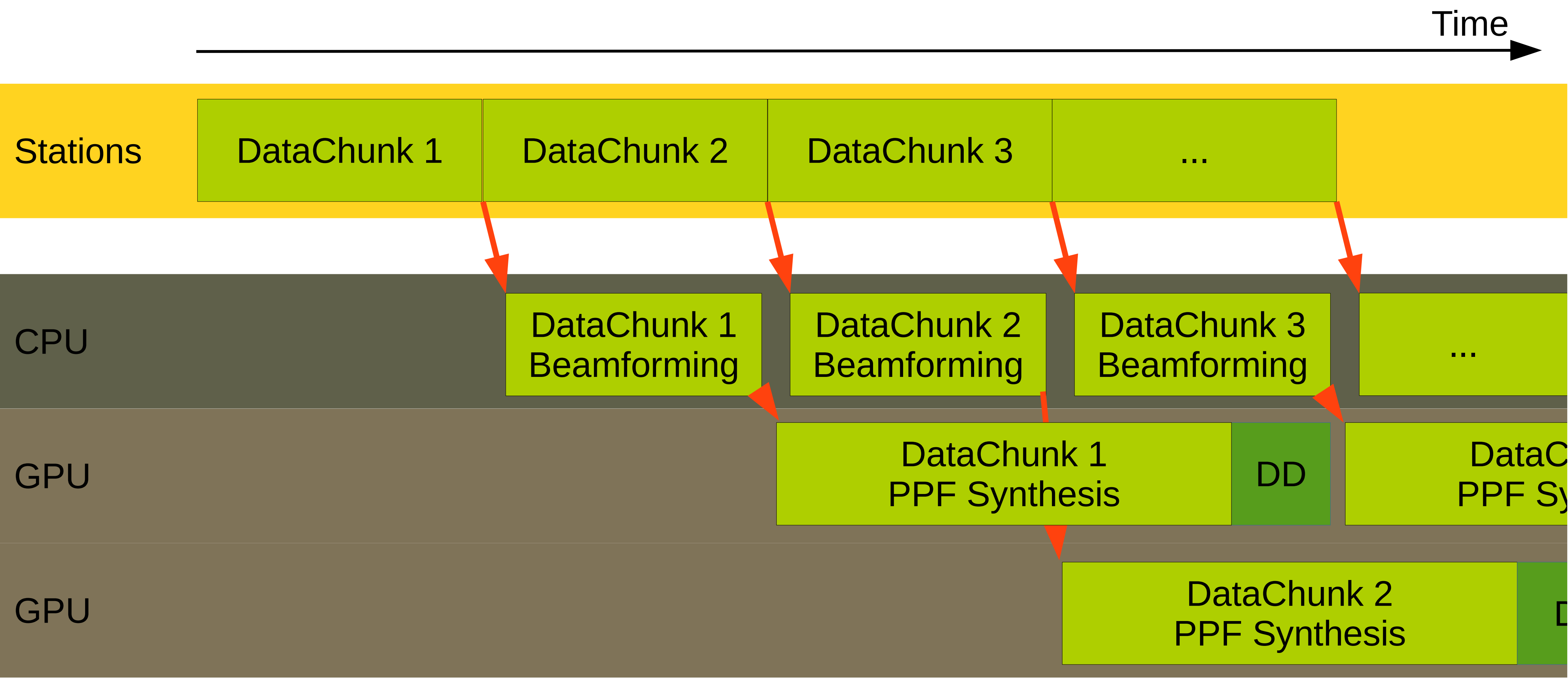




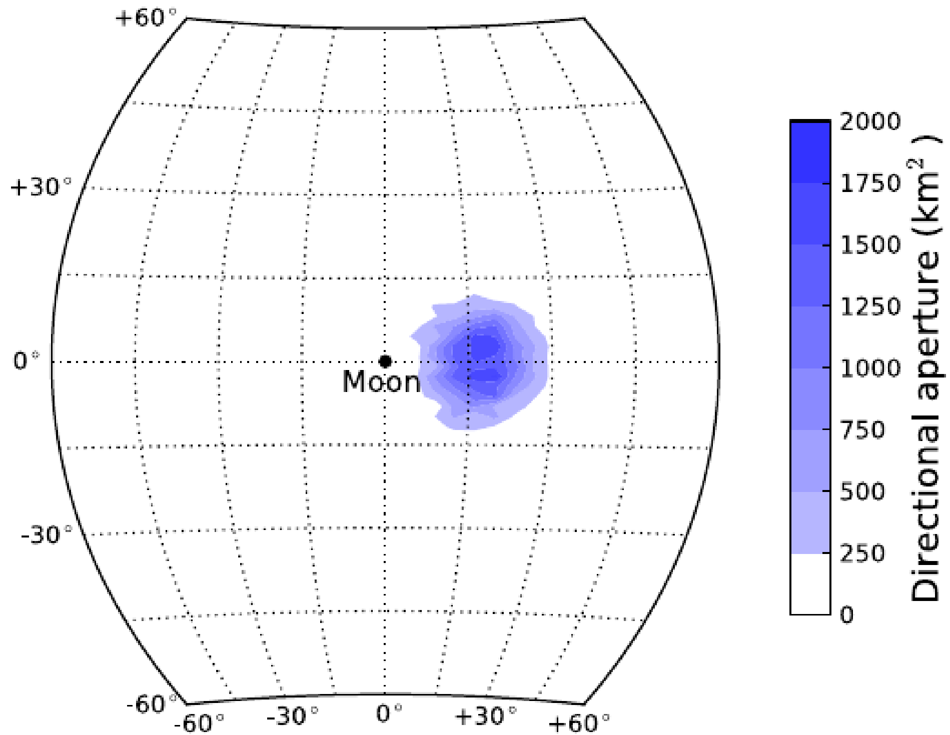
Prototype for online system in progress

Performance Prototype Pipeline

- Beamforming : CPU
- PPF Synthesis : GPU (160% Realtime)
- Dedispersion : GPU

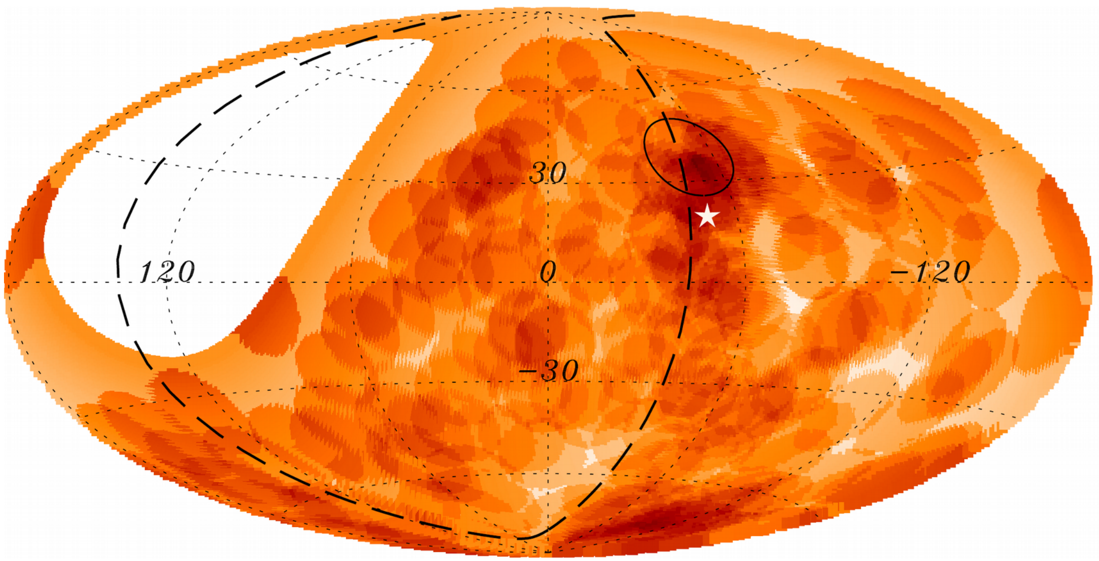


Angular Resolution of Lunar Mode



James, 2016

Cosmic Ray Excess at 15^{O} scales



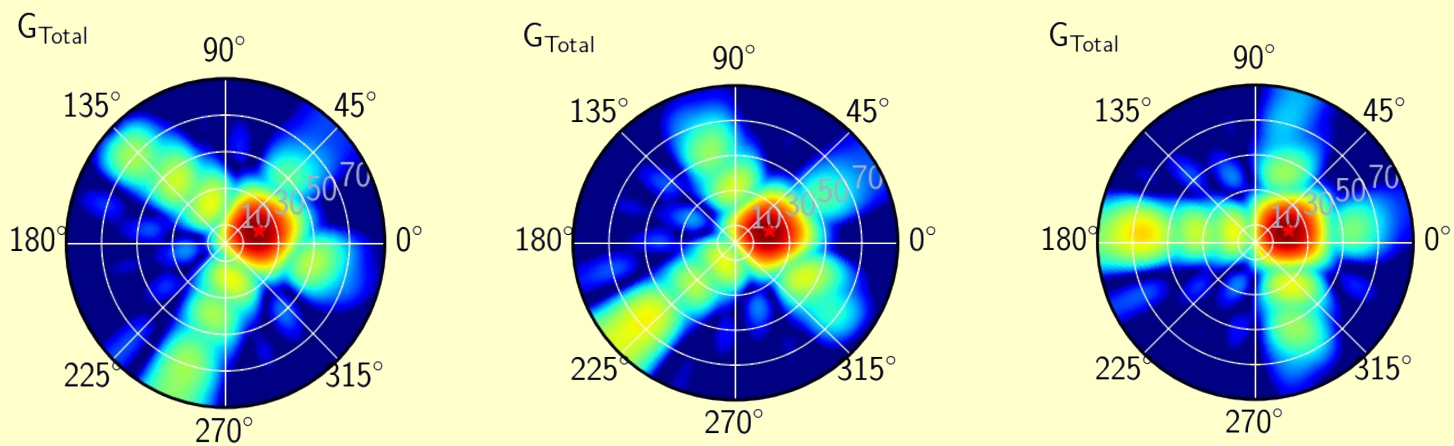
Aab et al, ApJ 804 (2015), 15

- Limit observations to rim
- Possible Incident angles yield ~5^{O} resolution
- Explicit reconstruction should do better

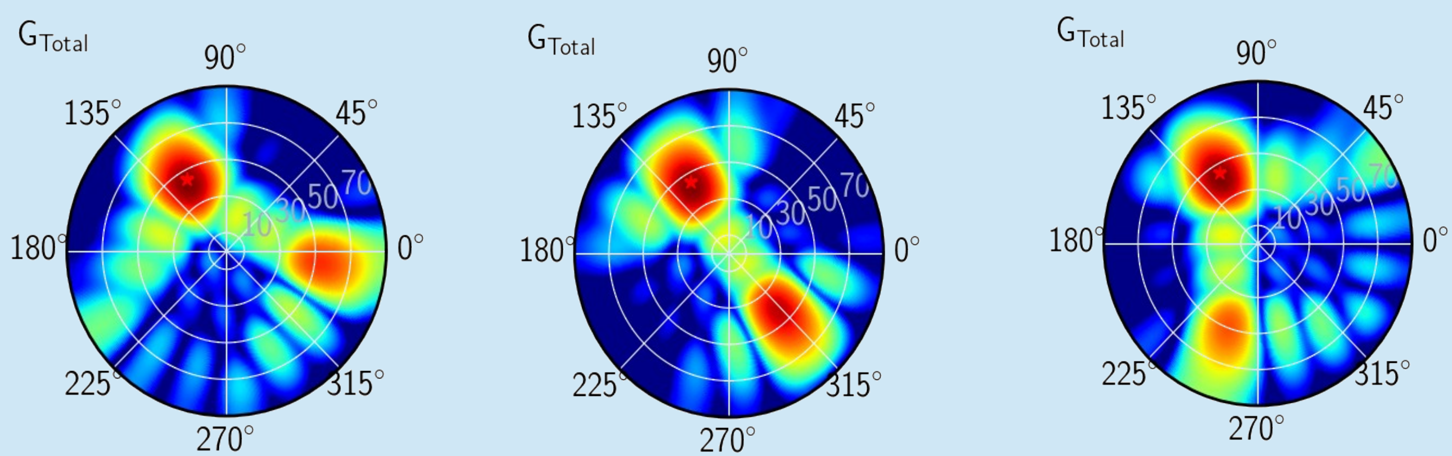
Challenge HBA Calibration

- Analog Beamforming of HBA Antennas to Tile
  - → Gain pattern (of tile) varies between events (beam direction) and stations (orientation of tiles)

CS003 CS013 CS501

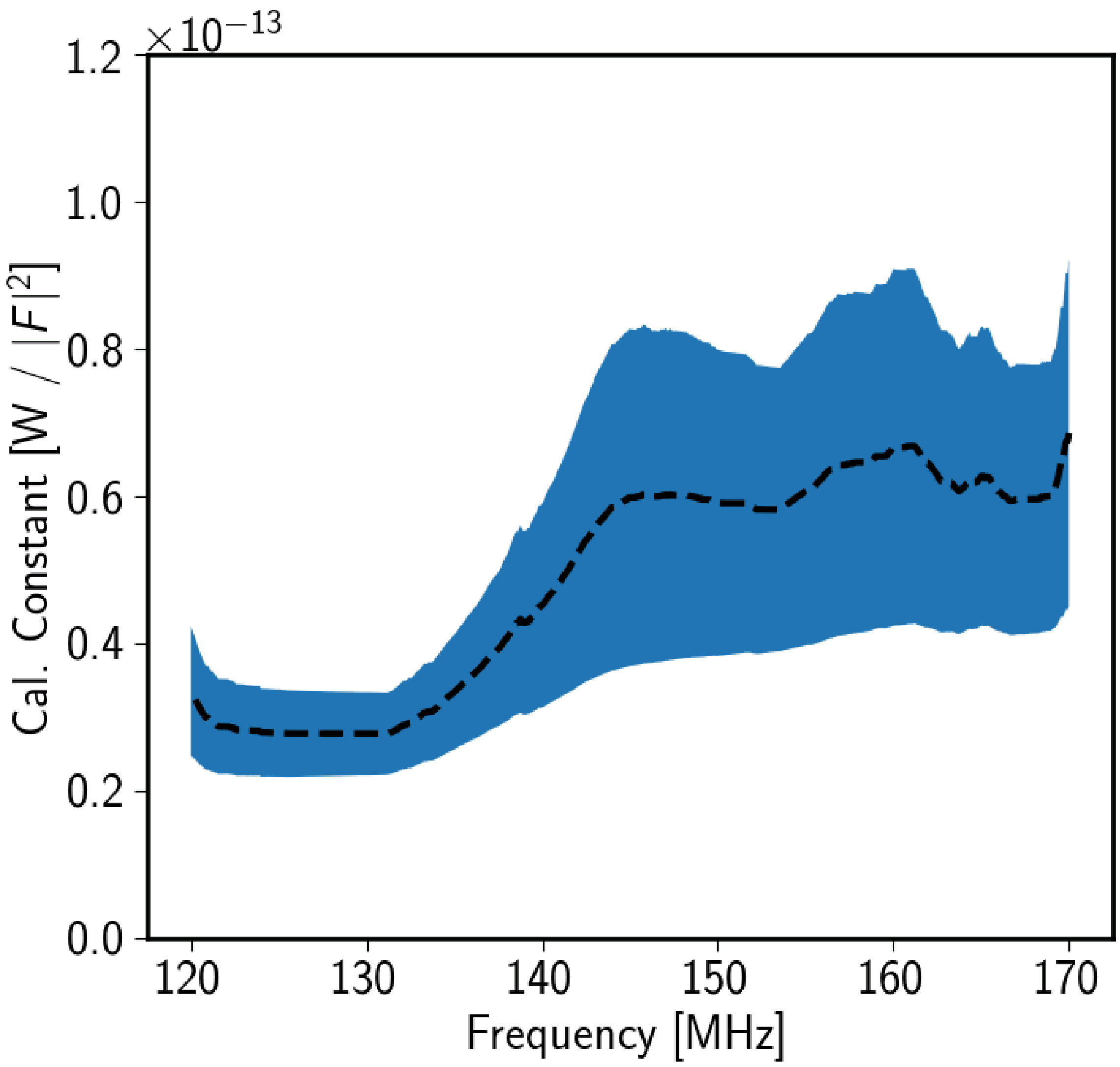


Beam direction 20°, 20°



Beam direction 45°, 120°

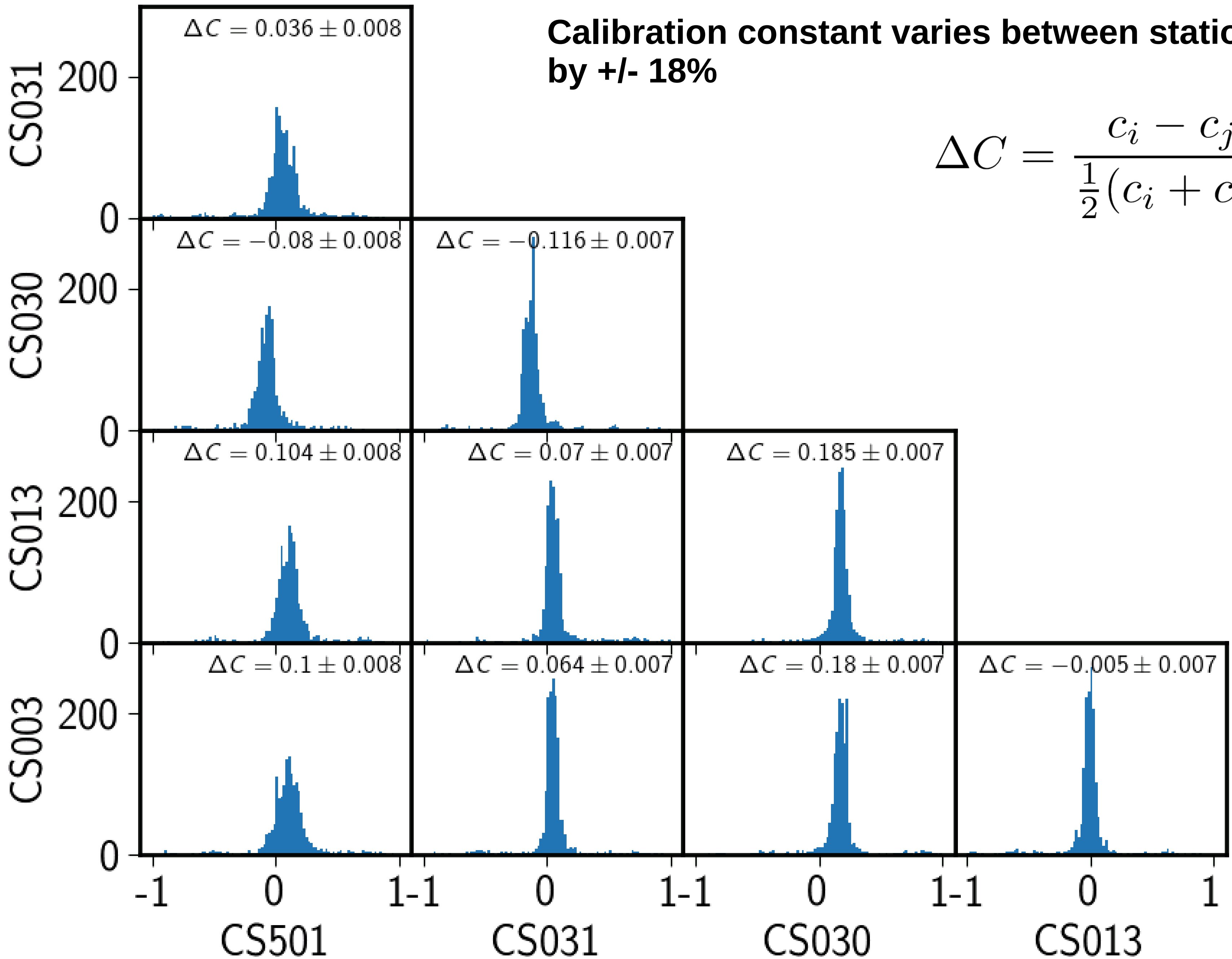
Calibration



→ Frequency dependency of same order of uncertainty
→ Use average value independent on frequency to simplify procedure

Next step: Investigate directional dependency using constant value for electronic noise

Differences between Stations

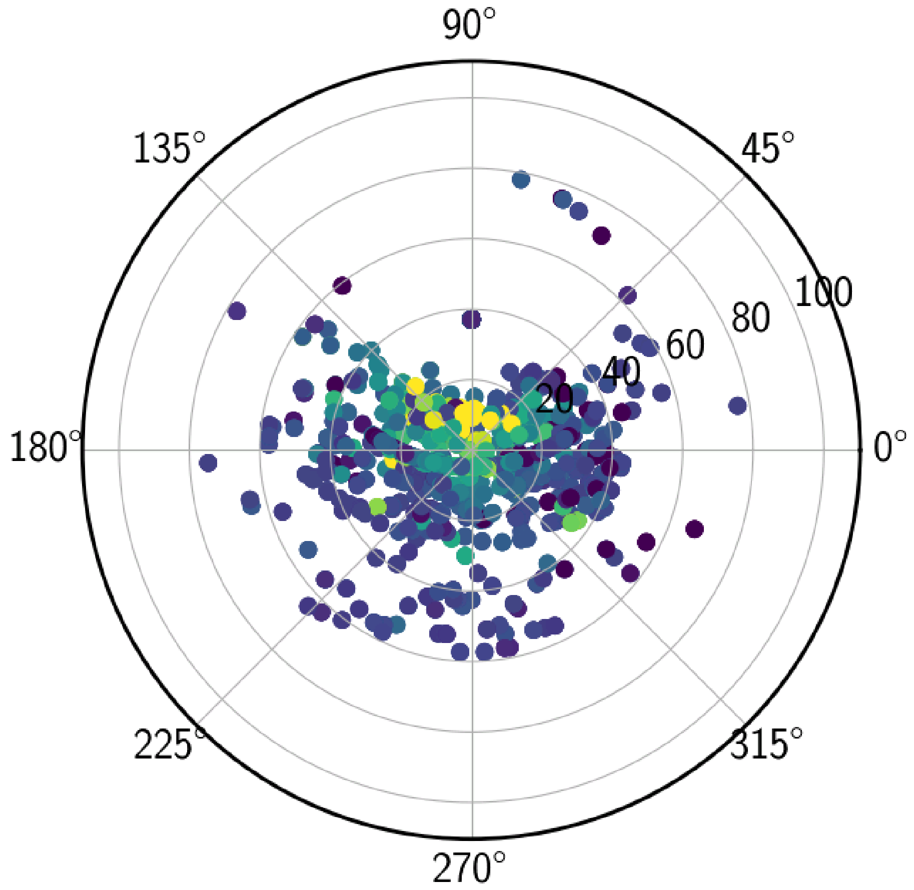


Calibration constant varies between stations by +/- 18%

$$\Delta C = \frac{c_i - c_j}{\frac{1}{2}(c_i + c_j)}$$

Directional Consistency

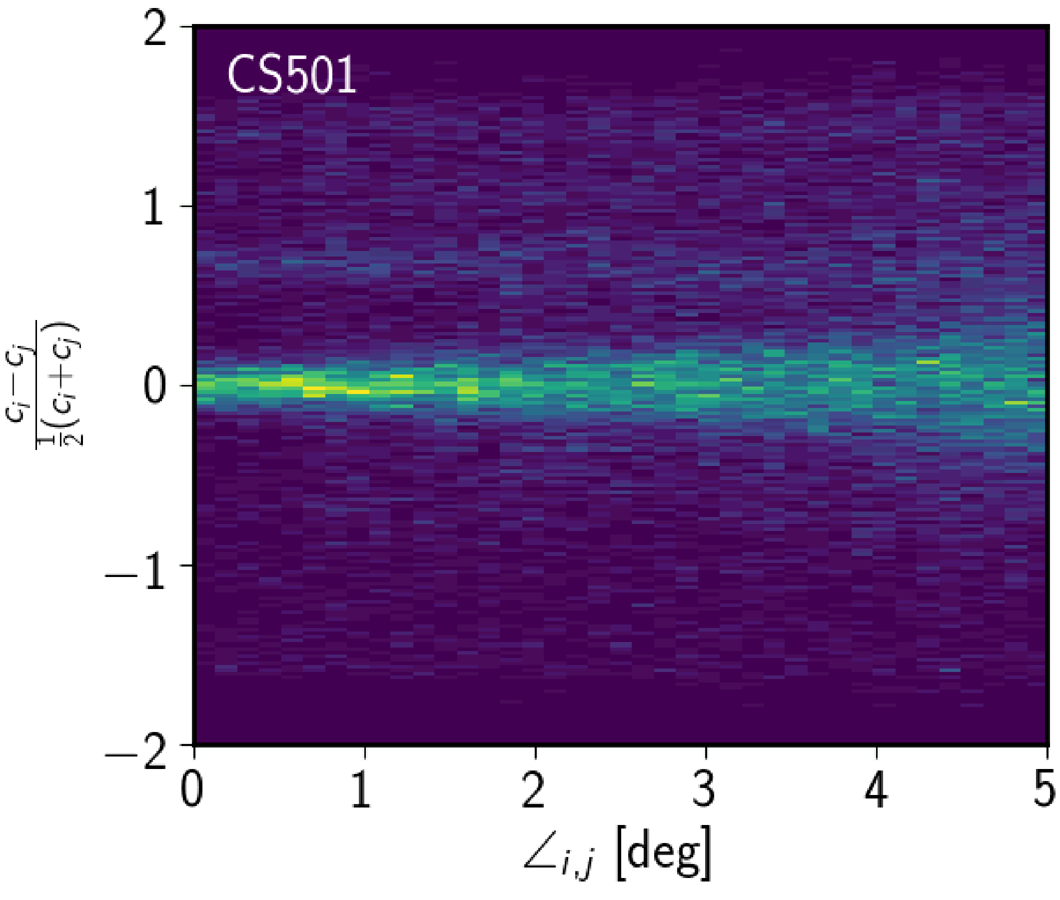
Color = Calibration value for event in direction

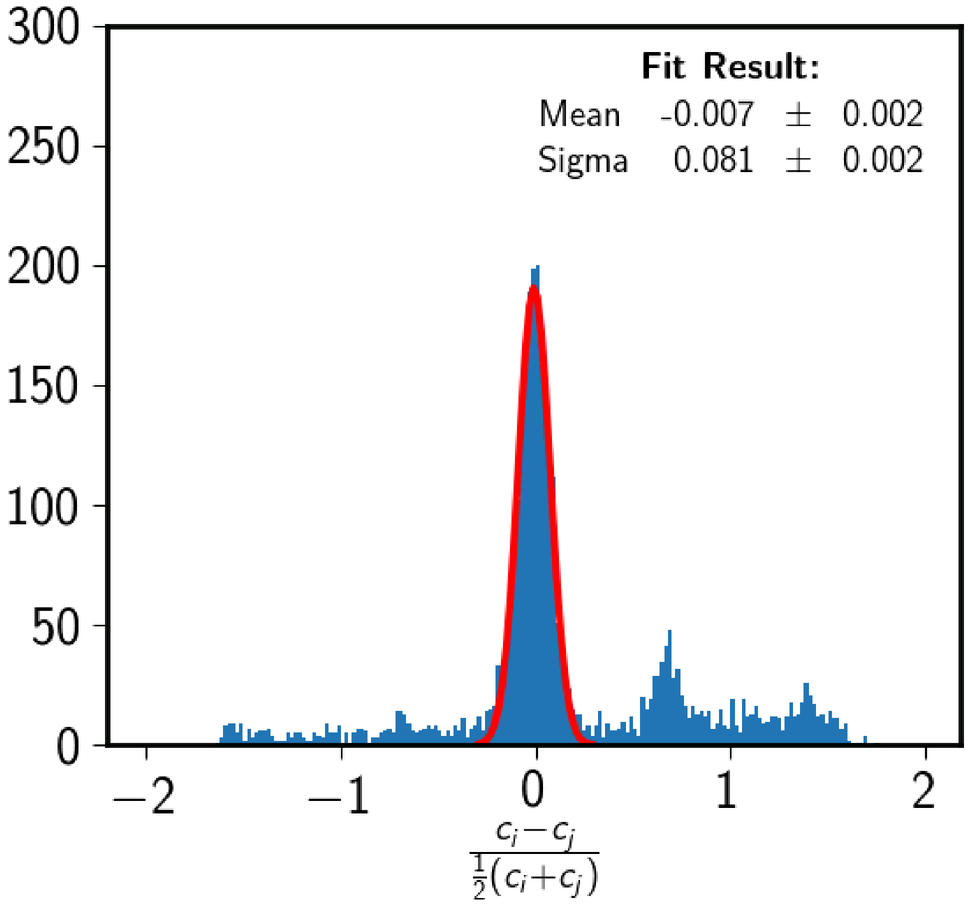


There is some directional structure in calibration constants
→ Look at variation between nearby beam directions

Directional Consistency

- Exclude values from celestial pole
- Histogram difference between calibration constant of events as function of angular distance





Some events with large discrepancy,
Most close-by calibration constants within +/- 8% of each other

Conclusion: HBA calibration

- HBA Calibration on Event-Event basis
- Uncertainty of calibration +/- 36 % (in Power)
  - → +/- 30% from frequency dependency
  - → +/- 18% from difference between stations
  - → +/- 10% based on variation of similar directions