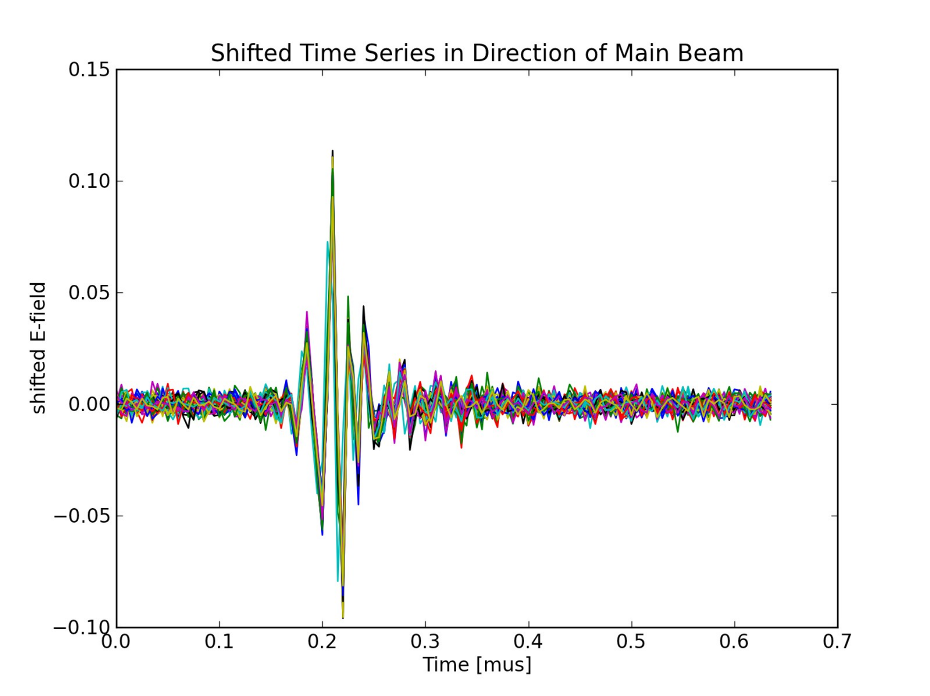
Detection of Air Showers with LOFAR (since June 6 2011)



Sander ter Veen, Radboud University Nijmegen

Martin van den Akker, Lars Bähren, Arthur Corstanje, Heino Falcke, Wilfred Frieswijk, Andreas Horneffer, Jörg Hörandel, Clancy James, John Kelley, Rebecca McFadden, Maaijke Mevius, Anna Nelles, Pim Schellart, Olaf Scholten, Kalpana Singh, Satyendra Thoudam

Why study Cosmic Rays?

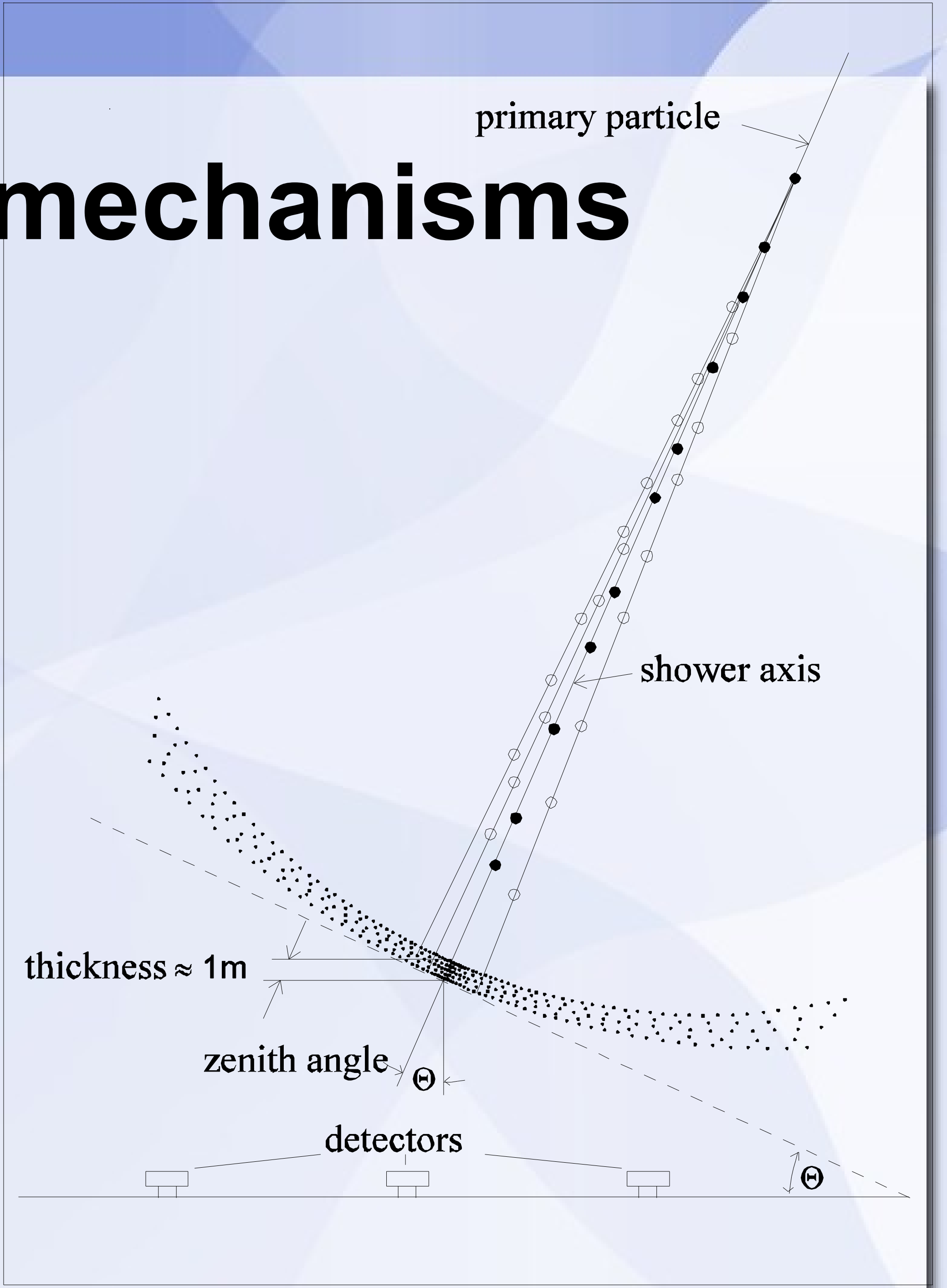
- Most energetic particles
- Origin: AGN ?
- To determine
  - Chemical composition
  - Direction
  - Energy
- Radio emission
  - complementary probe
  - 100% duty cycle

Radiation mechanisms

Two main coherent emission mechanisms:

Charge excess (Askaryan, NuMoon in air)

Geomagnetic effect



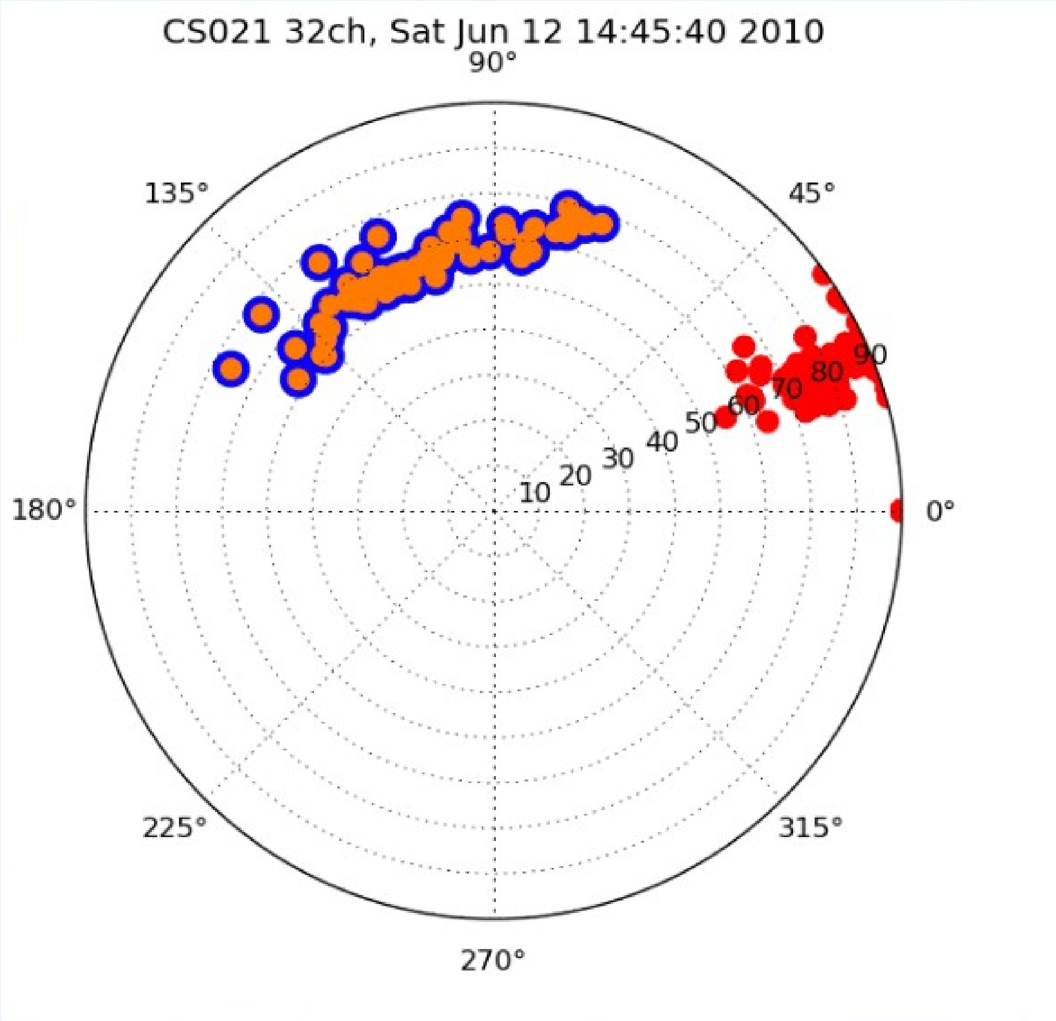
Why CR + LOFAR

- Dense instrumentation (polarization!)
- Probe electromagnetic field at many points
- Pin down emission processes
- Derive the properties of air showers through radio emission
- Measure spectrum and composition of CR from 10^{17} -10^{19} eV (transition Galactic to extragalactic origin)

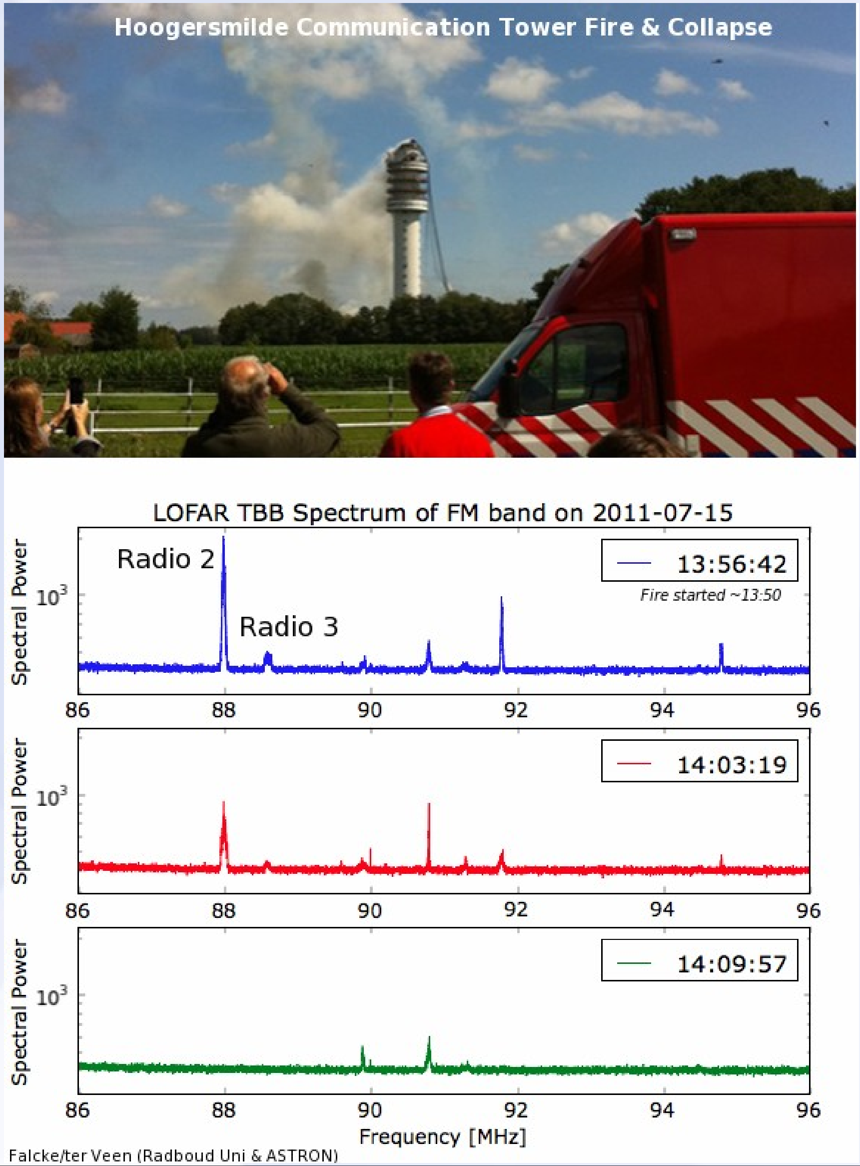
Cosmic Ray Detection

- Two methods:
  - Radio self-trigger
    - Any LOFAR station (large area)
    - But also RFI triggers
  - LORA triggered
    - No false triggers
    - Small area (only CRs near Superterp)
    - Train radio-only trigger
- Obtain 1-5 ms of Transient Buffer Board data

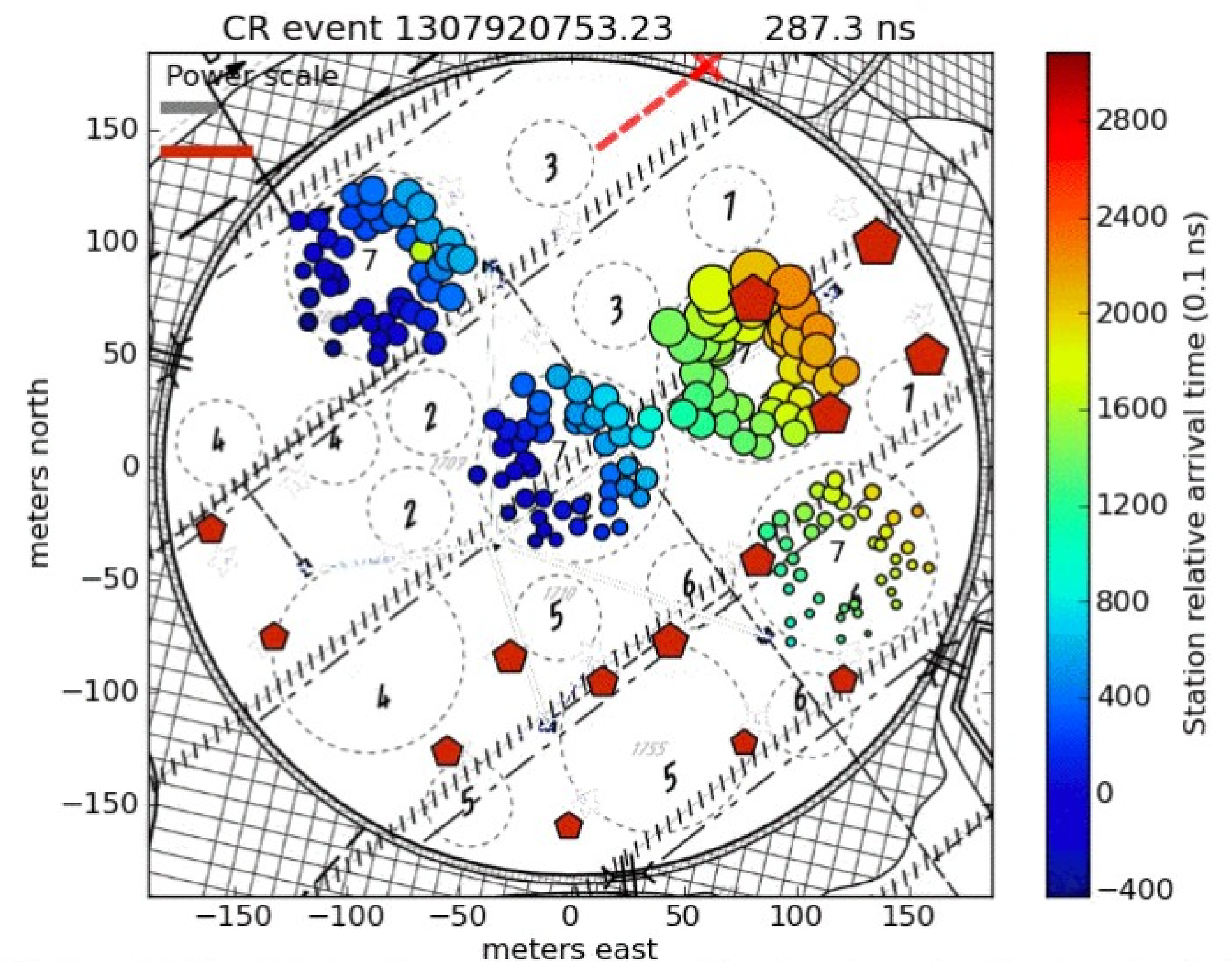
Royal Festive Intermezzo (RFI)



Effective RFI excision

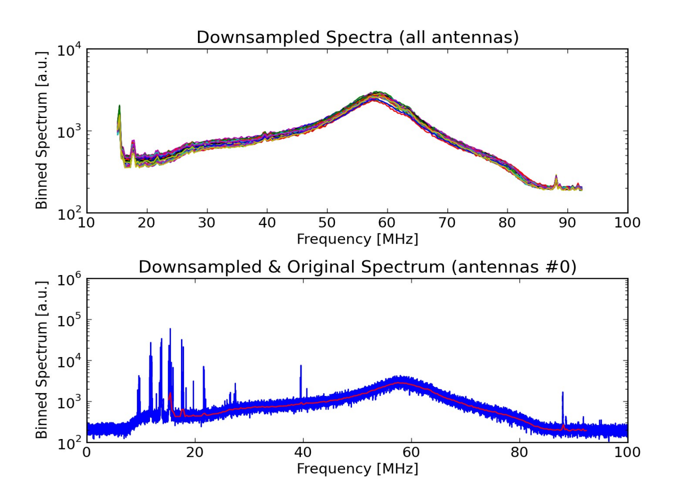


Cosmic Ray Foot(finger) Print

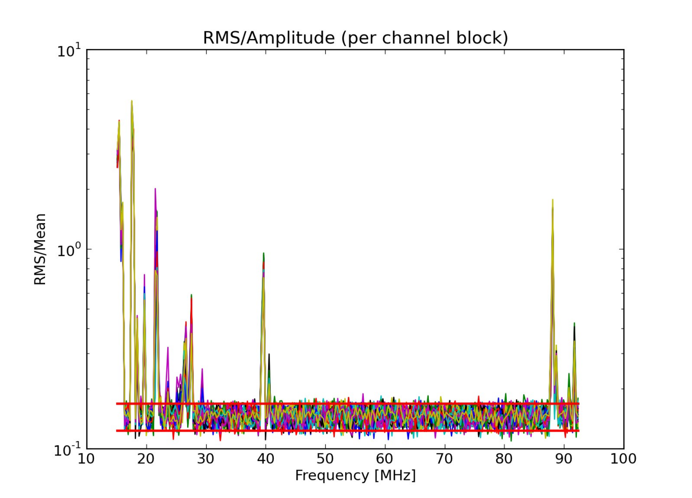


Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

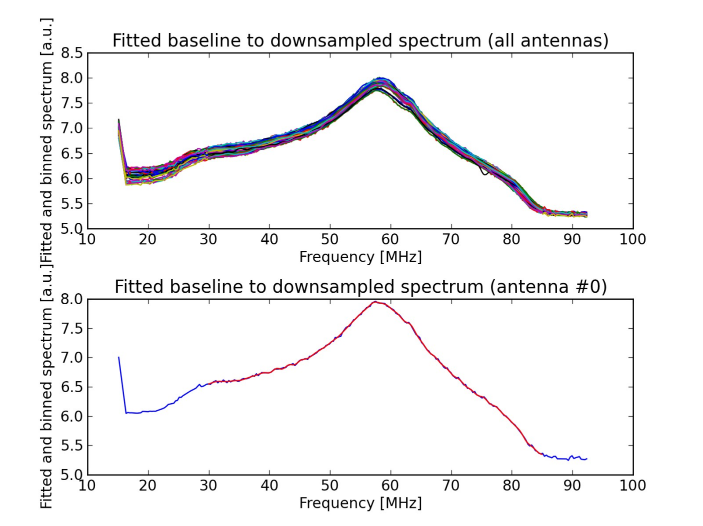
Analysis pipeline



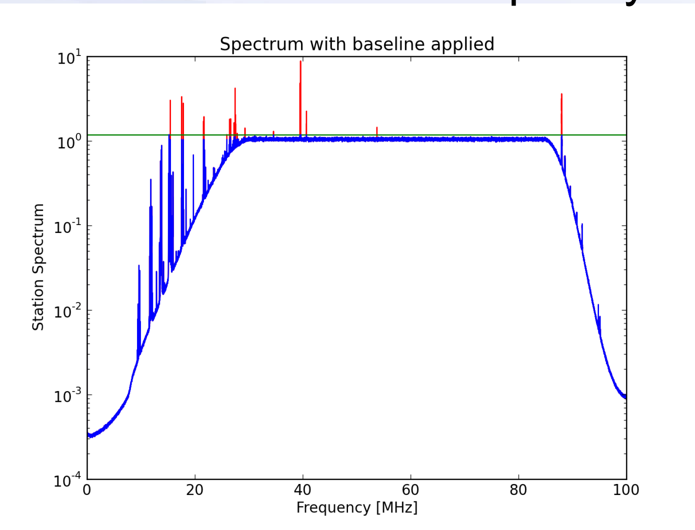
Take the average spectrum



RMS value at each frequency

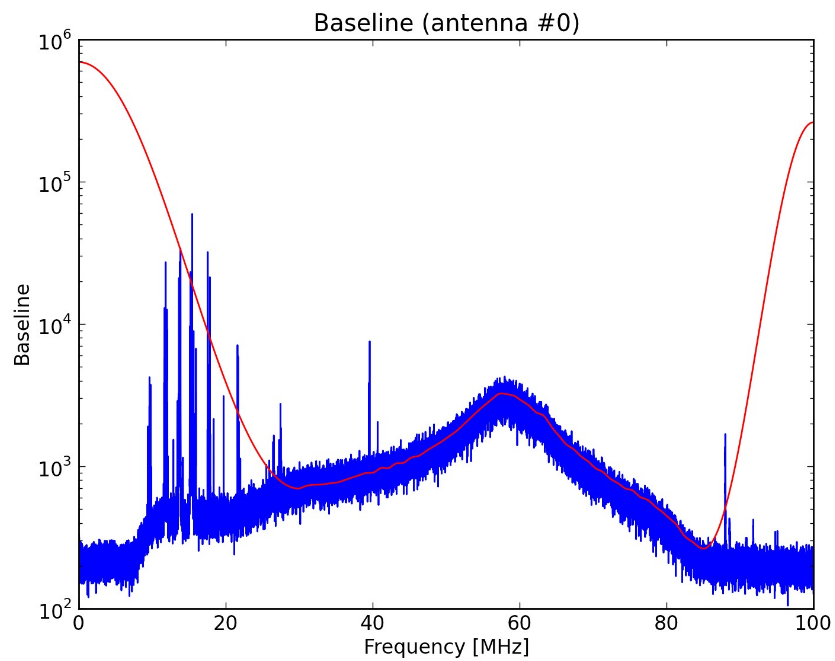


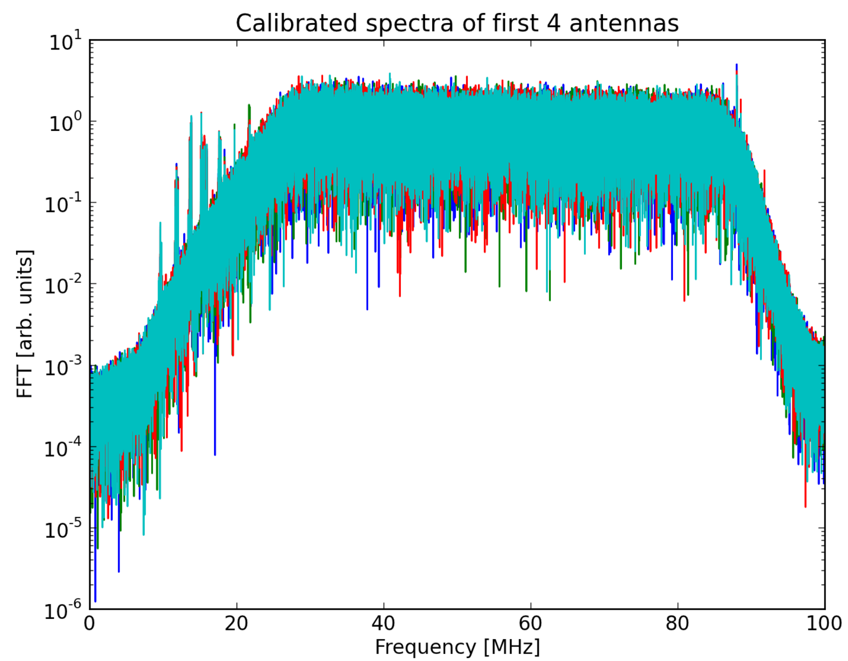
Calculate the baseline



Apply the baseline to identify RFI

Calibration

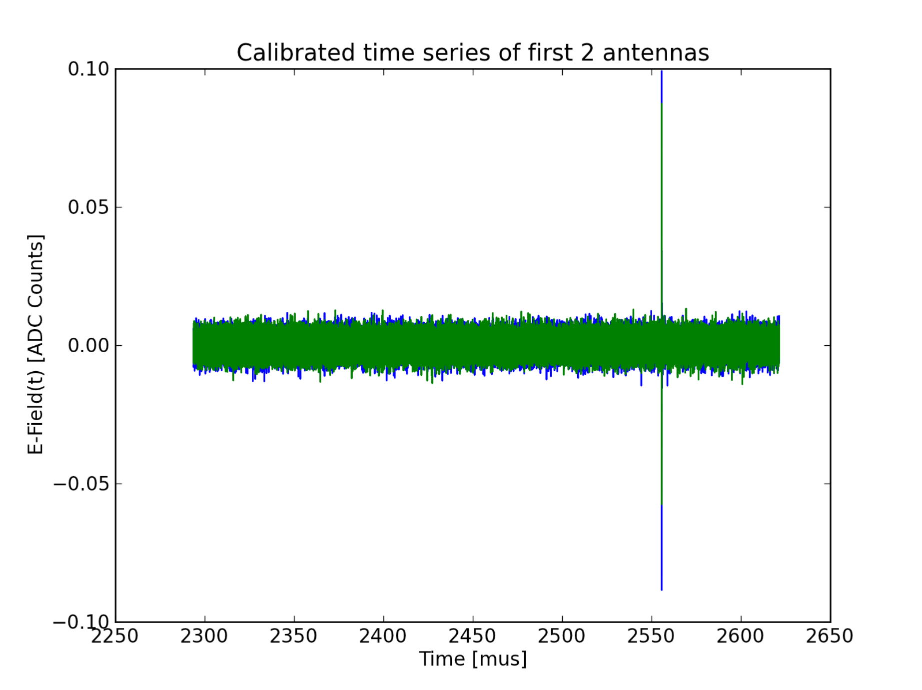




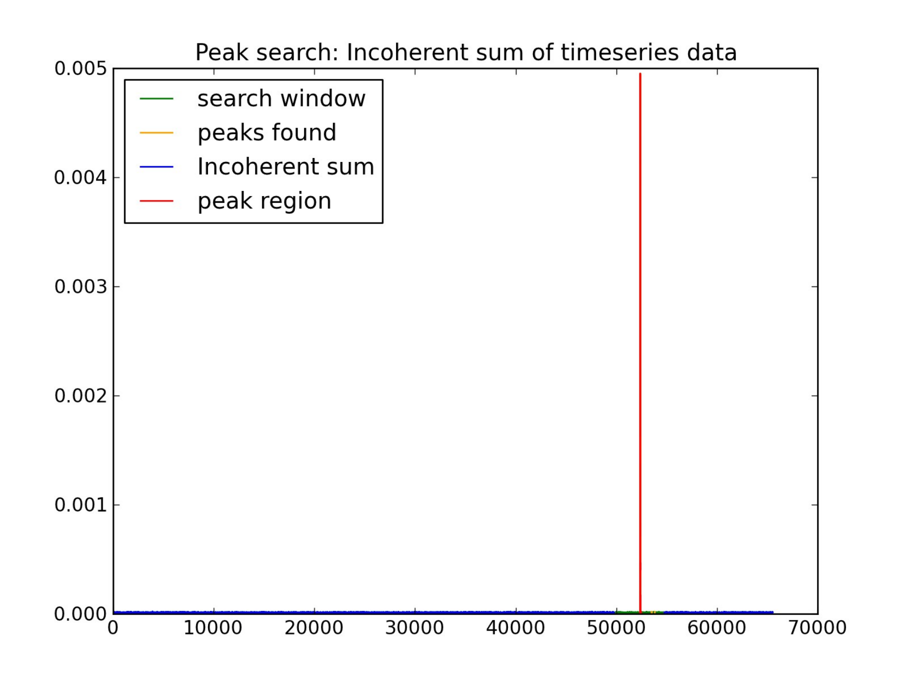
Use the LORA timestamp to select a block of 300 us where the pulse should be.

Cut out RFI
Apply the baseline assuming galactic noise to be dominant ($\nu^{-0.5}$).

Peak identification

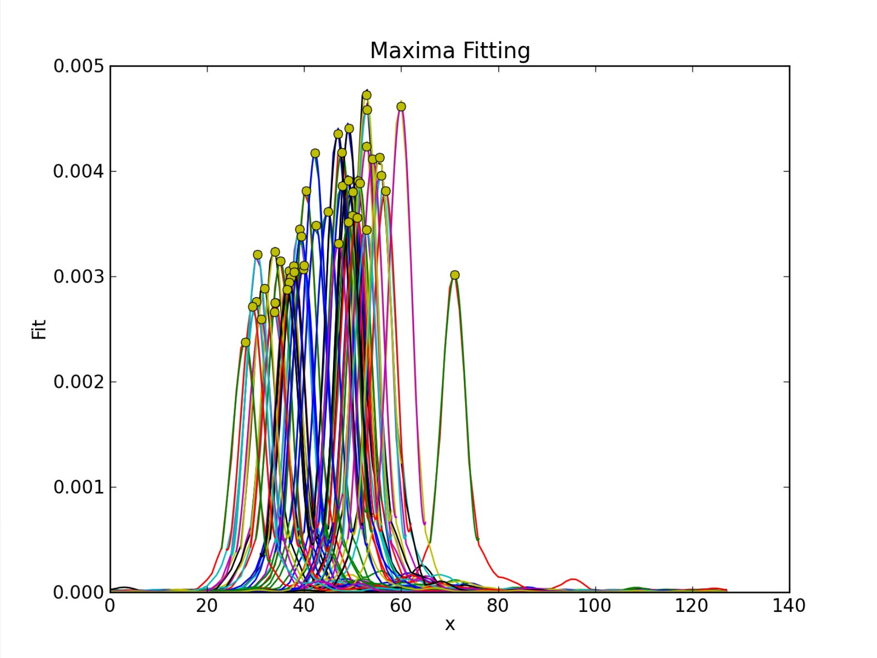


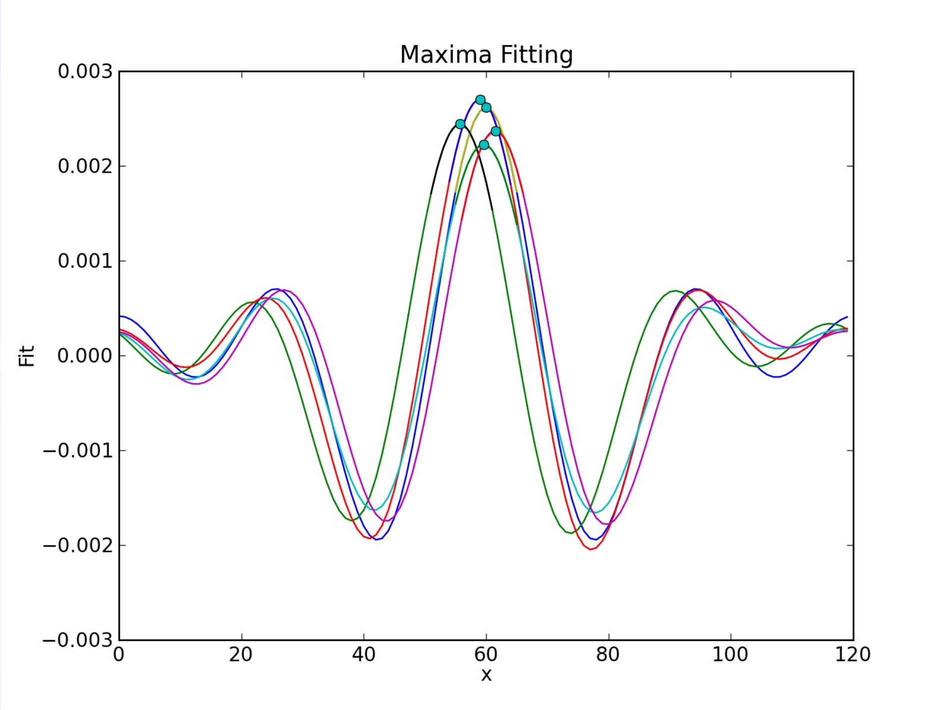
Go back to time domain



Use an incoherent sum in the direction of the cosmic ray to find the position of the pulse.

Find delays between dipoles

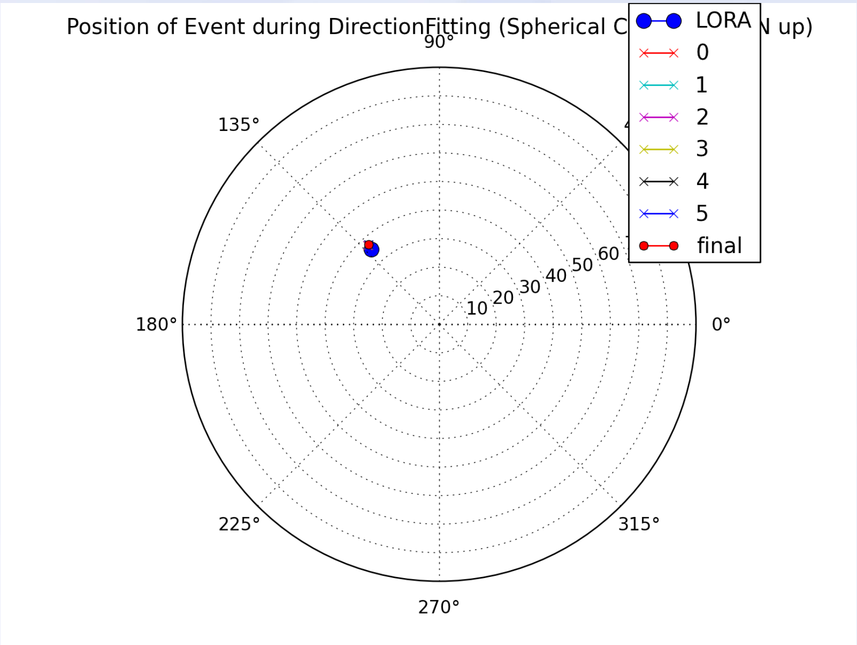


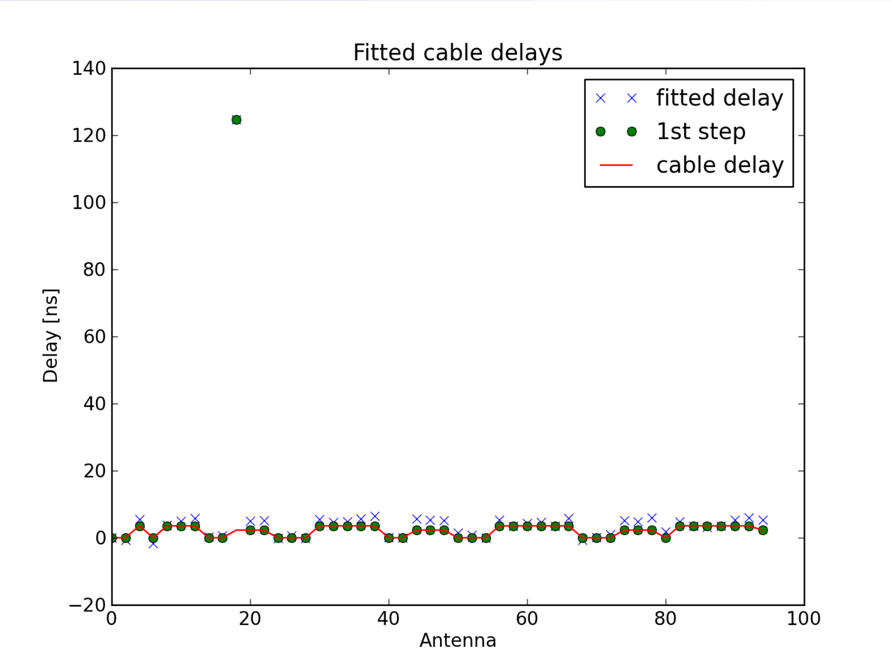


Find the maxima for each dipole.

Crosscorrelate the dipoles to find the delays.

Direction estimation

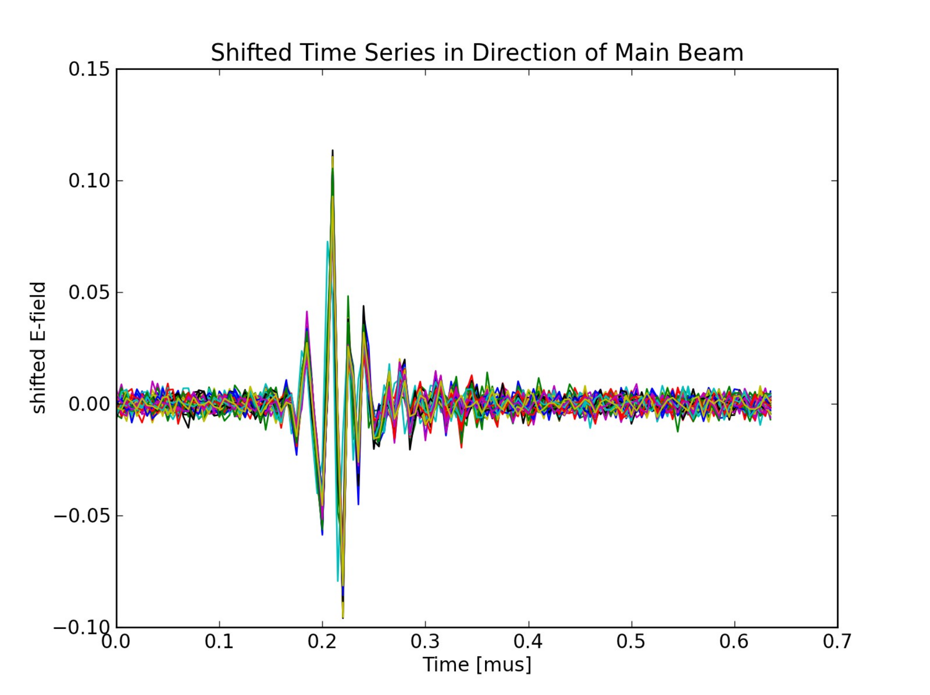




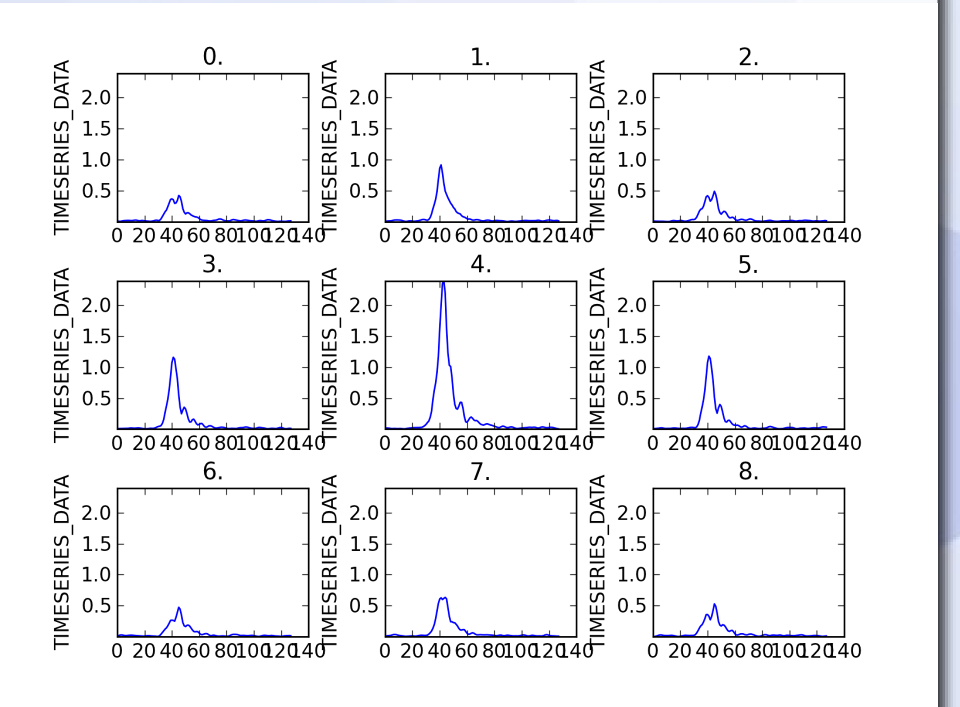
Use the timedelays to find the direction of the pulse.

Check the fitted delays for anomalies. Compare with cable delays and calibration tables.

Beamforming

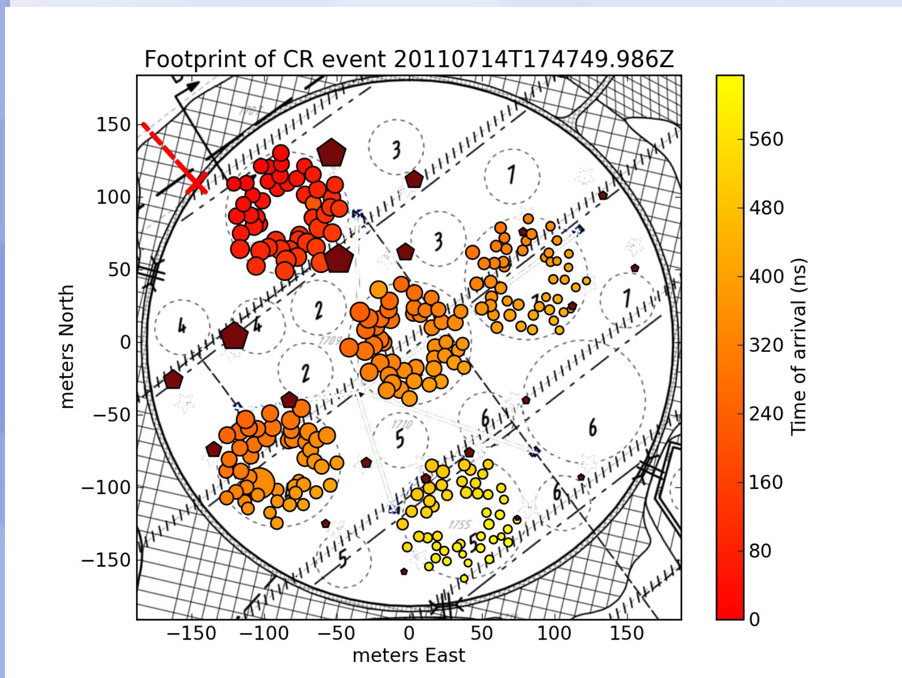


Shift timeseries with delay. This shows a very coherent pulse.

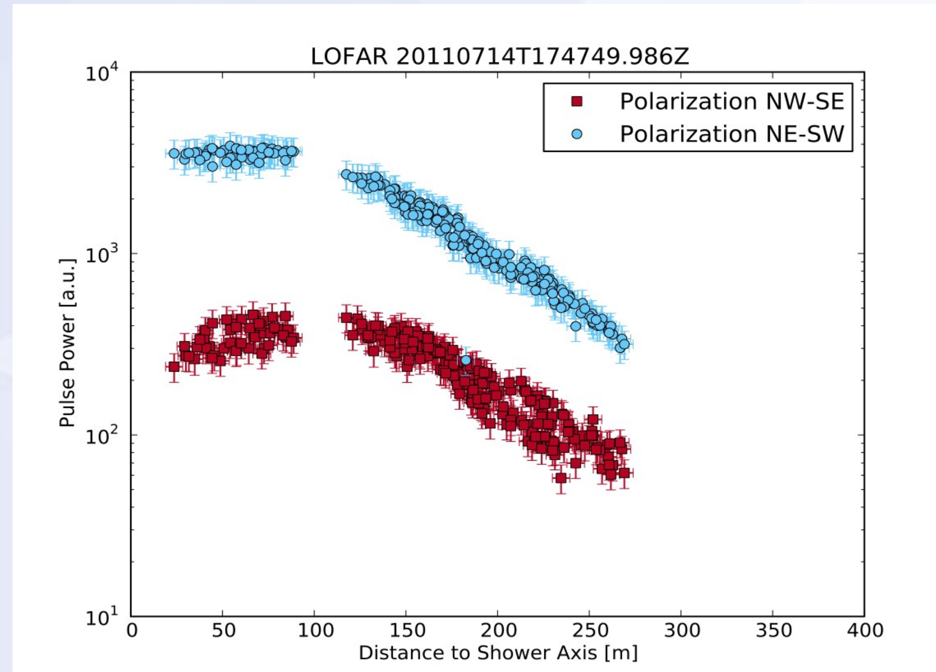


Do coherent beamforming in the pulse direction and in 8 directions around it with a 5 degree offset.

Lateral Distribution Function

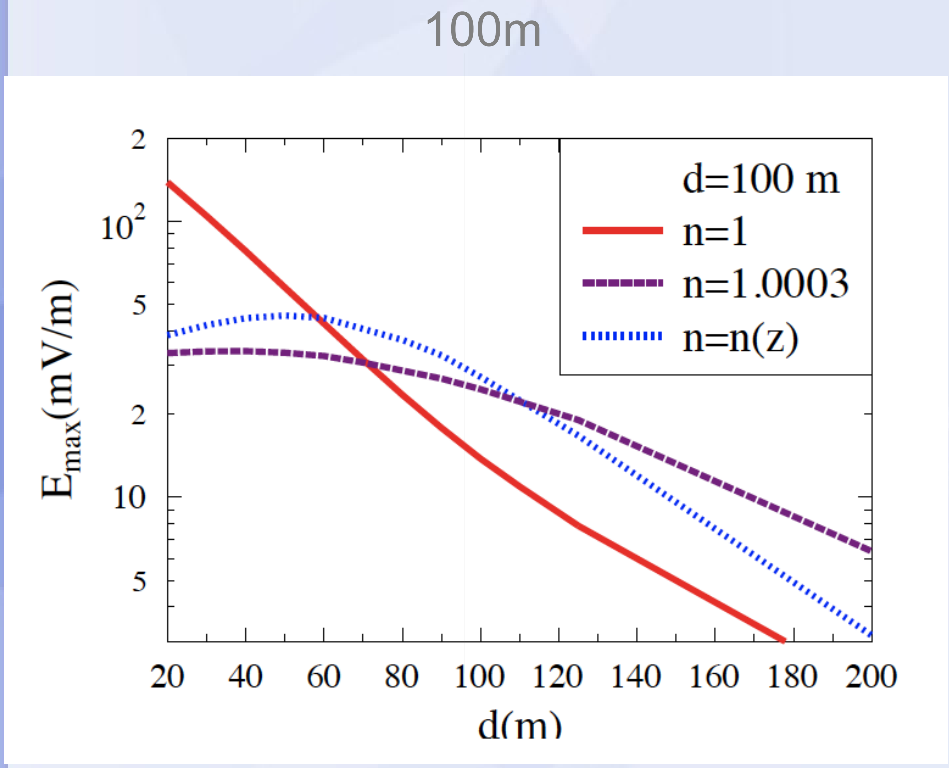


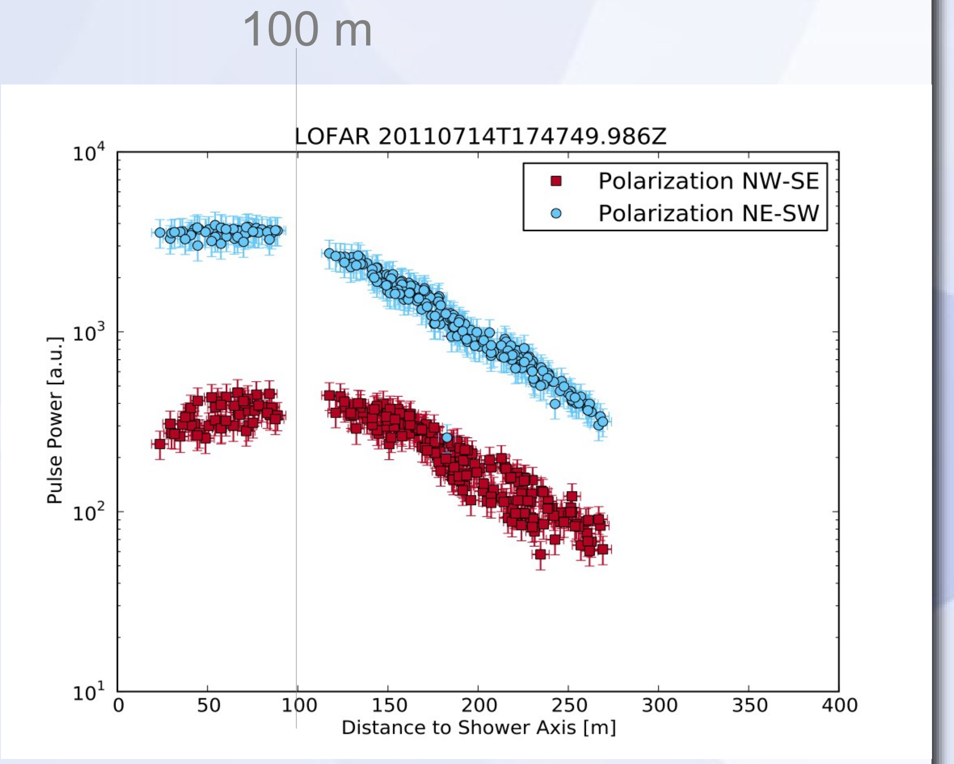
Footprint of this event.



Lateral distribution function
Signal as function of distance from shower core.

Theory matches signal?





Prediction:
Refraction index of air flattens LDF closer than 100 m from shower core.
K. de Vries et al.
(Phys. Rev. Lett. 107,061101 (2011))

Possibly observed around time of publication

Preliminary

Summary

- First cosmic rays detected with LOFAR!
- What can LOFAR do for Cosmic Rays?
  - Pin down emission mechanism
  - Measure composition and energy
- What can Cosmic Rays do for LOFAR?
  - Commission Transient Buffer Boards
  - Inspect the instrument at the basic level