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Status of the VHECR Pipeline

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for the LOFAR-CR Team

LOFAR

Outline

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IN·DEI·NOMINE·FELICITER

1. cosmic ray and air shower physics and what it means for the VHECR mode
2. TBB data taking and VHECR triggering
3. offline analysis pipeline
   - LOPES pipeline
   - changes for LOFAR
4. The End

LOFAR-CR Energy Ranges

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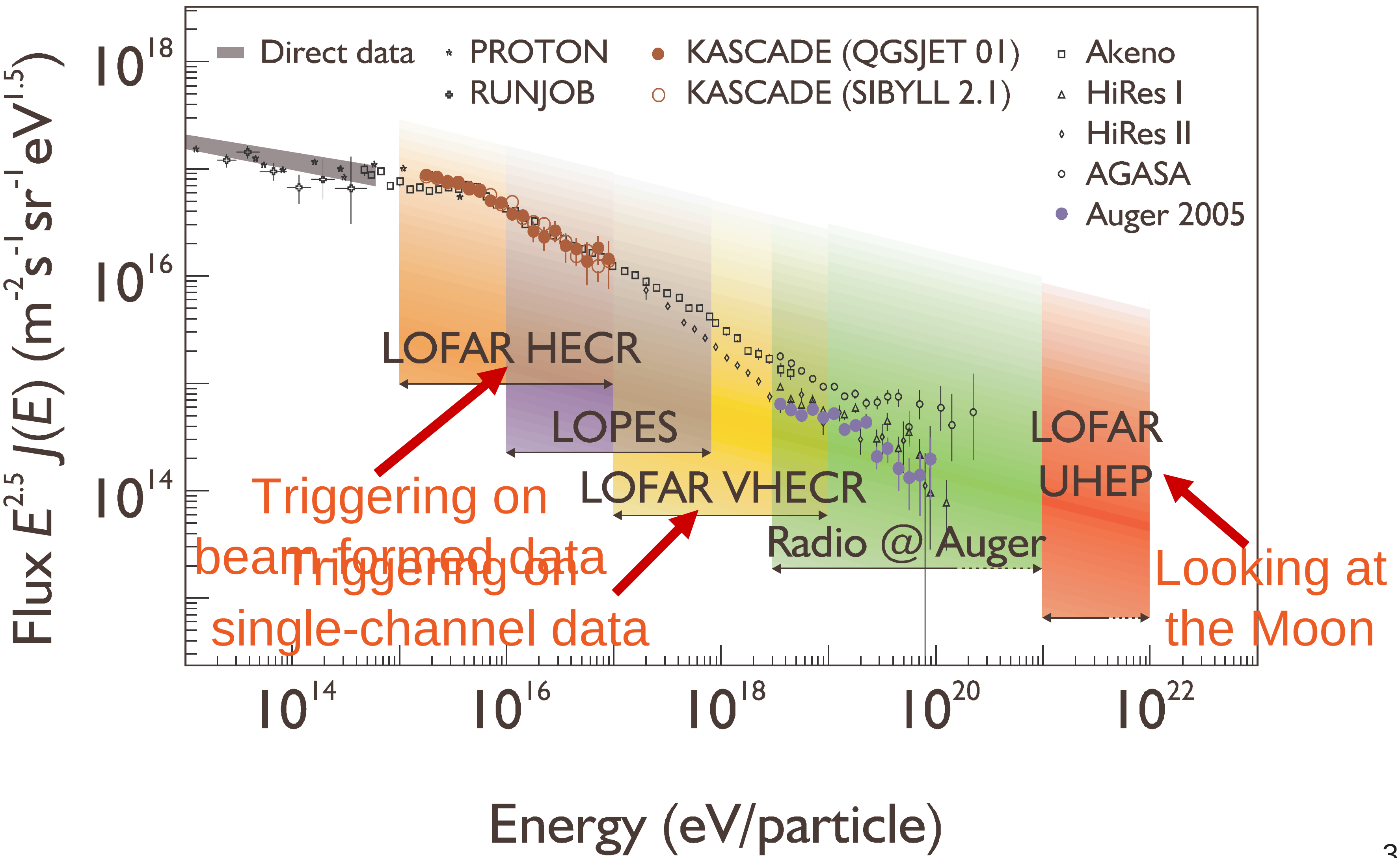
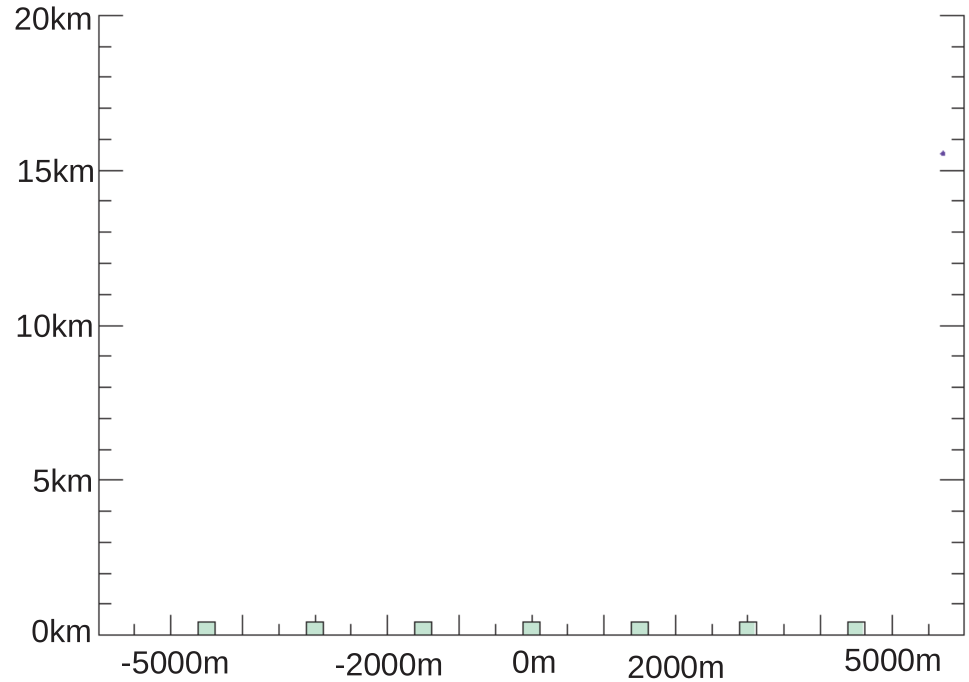


Air Showers

- high energetic cosmic rays interact with nuclei in the atmosphere
- in a cascade lots of secondary particles emerge
- a “pancake” of particles



- these “pancakes” emit radio pulses (geosynchrotron radiation)
- due to coherence the emission peaks at about 10 MHz

LOPES

(LOFAR Prototype Station)

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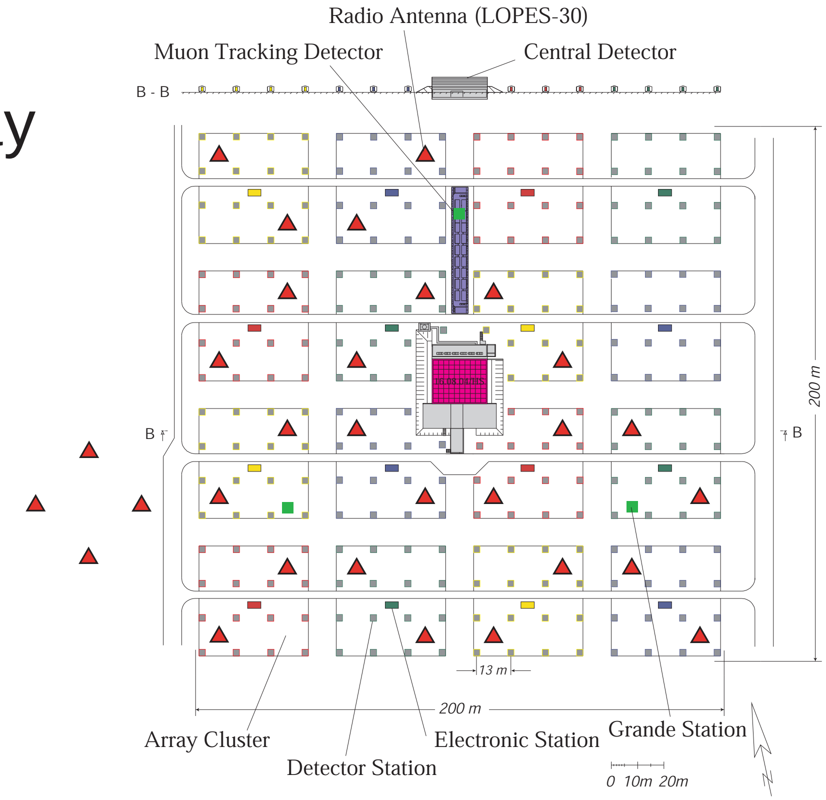
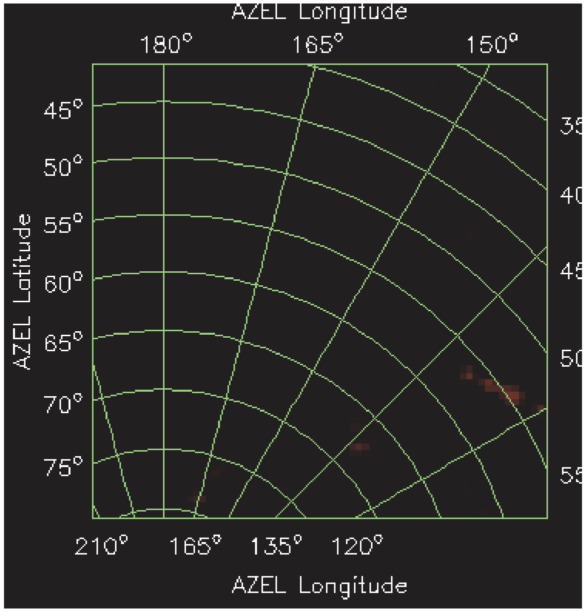
- Prototype of a LOFAR station
- Set up inside an air shower array
- Frequency range of 40–80 MHz
- Triggered by particle detectors
- Detection of air showers with LOFAR technology





Falcke et al. (LOPES collaboration), Nature, 435, 313, 2005

LOPES Example Event

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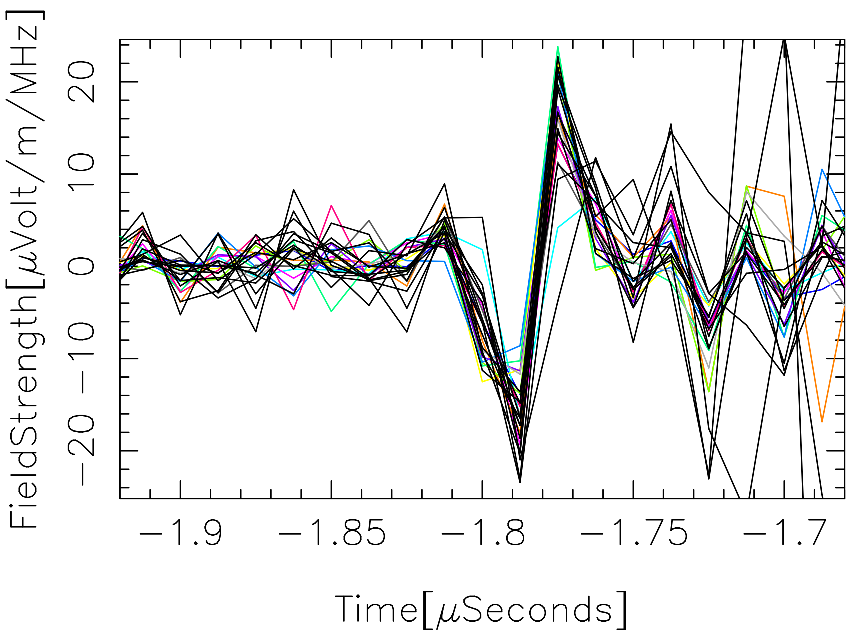
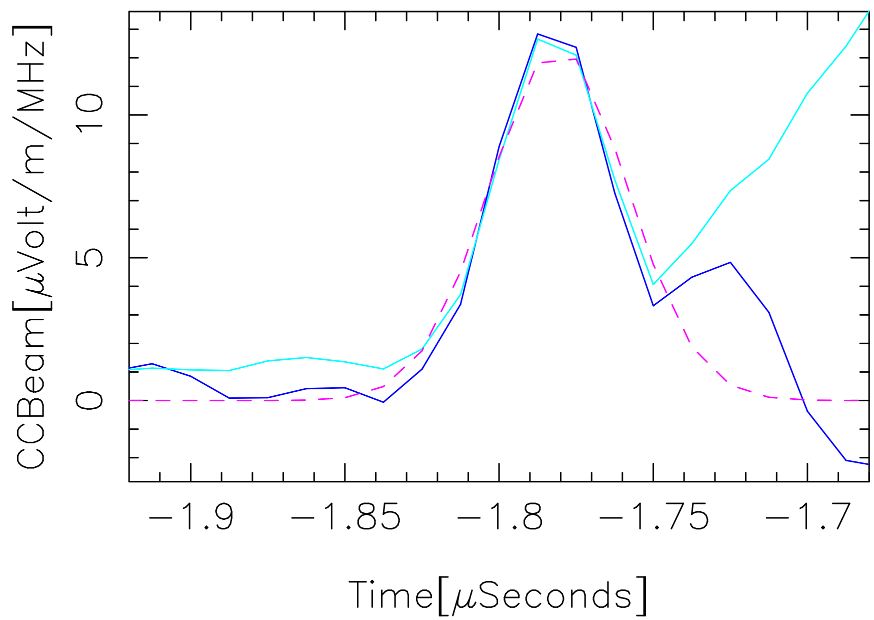
single antenna traces



after beam-forming



Radio Signature of Air Showers

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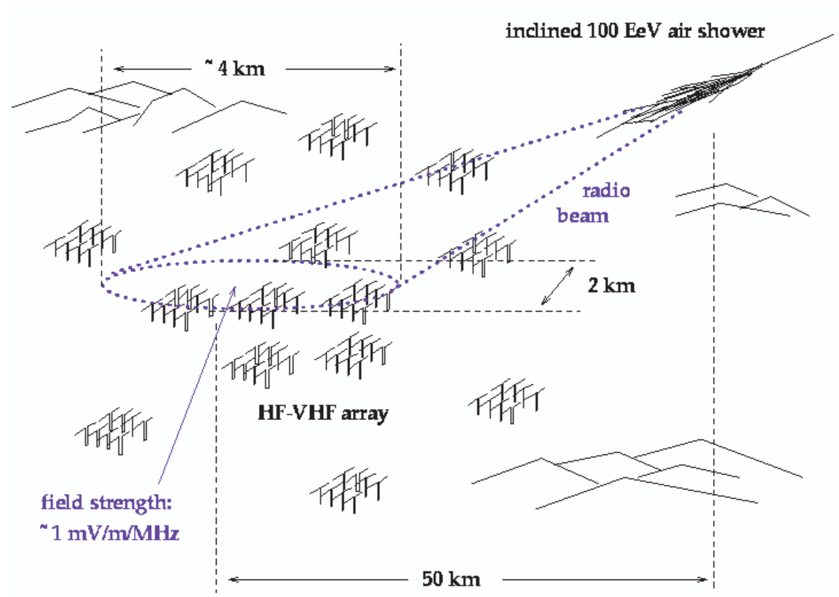
- random arrival times and directions
  - can ignore (man made) pulses from the horizon
- broad-band, short time pulse (~10ns)
- limited illuminated area on the ground
  - depending on primary energy
- curvature of radio front
  - similar (but not identical) to point source in few km height
- coincident with particle disc
  - build particle detector array



TBB
Data Acquisition

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- old way: dump to LCU
  - works reliably
  - has some drawbacks: slow, inconvenient, disk space
- TBB dump-to-CEP mode:
  - works, somewhat…
  - some problems were reported and worked on, but not (yet) tested by me.
    - RSP time-stamps, “end of transfer” problem, transfer speed
  - other problems take longer (manpower…)
    - tbb2h5, acquisition scripts, metadata, MAC integration

VHECR Trigger I

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- runs on the FPGAs of the TBBs
- pulse detection for single channels
  1. digital Filtering of some RFI (IIR-filters)
  2. peak detection
  3. calculation of pulse parameters (position, height, width, sum, avg. before, avg. after)
- peak detected if:

$$|x_i| > \mu_i + k_1\sigma_i$$

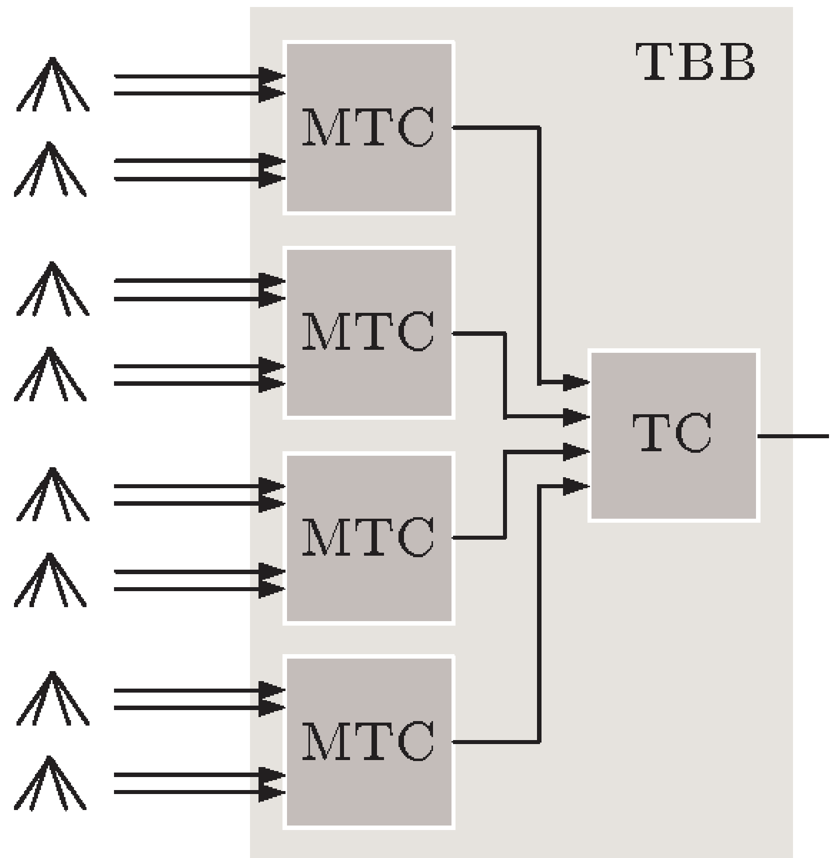
- can be simplified to:

$$|x_i| > k_2\mu_i$$

Transient Buffer Boards

- one TBB for 16 channels
- one FPGA for 4 channels
- larger FPGA allows 3 IIR filters plus peak detection per channel

- has been implemented in the FPGAs
- recent tests found some (IMHO minor) bugs
- testing continues



VHECR Trigger II

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- TBBs send “trigger messages” to station LCU
- coincidence trigger at station level
  - filtering of “bad” pulses
  - coincidence detection
  - (direction fit)
  - data dump if pulse is found
- stations send messages to CEP
  - dump more (all) stations for large events
- after trigger: dump 1ms worth of data
  (1kHz frequency resolution)

LCU/CEP Trigger Status

- module for a simple coincidence trigger has been implemented
- needs to be integrated into the driver and tested
  - question about best way for fast development of trigger algorithm
- no work yet on CEP trigger
  - but will be very similar to LCU trigger

LOPES Analysis Software

- original version was Glish-based
  - Slow, ugly, not supported anymore!
- new version in plain C++
  - part of the usg-software repository
  - current “workhorse” of the LOPES analysis
  - will be expanded/modified to work with LOFAR data
- Python/C++ based interactive version
  - Not ready yet!

LOFAR CR Data Processing

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- steps of the data processing:
  1. delay/phase correction
  2. filtering of narrow band Interference
  3. frequency dependent gain correction
  4. flagging of antennas
  5. correction of trigger delay
  6. beam forming in the direction of the air shower
  7. direction fitting
  8. quantification of peak parameters
  9. event discrimination

Delay correction

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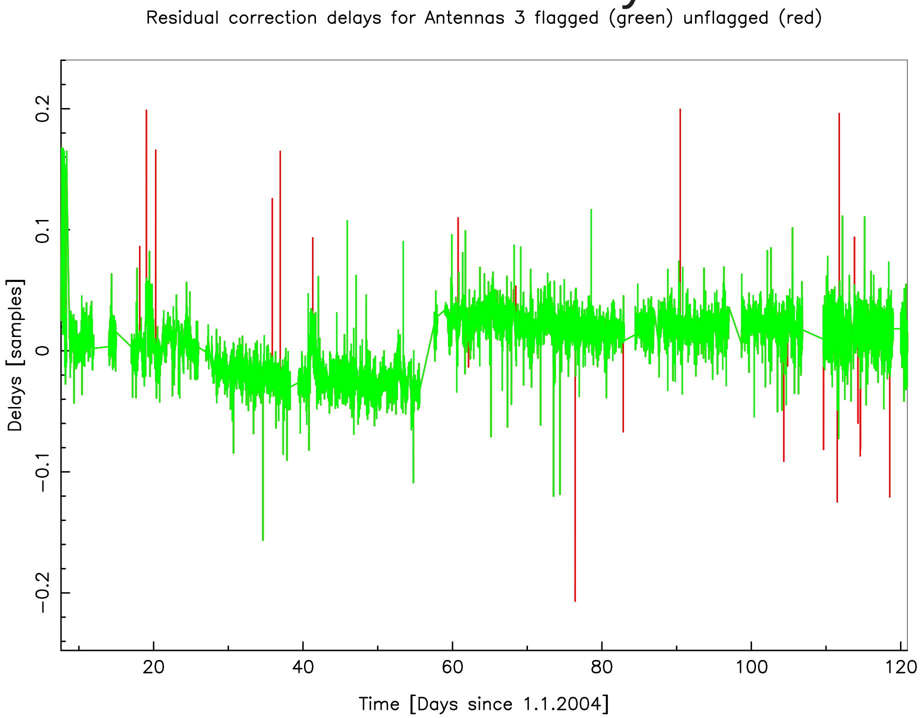
- at LOPES: calibrate on relative phases from a TV-transmitter or extra beacon
- at LOFAR: solutions from standard calibration

residual delays



Digital Filtering

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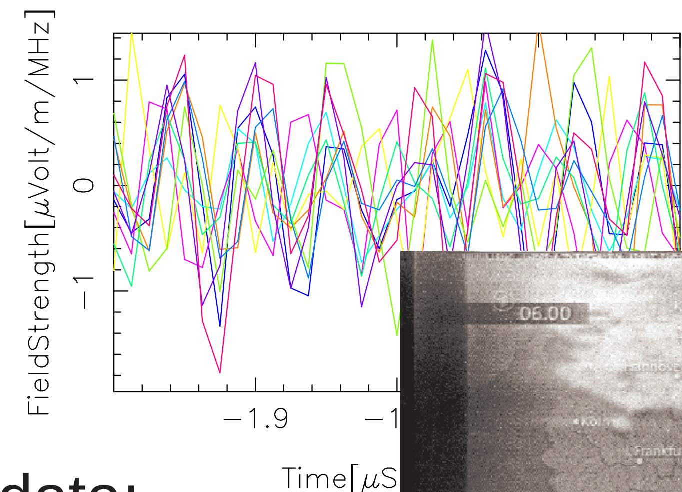
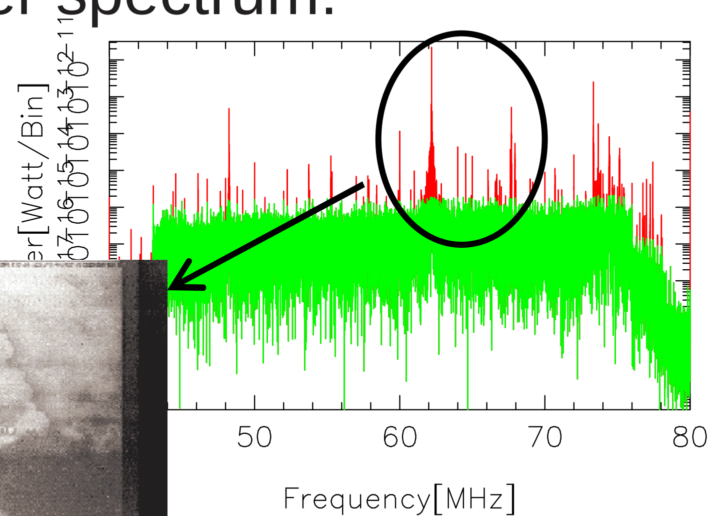
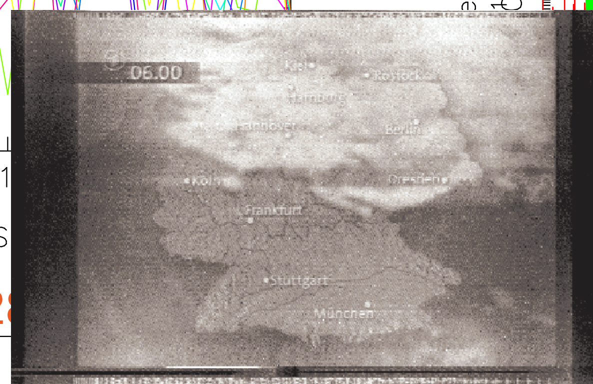
raw data:



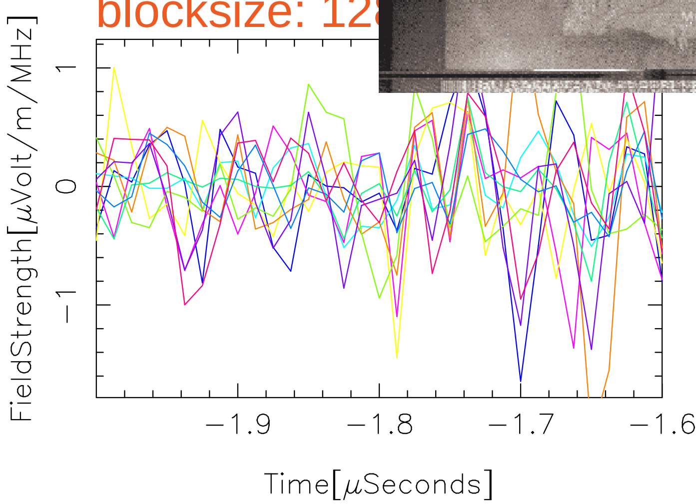
power spectrum:



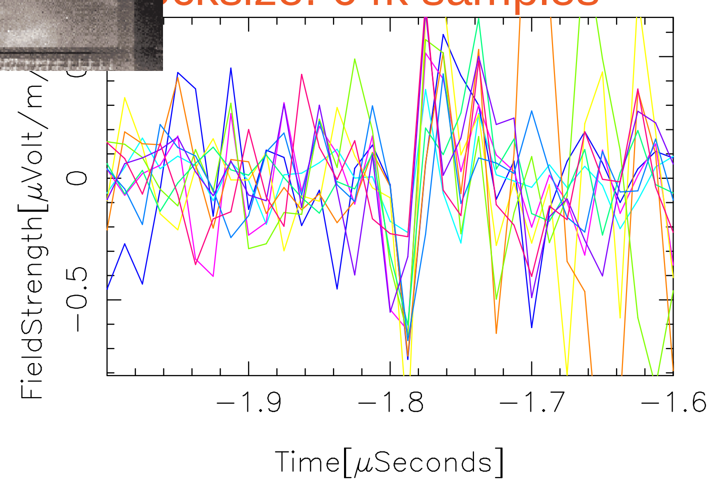


filtered data:

blocksize: 128



blocksize: 64k samples



Gain Calibration

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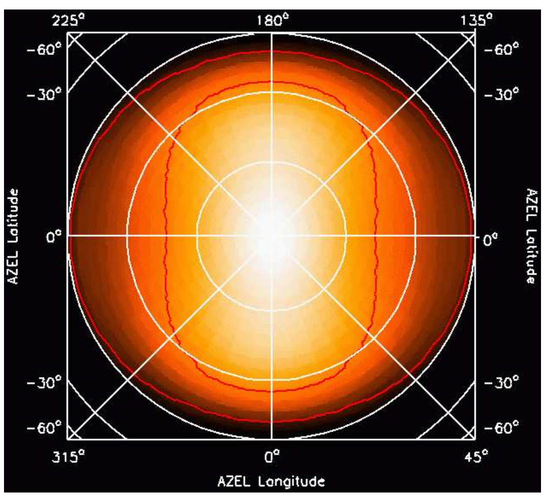
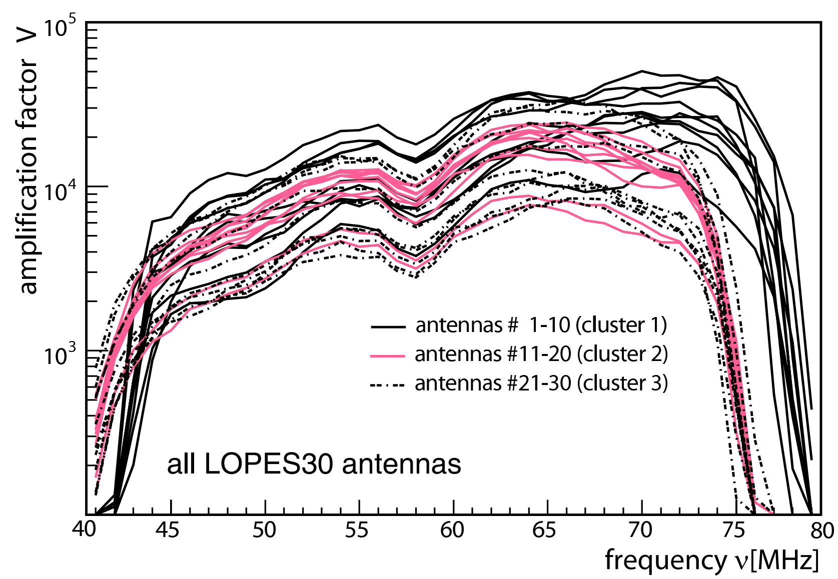
- convert measured ADC values into field-strength
- at LOPES: Gain measurements with reference source
- at LOFAR: Station calibration

$$\varepsilon = \sqrt{\frac{4\pi\nu\mu_0}{G_{(\theta,\phi,\nu)}c}\frac{1}{A_{ele(\nu)}R_{ADC}}V_{ADC}}$$





Beam Forming

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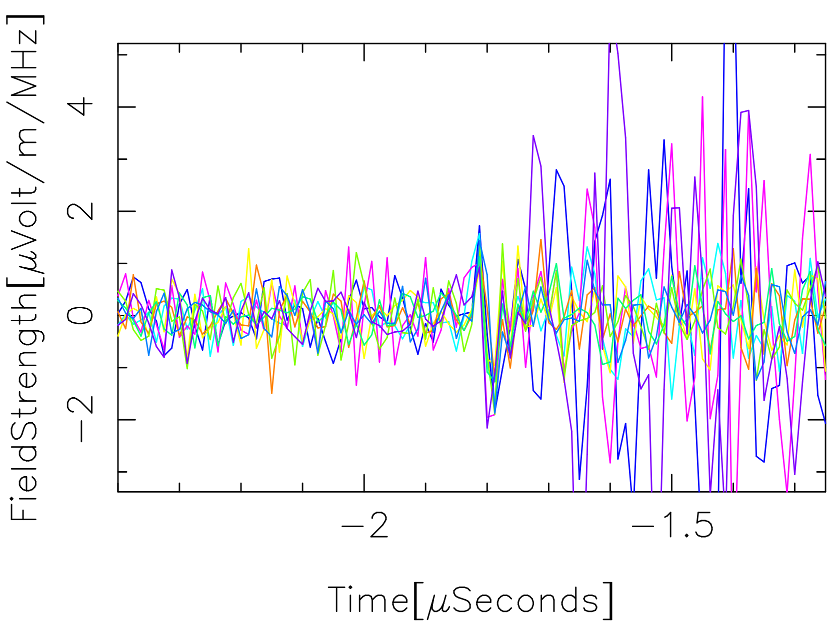
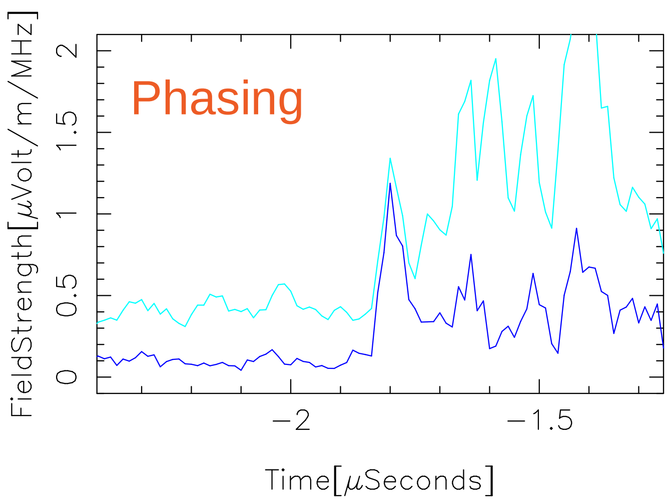
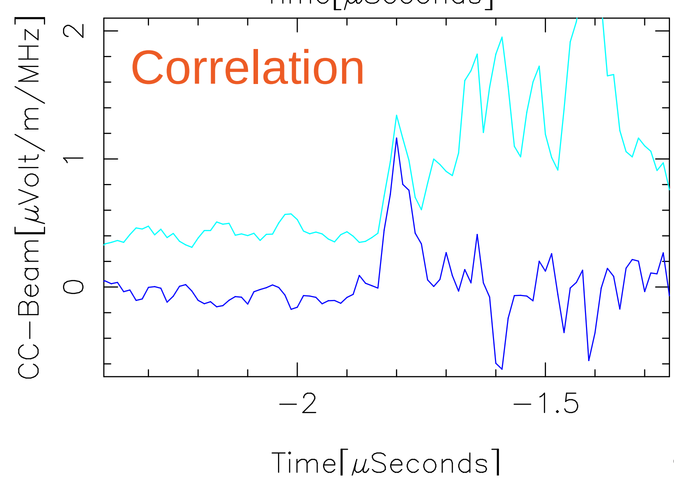
- filtered and time shifted data from single antennas
- beamformed data after correlation of all antennas
  - air shower pulse at -1.8μs
  - particle detector noise
    from -1.75μs to -1.3μs
  - Phasing ↔ Correlation







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Position Fitting

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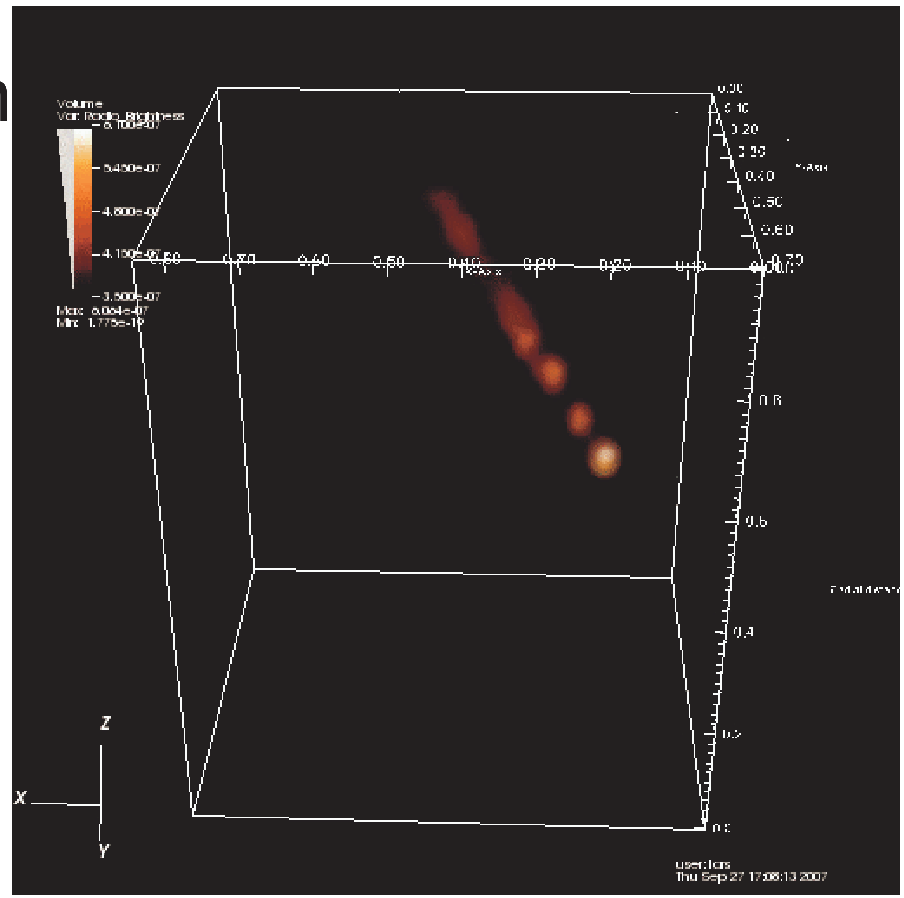
- find maximum pulse height in 3d space (azimuth, elevation, radius)
- plus: time and position on the ground

1. start with image cube (around KASCADE values of the full sky)
2. do a fit around the maximum of the cube



Event Discrimination

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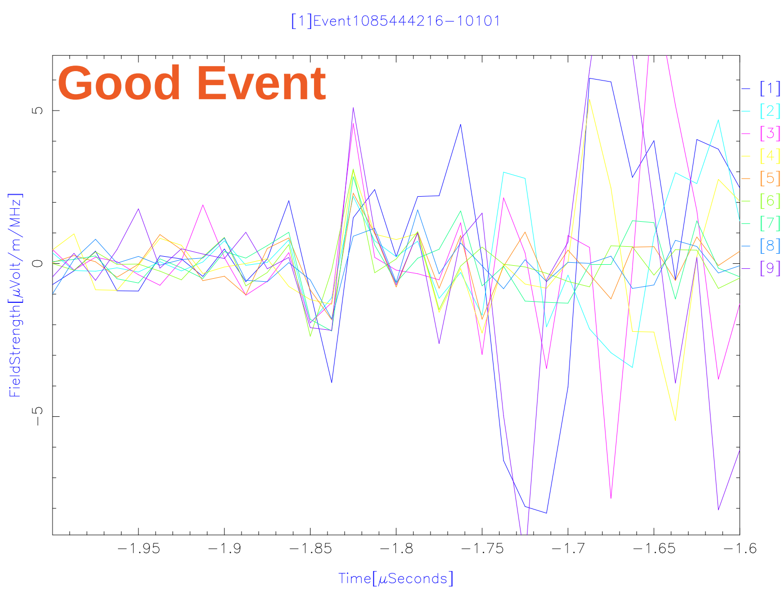
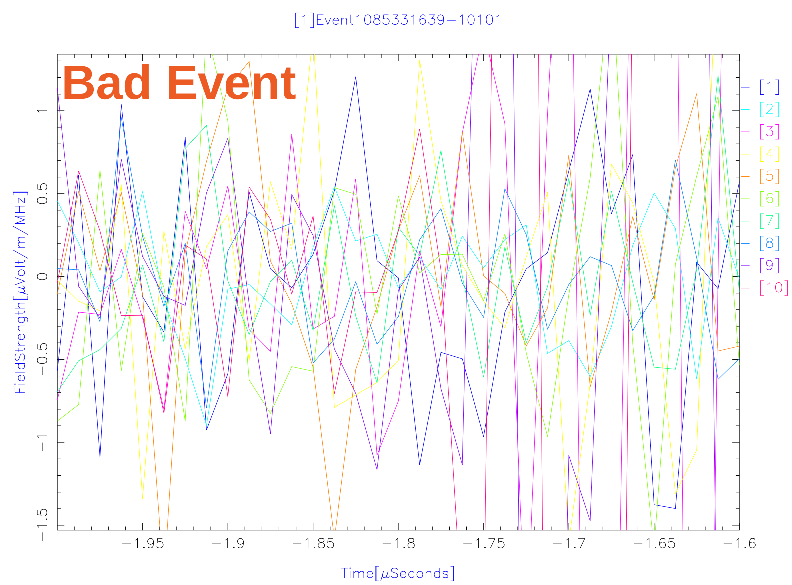
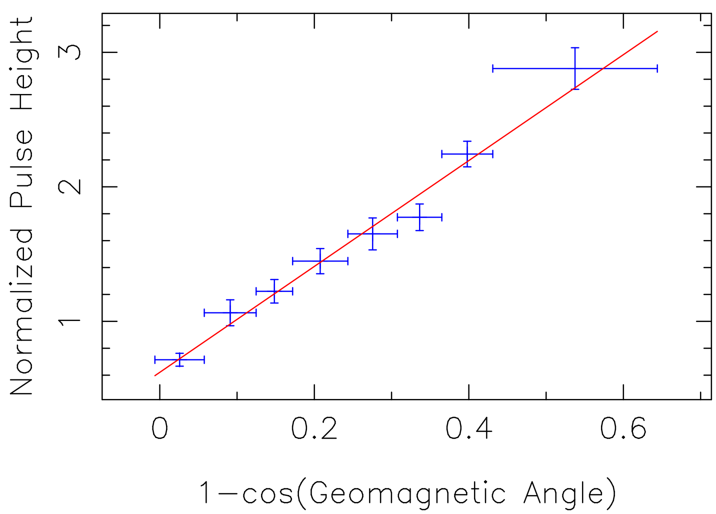
- criteria for “good” events:
  - existence of a coherent pulse
  - lateral distribution of pulse height in the antennas
  - position in time of pulse (only LOPES)
- selection for LOPES currently done manually
  - automated selection discards too many low S/N events
  - high S/N events can be automatically selected!

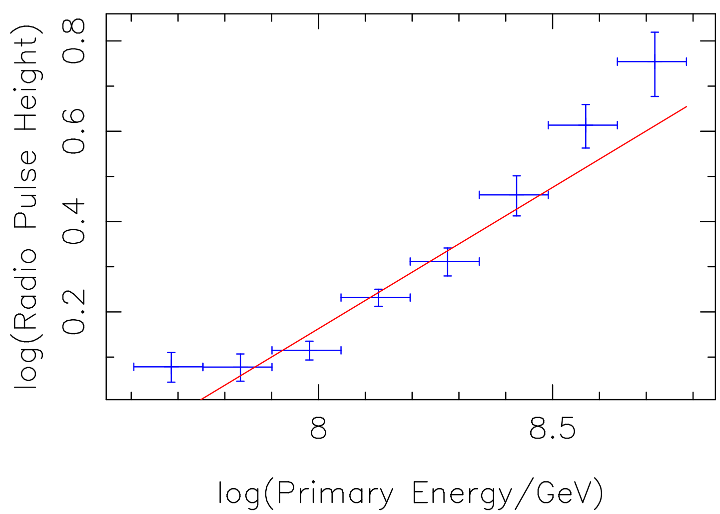




Statistical Analysis

- the output of the processing pipeline is a list of events and their parameters
- these are then analyzed to determine properties of the radio emission or the cosmic ray spectrum, composition etc.





Offline Pipeline Changes for LOFAR

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- calibration (Gain and Phase)
  - need to define metadata interface to station calibration
- direction finding
  - finish the skymapper
  - include skymapper as initialization for direction fit
  - *include trigger parameters for optimization*
- general:
  - *ability to deal with many channels (parallelization?)*

Summary

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- VHECR trigger has three stages
  - TBB trigger is running and being tested
  - preliminary version of the LCU trigger exists
  - CEP trigger will be very similar to LCU trigger
- LOPES (batch-mode) analysis pipeline is running
- needs to be modified for LOFAR
  - only major change in the algorithm will be integration of the skymapper
  - “peripheral” changes (e.g. metadata interface) will probably also take some time