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Detecting Radio Pulses from Air Showers

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for the LOPES Collaboration

Cosmic Rays

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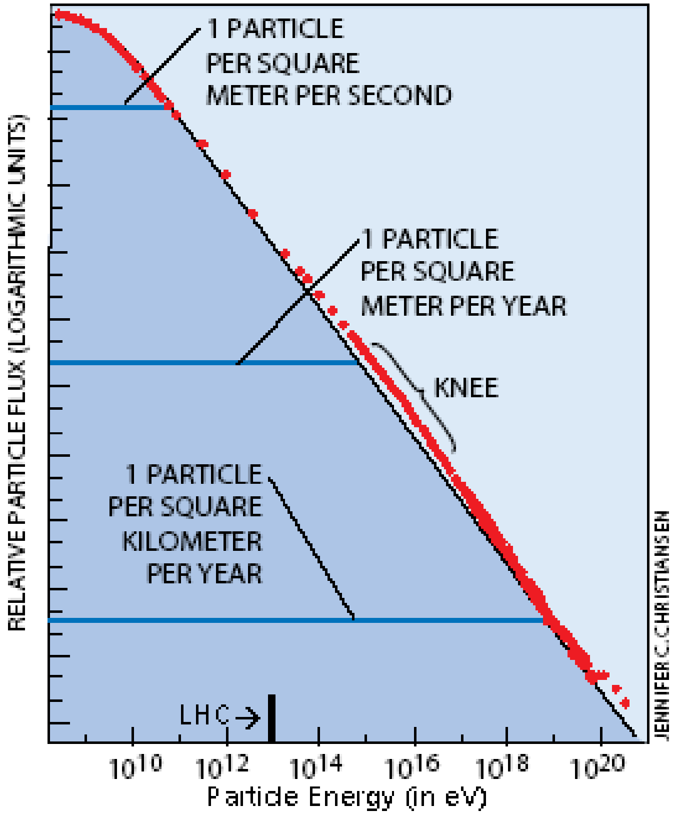
- high energy particles
- dominated by hadrons (atomic nuclei)
- similar in composition to solar system
- broad range in flux and energy
- different energy regimes:



$< 10^{10}$ eV	modulated by solar wind
$< 5 \cdot 10^{14}$ eV	direct detection possible
$> 5 \cdot 10^{14}$ eV	indirect detection (air showers)

Sources of Cosmic Rays

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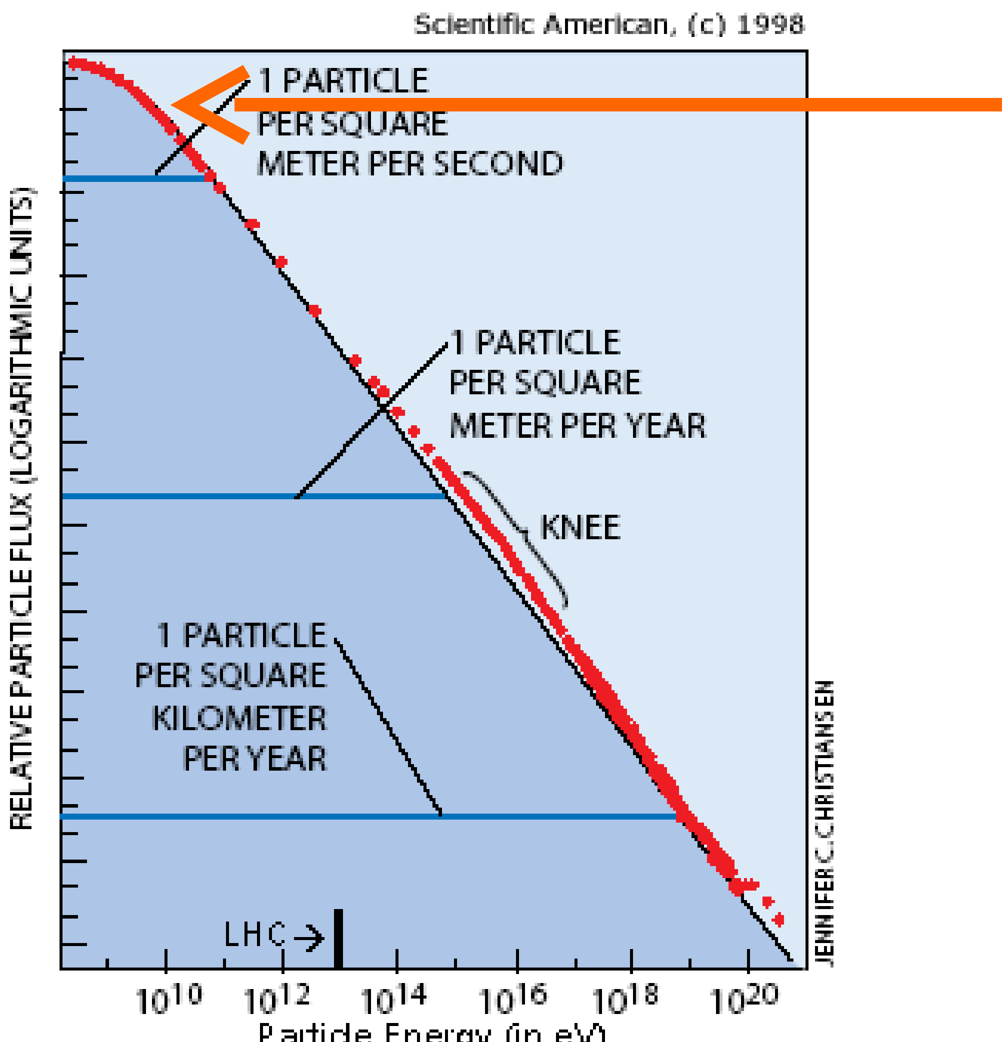

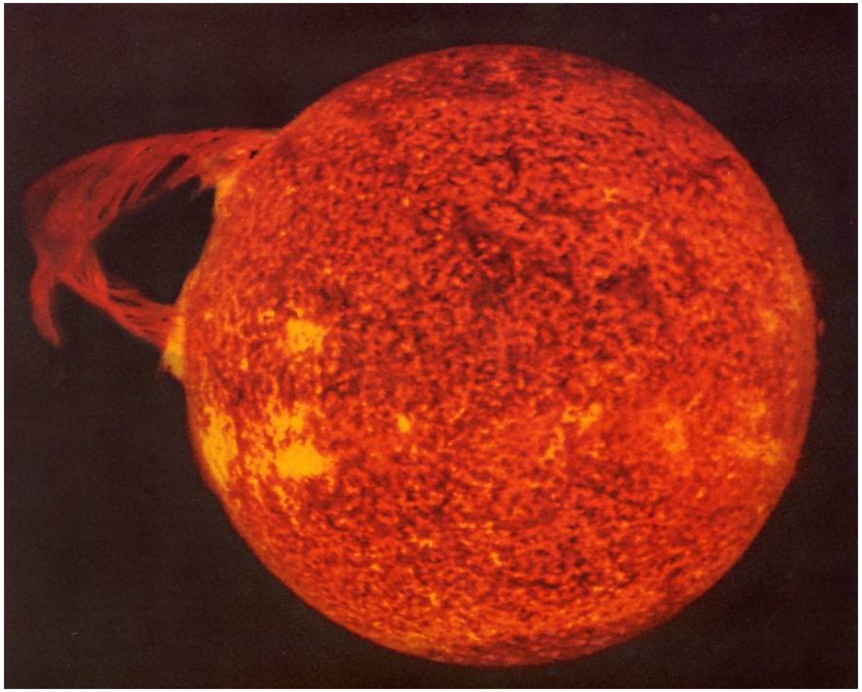

Sources of Cosmic Rays

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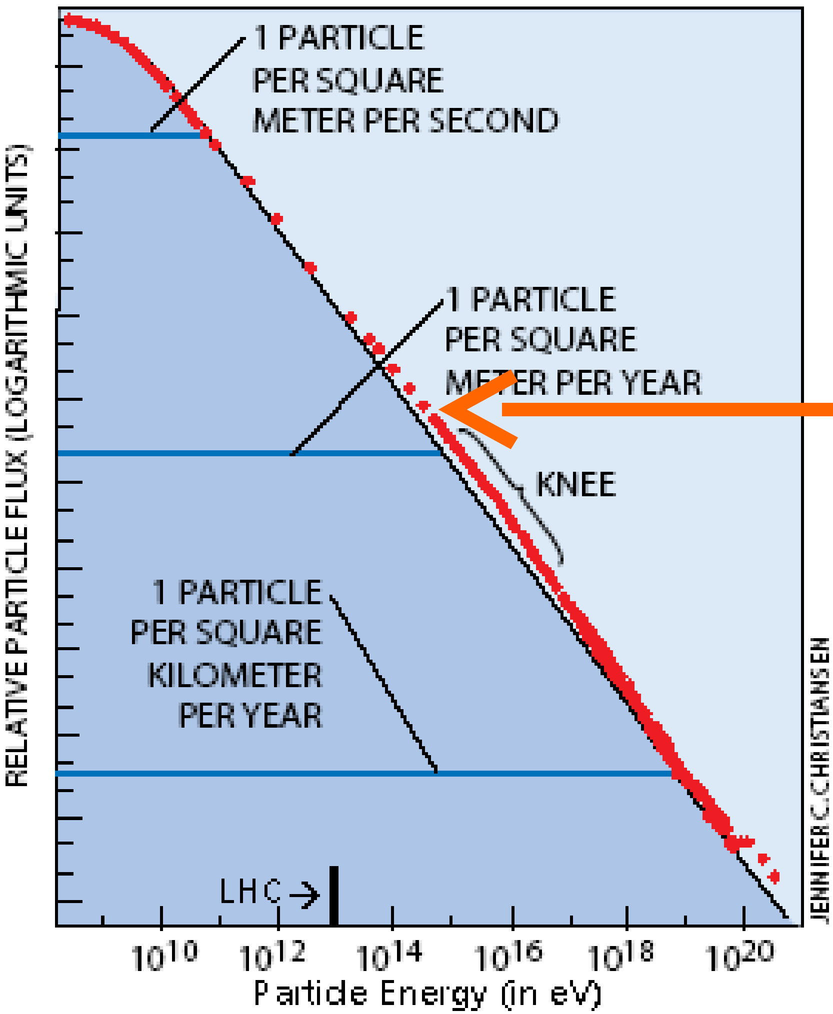
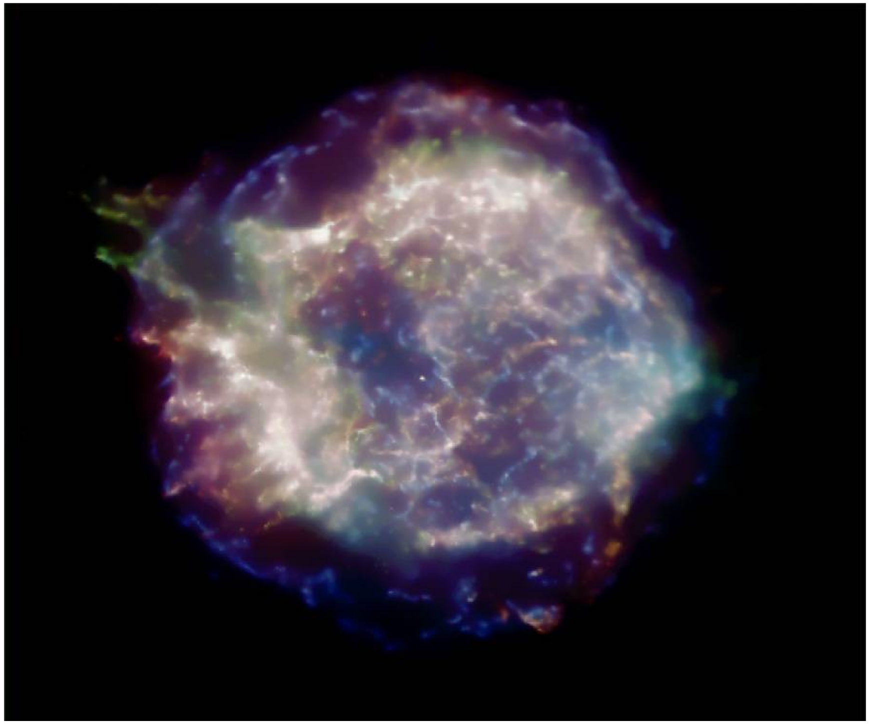
Scientific American, (c) 1998





Sources of Cosmic Rays

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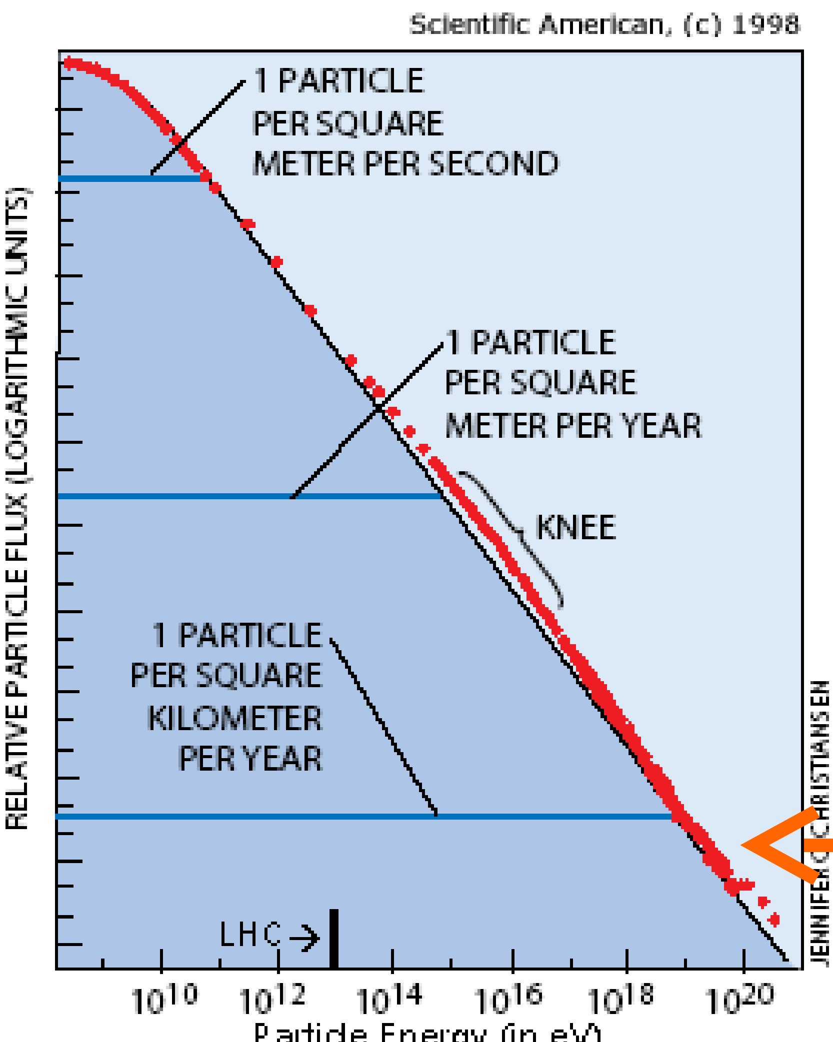

???

Correlated with nearby Galaxies

Air Showers

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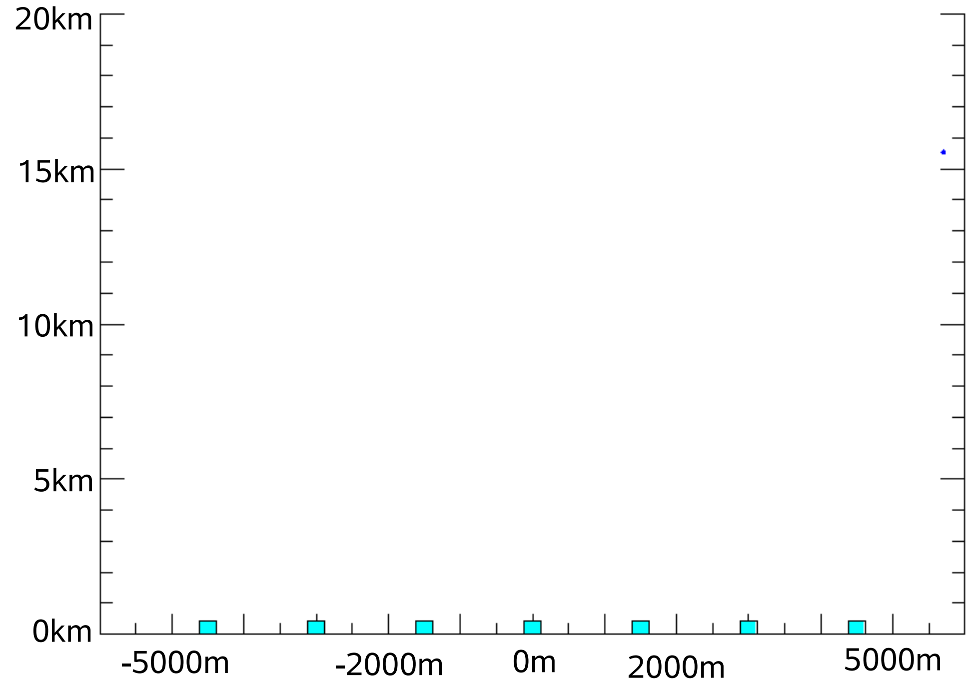
- high energetic cosmic rays interact with nuclei in the atmosphere
- in a cascade lots of secondary particles emerge
- a “pancake” of particles
  - a few meters thick (with trailers)
  - up to a few kilometers wide
  - travelling with about light speed in the direction of the primary particle



Detection of Air Showers

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- Air-Cherenkov

  detection of (visible) Cherenkov light with telescopes

  - allows discrimination of gamma induced air showers
- Air-Fluorescence

  detection of fluorescence light from nitrogen molecules

  - used at highest energies
  - allows determination of primary particle mass & energy
- Ground based Particle Detectors
  - high duty cycle; measuring around the clock
  - determination of primary mass & energy by measuring different components e.g. muons and electrons

Radio Emission from Air Showers: History

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- first detection of radio pulses from air showers 1965 by Jelley et al.
- intensive research in the following years
- measurements ceased after the 1970s mostly due to difficult interpretation, success of other methods, and radio interference

Jelley et al. (1965)

Radio Emission from Air Showers: Facts

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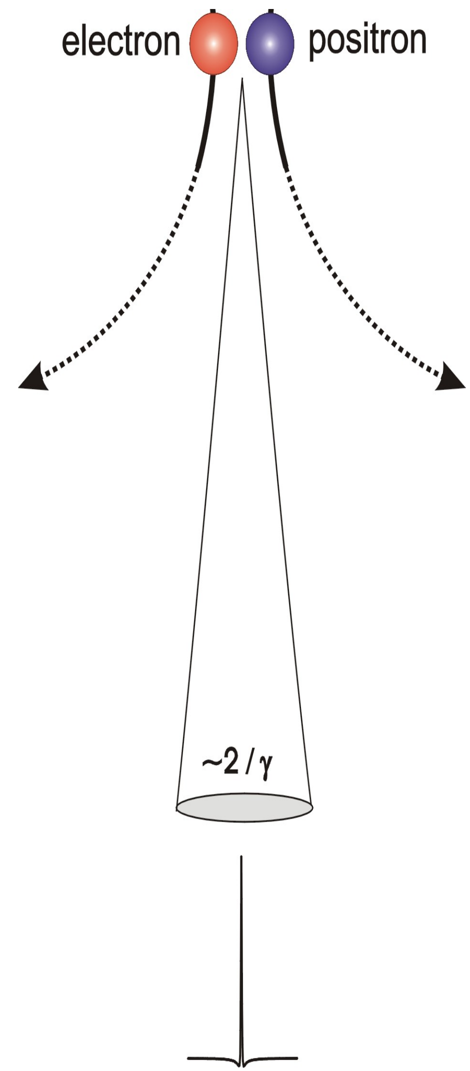
- air showers emit a radio pulse with less than 20ns width
- radiation due to geomagnetic emission process e.g. geosynchrotron
- coherent emission at low frequencies
- measuring the radio emission from air showers could give several benefits:
  - higher duty cycle than fluorescence telescopes
  - effective RFI suppression allows measuring in polluted (populated) areas
  - data integrated over the shower evolution, can be complementary to particle detectors
  - high angular resolution possible
- this can be achieved by new digital radio telescopes



Analog vs. Digital Receiver

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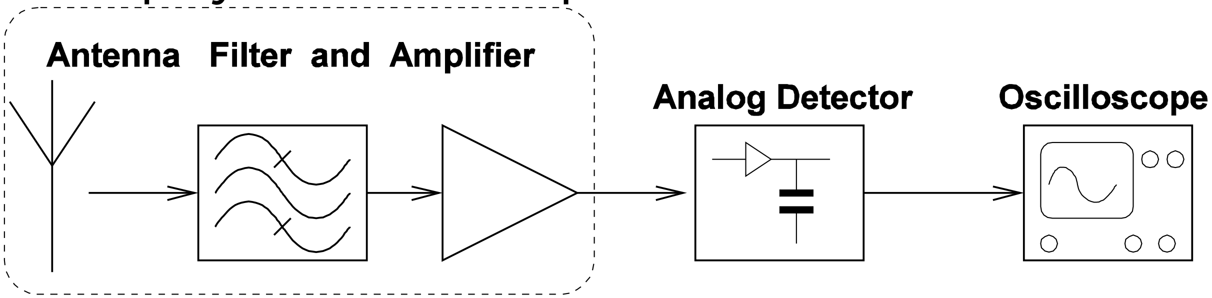
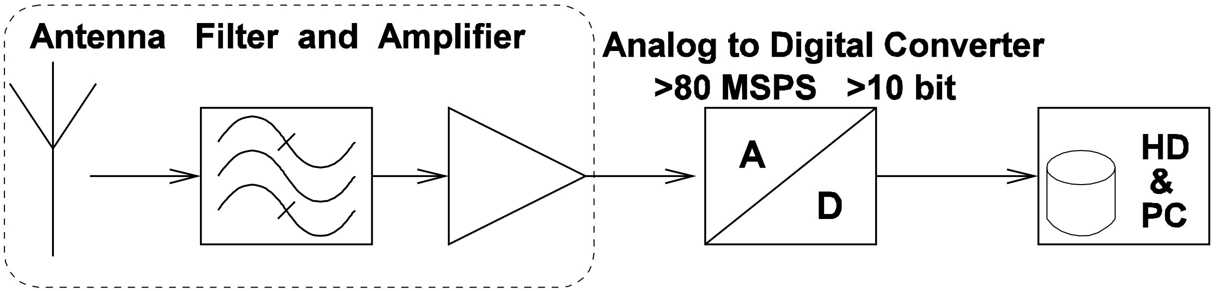
- In the 1970ties:
  - analog detection/demodulation of signals
  - display on oscilloscopes



- Now:
  - fast ADCs sample the whole waveform
  - processing and display on computers



Analog vs. Digital Receiver

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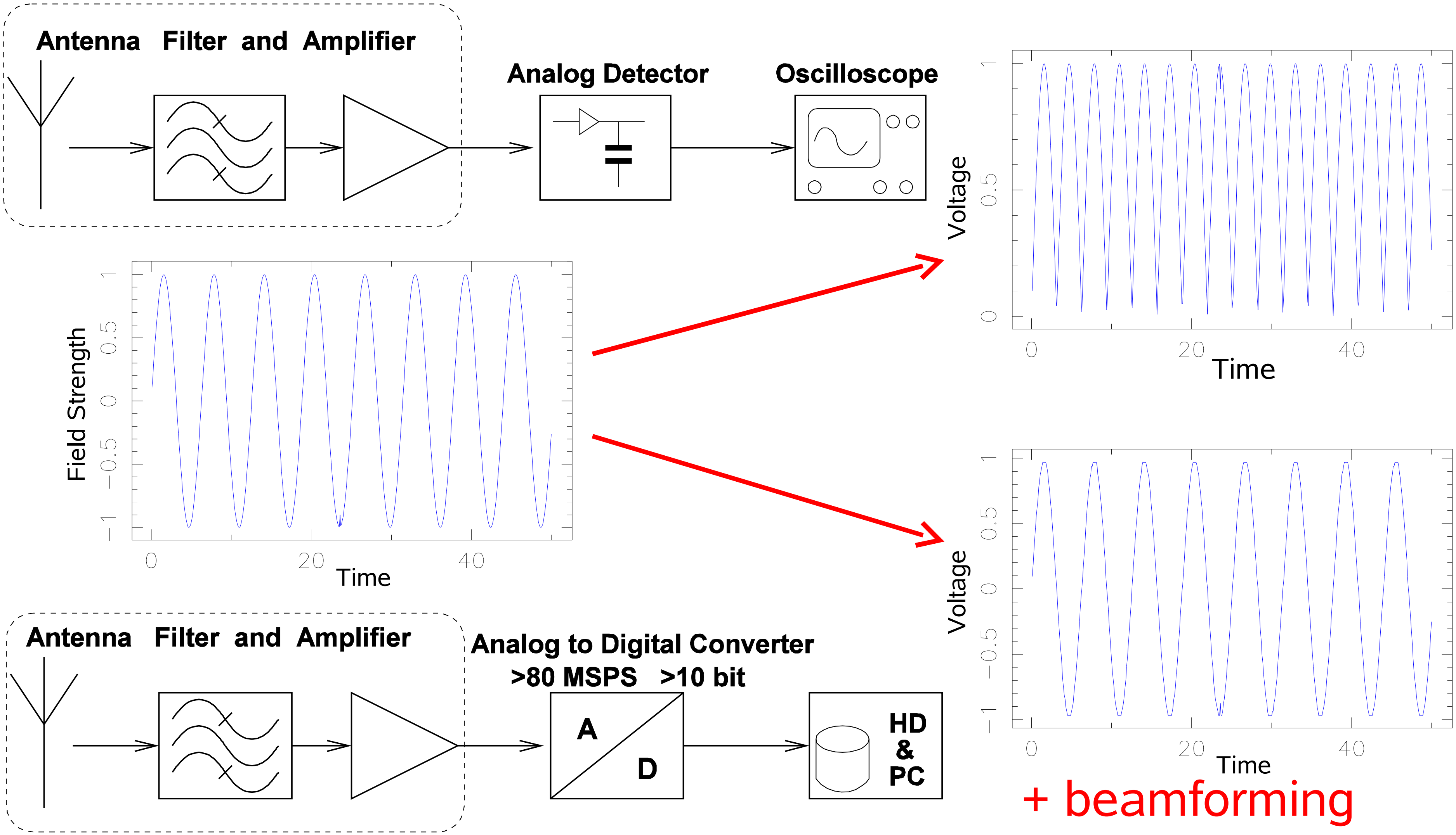

Analog vs. Digital Receiver

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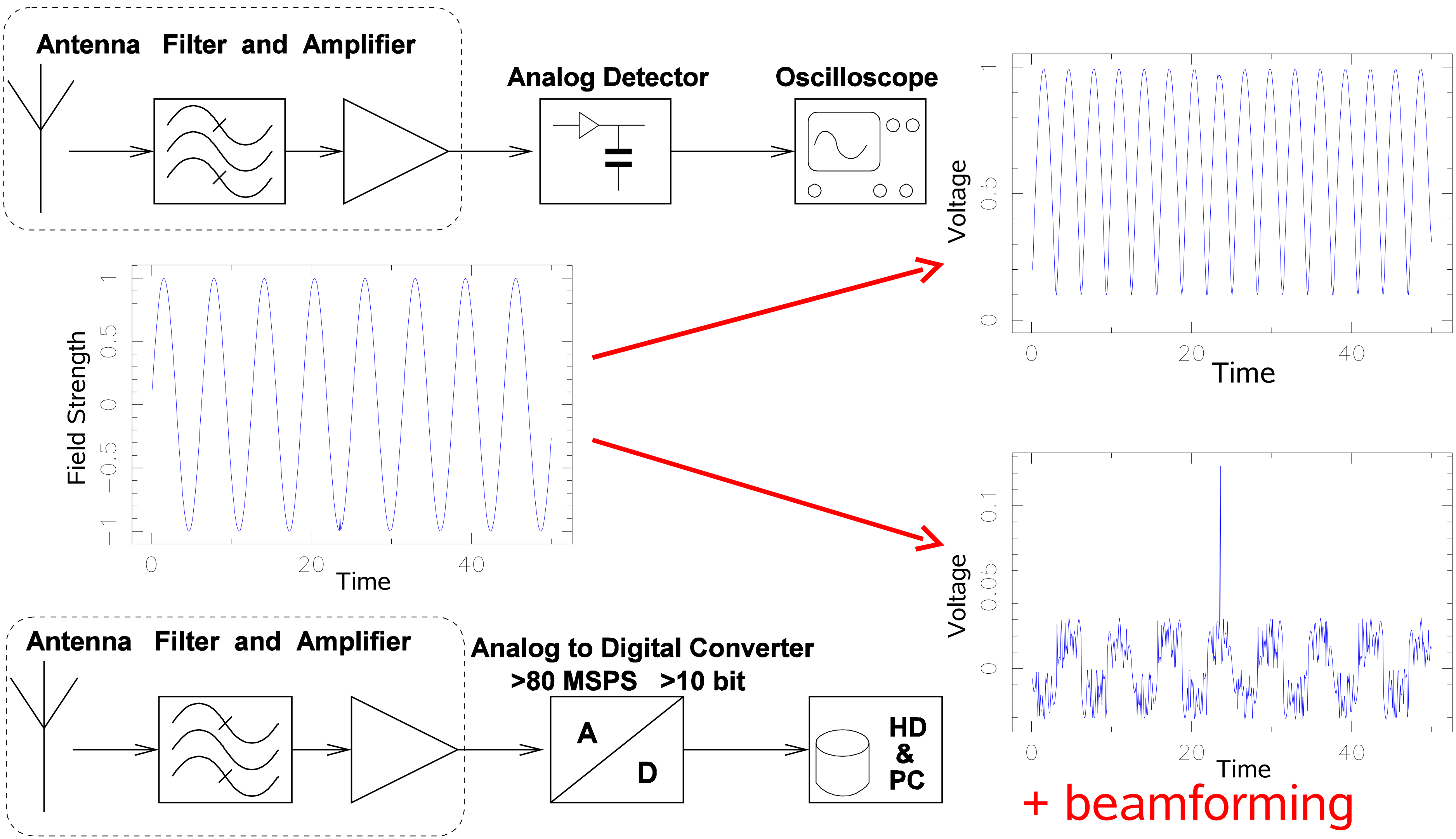

LOFAR

A new kind of Radio Telescope

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- digital radio interferometer for the frequency range of 10 - 270 MHz
- array of 36+ Dutch and 8+ international stations of 48 to 96 simple antennas
- fully digital: received waves are digitized and sent to a central computer cluster
  - digital radio interference suppression
  - ability to store the complete radio data for a short amount of time
  - this allows to form beams after a transient event has been detected, combining the advantages of low gain and high gain antennas

KASCADE-Grande

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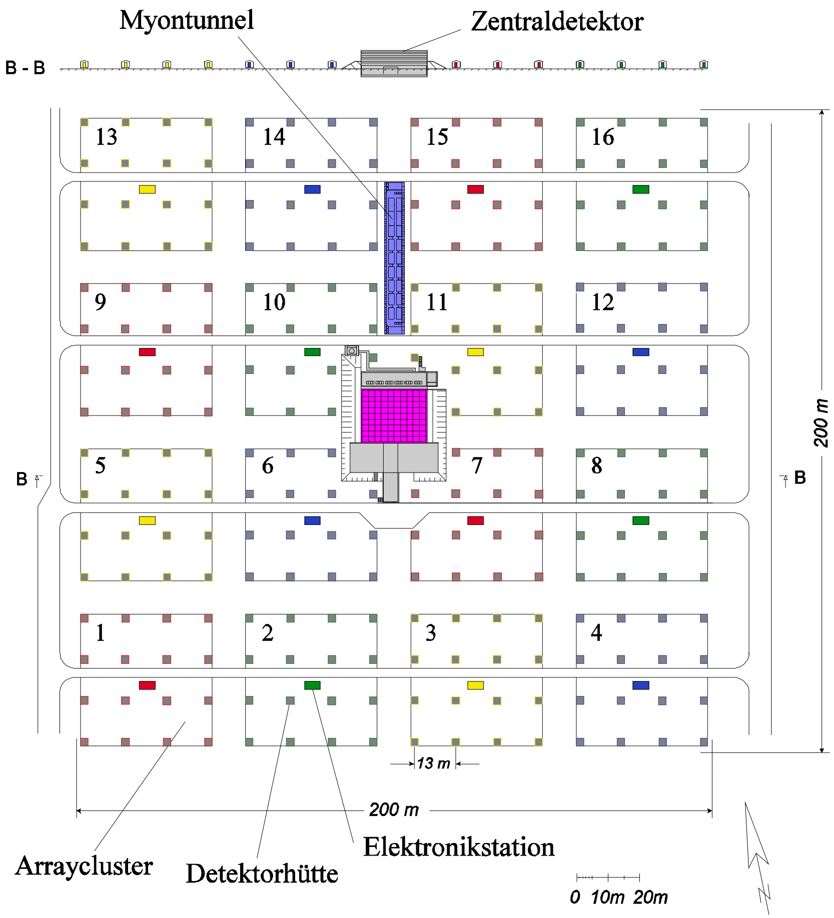
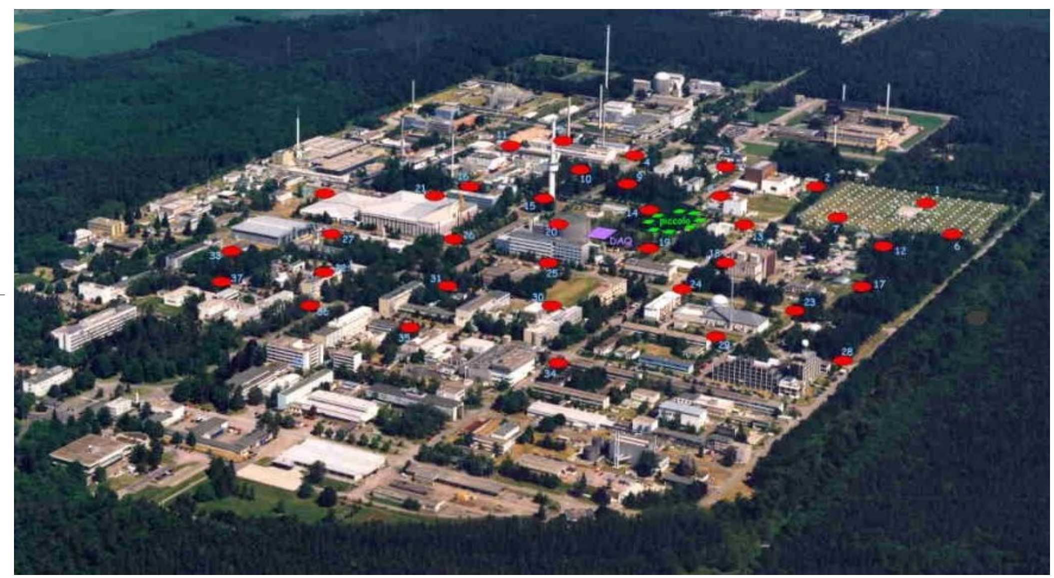


example of an air shower experiment with ground based particle detectors



LOPES

(**LO**FAR **P**rototyp**e** **S**tation)

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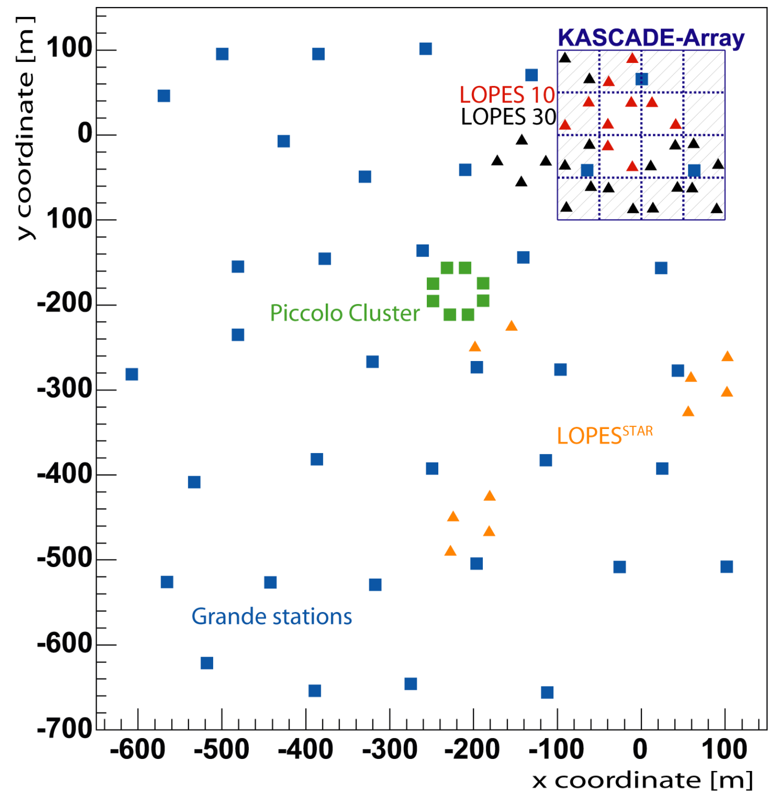
- set up at and working together with KASCADE-Grande
- frequency range of 40 – 80 MHz
- Triggered by KASCADE or Grande large event trigger
  - 10 antennas in the first phase
  - 30 antennas in second phase
  - reconfigured for dual-polarization
- plus LOPES^{STAR} antennas



- Goals:
  - develop techniques to measure the radio emission from air showers
  - determine the radiation mechanism of air showers
  - measure the properties of the radio emission from air showers
  - calibrate the radio data with theoretical and experimental values from an existing air shower array

Hardware of LOPES

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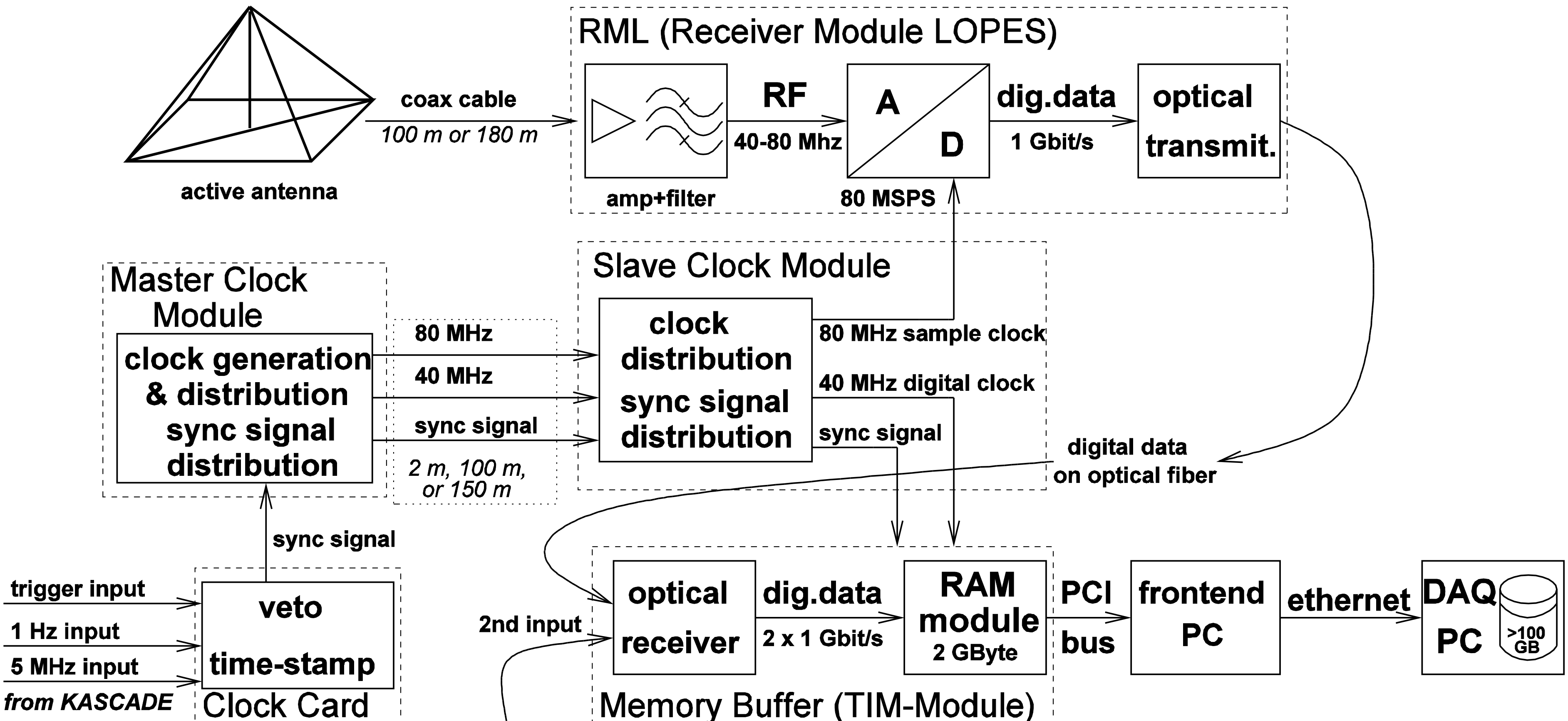

Hardware of LOPES

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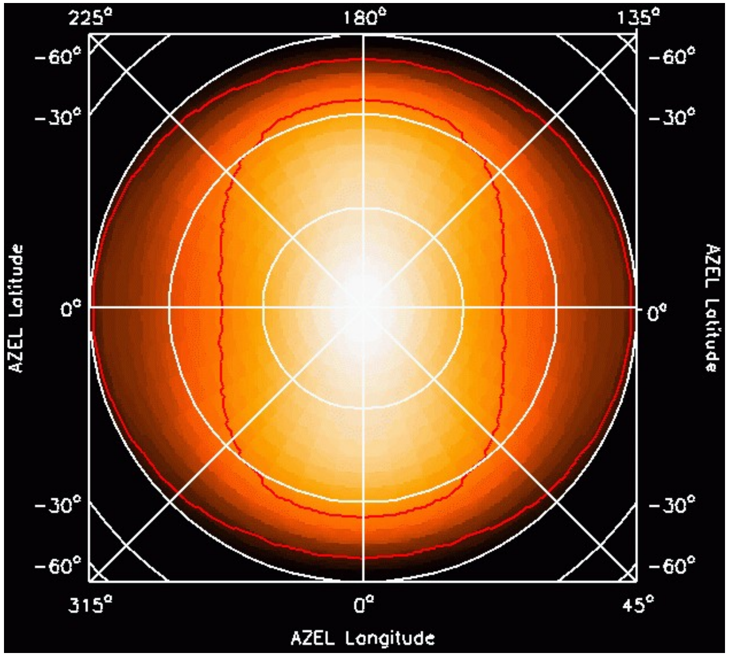
LOPES-Antenna

- short dipole with “inverted vee shape”
- beamwidth 85°-130° (parallel/ perpendicular to dipole)



Hardware of LOPES

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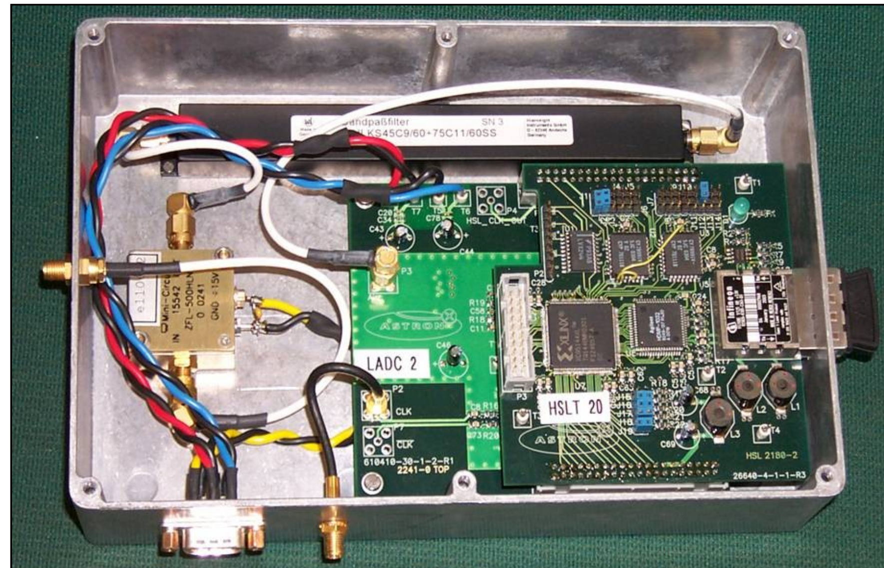
Receiver Module

- direct sampling of the radio signal with minimal analog parts: amplifier, filter, AD-converter
- sampling in the 2nd Nyquist domain of the AD-converter



Hardware of LOPES

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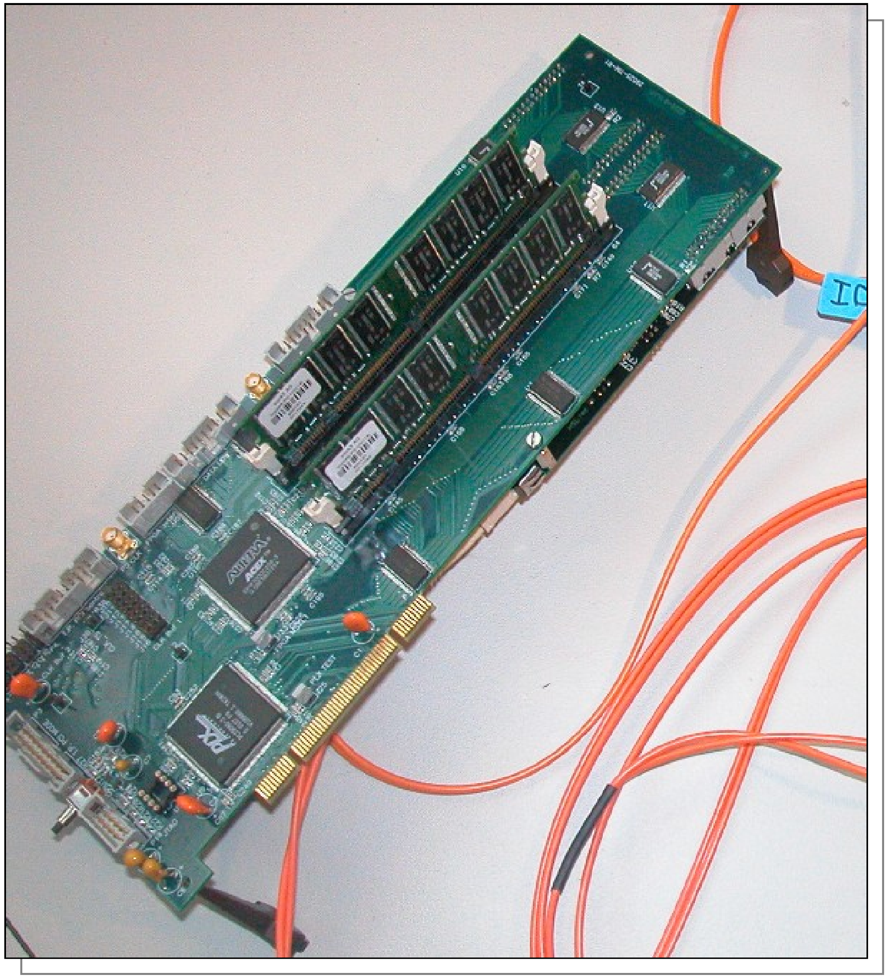
Memory Buffer aka. TIM-Module

(Twin Input Module)

- uses PC133-type memory
- memory for up to 6.1 seconds per channel
- pre- and post-trigger capability



Hardware of LOPES

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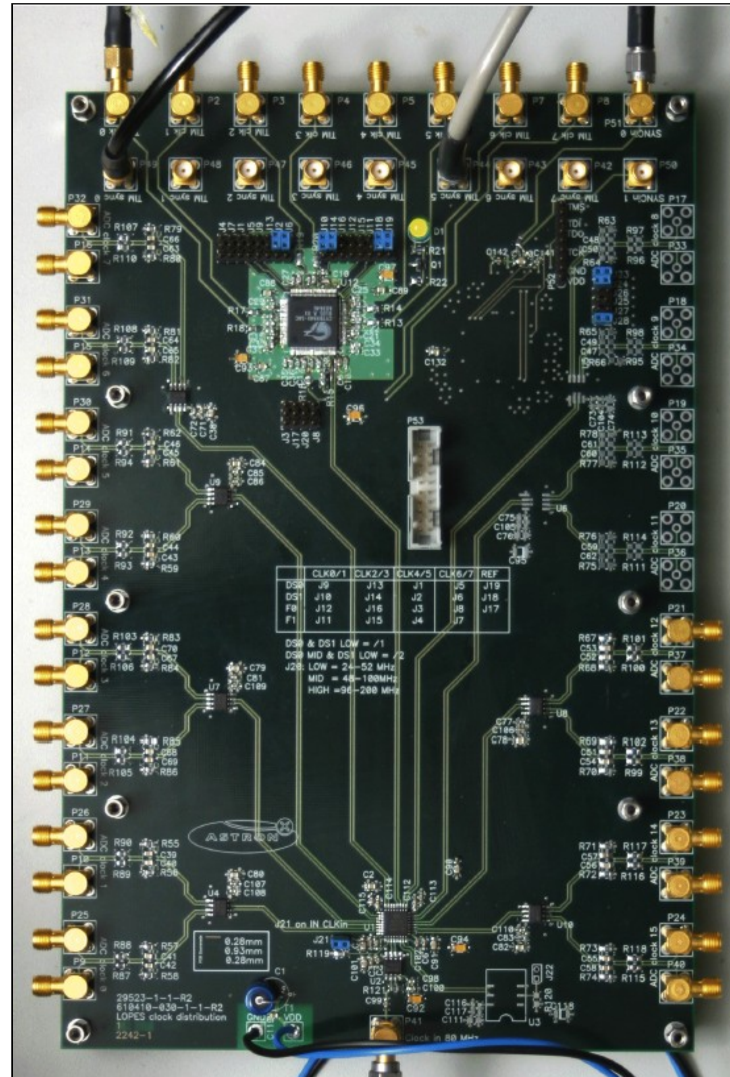
Clock & Trigger distribution board

- 1 master & 3 slave boards
- master board generates clock and accepts trigger
- slave boards distribute clocks and trigger



Data Processing

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- steps of the data processing:
  1. instrumental delay correction from TV-phases
  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. 3D direction fitting
  8. quantification of peak parameters
  9. event discrimination

Delay correction

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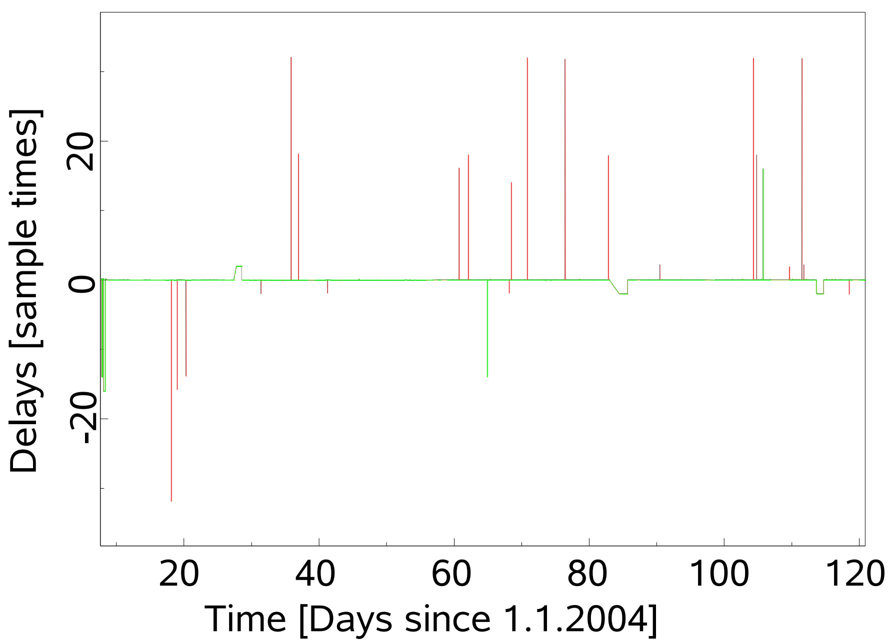
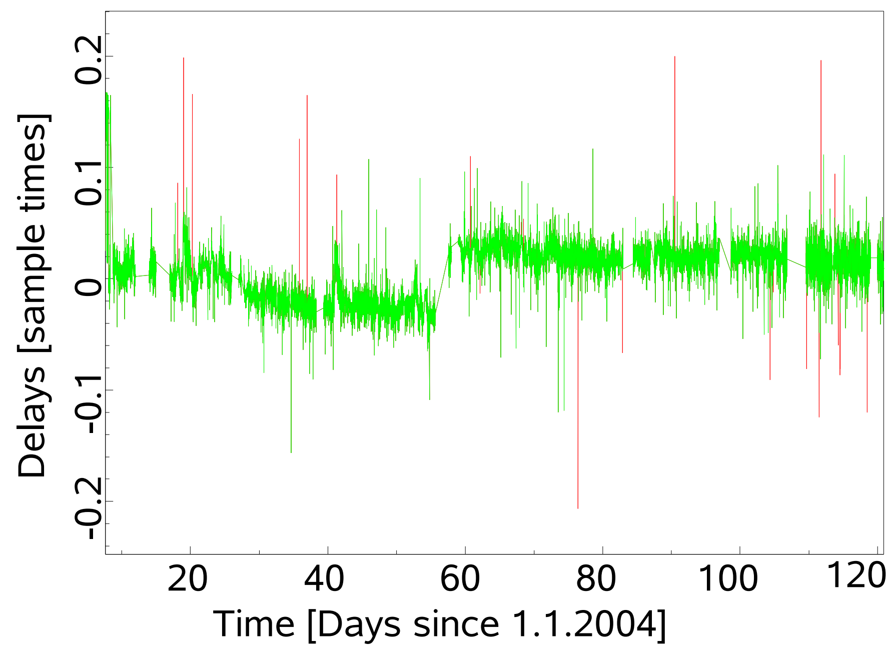
- TV-transmitter with picture- and two sound carriers
- relative phases between antennas lets us correct for delay errors

delay corrections



residual delays



Digital Filtering

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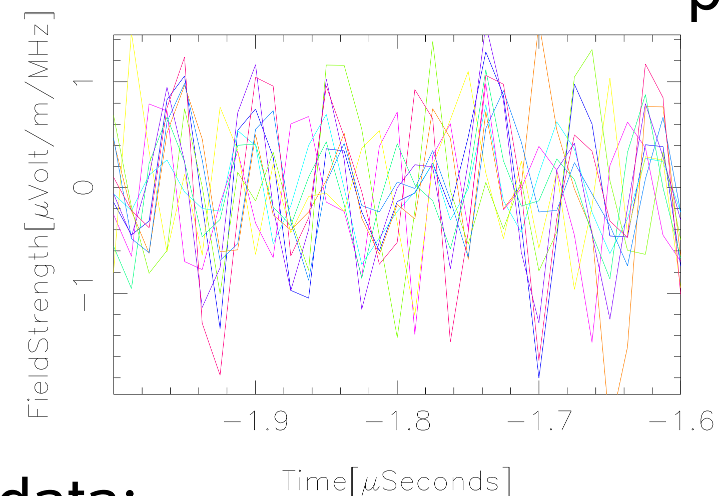
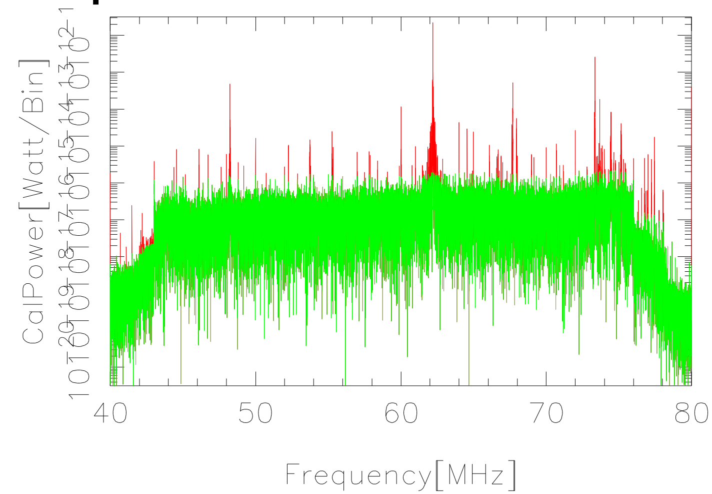
raw data:

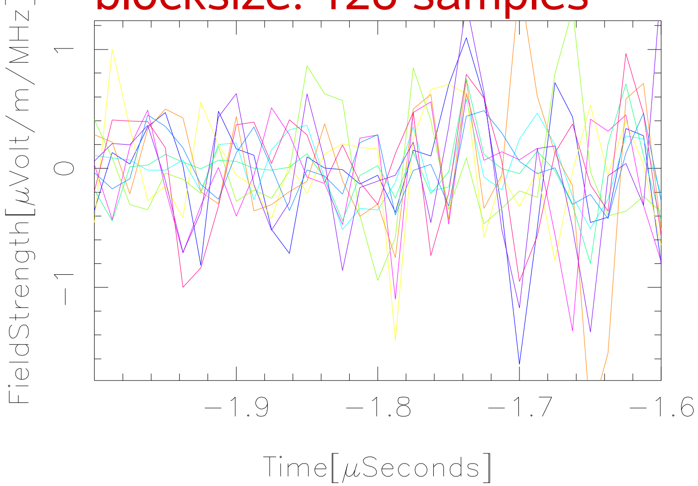


power spectrum:

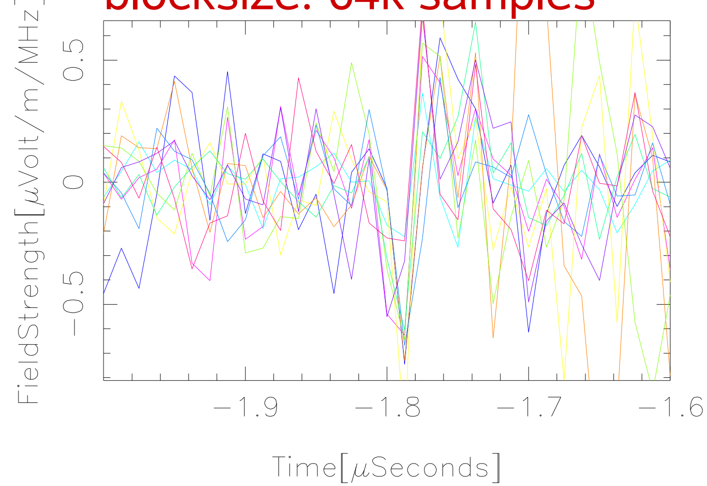


filtered data:

blocksize: 128 samples



blocksize: 64k samples



Digital Filtering

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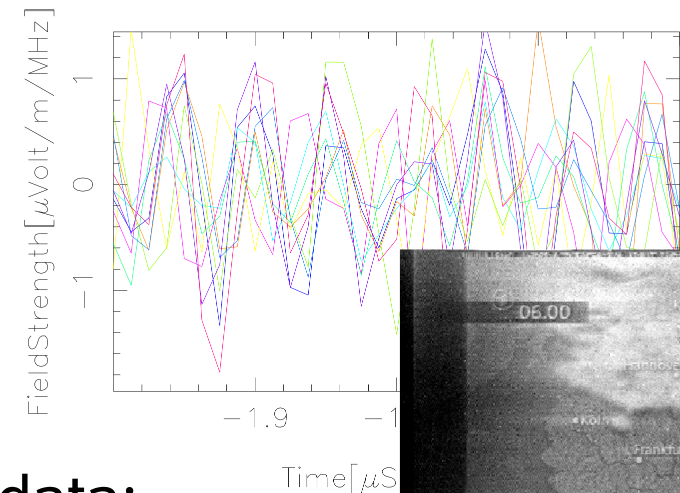
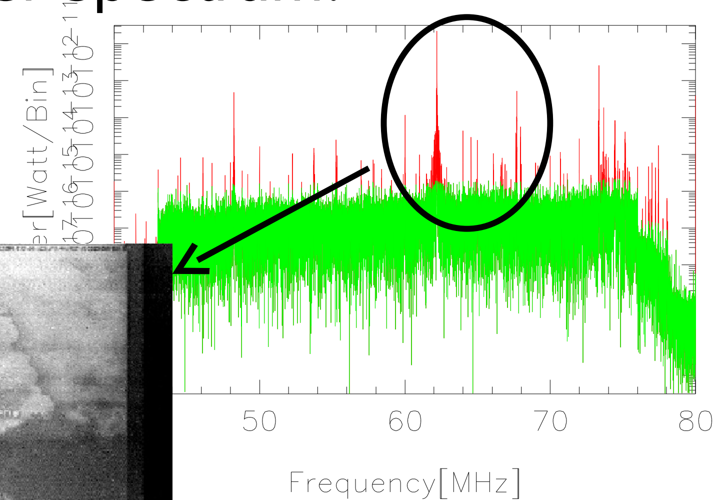
raw data:



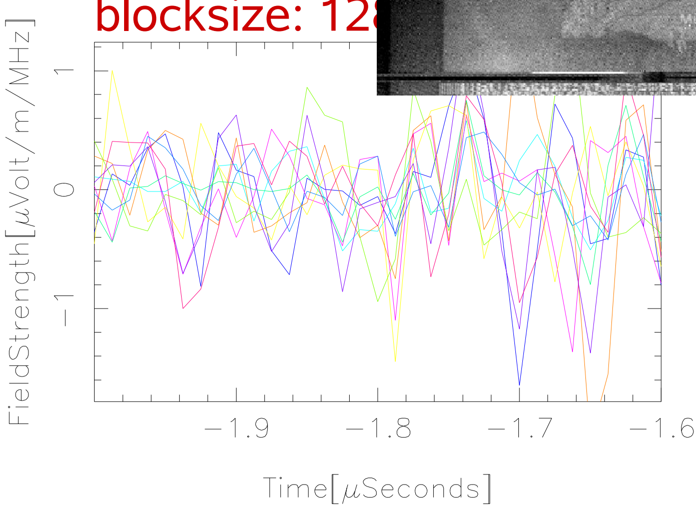
power spectrum:

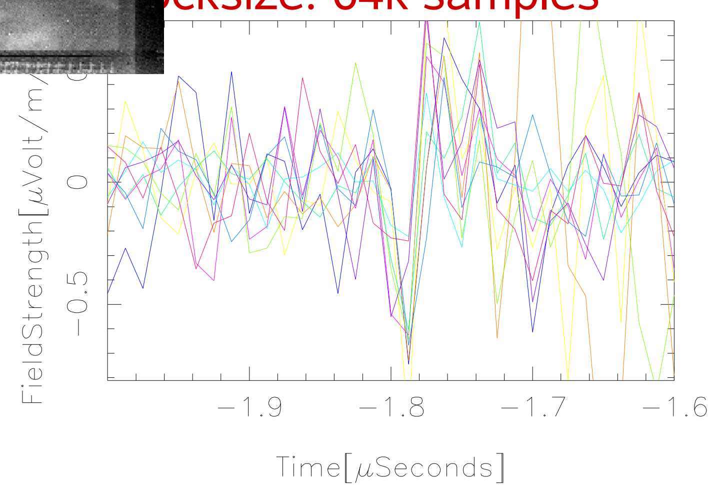


filtered data:

blocksize: 12

ocksize: 64k samples





Gain Calibration

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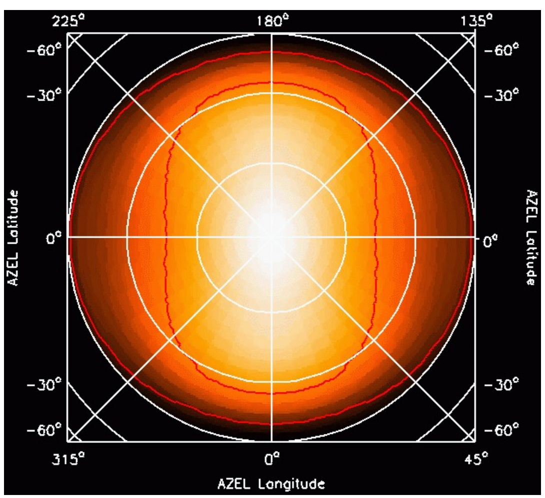
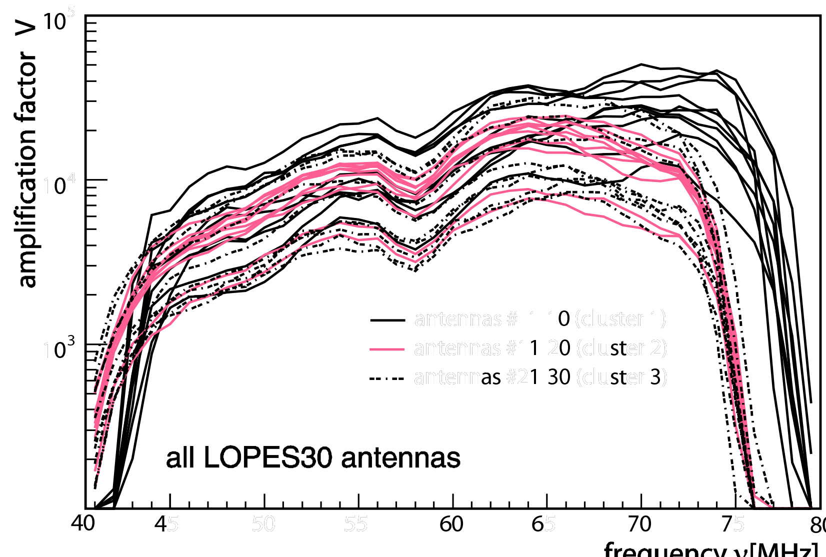
- Antenna gain from simulations
- Electronic Gain from measurements with reference source
  - Also mitigates errors of the antenna simulations

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





Beamforming Step 1

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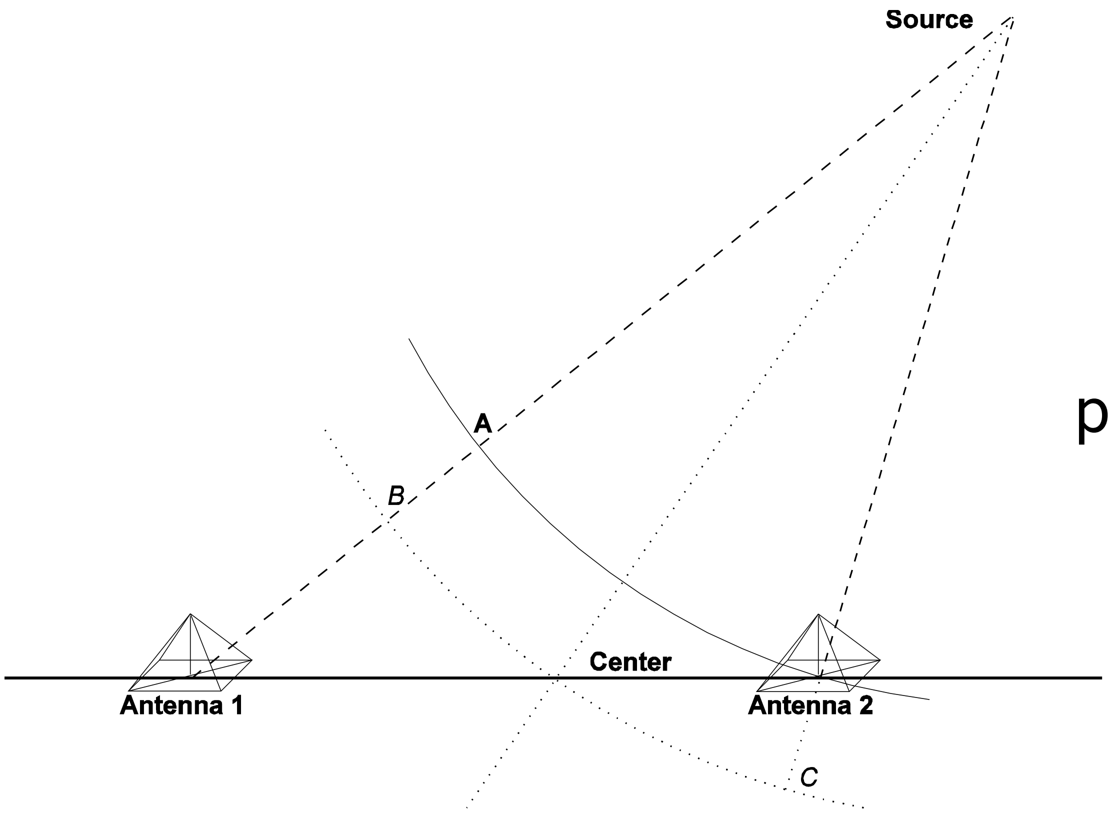
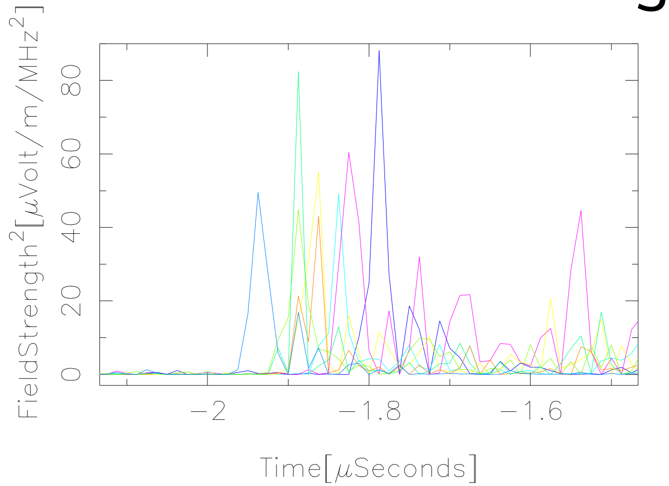
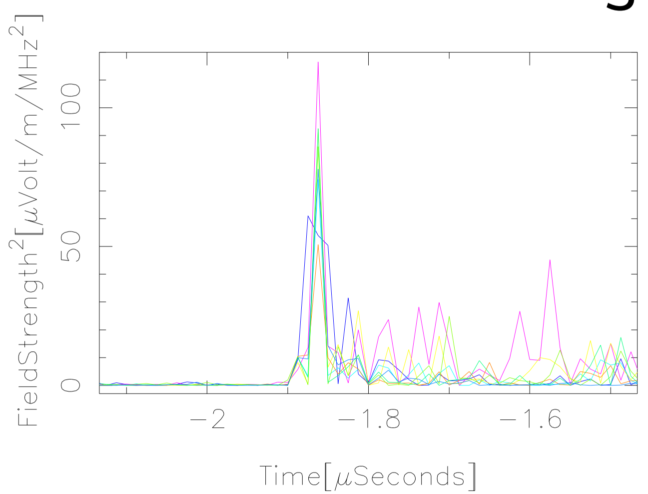
- shift data in time to compensate for arrival delay



power before time shifting



power after time shifting



Beam Forming Step 2

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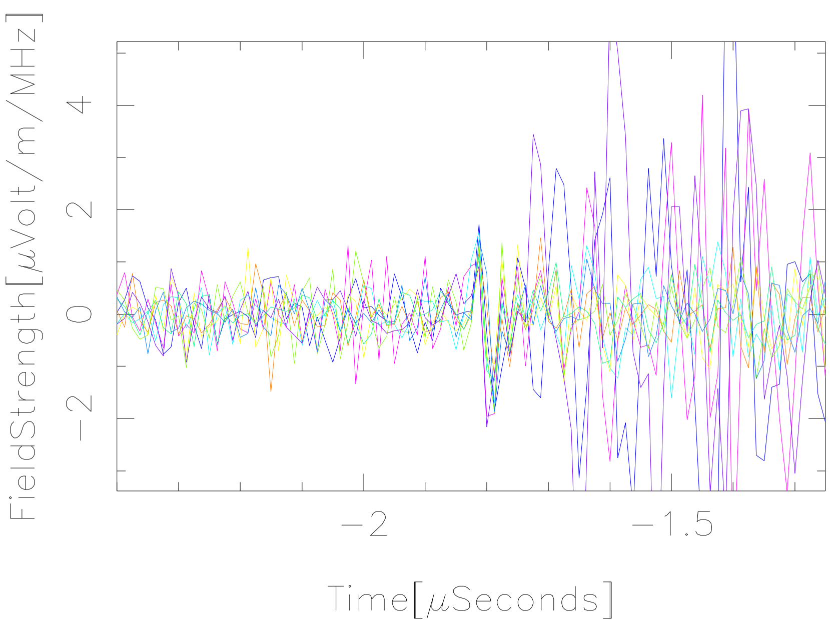
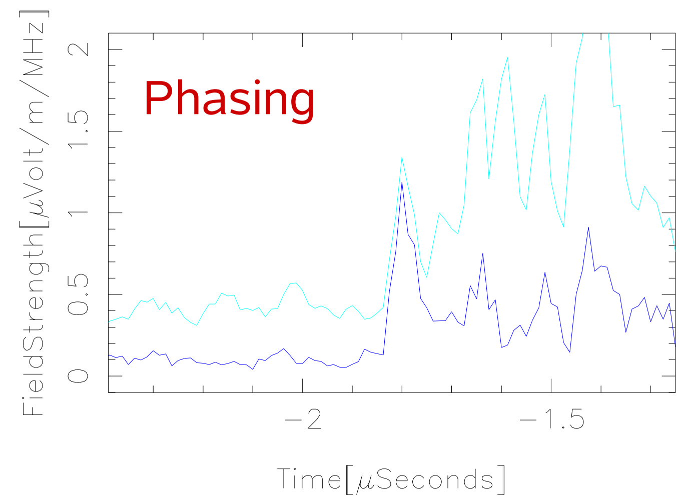
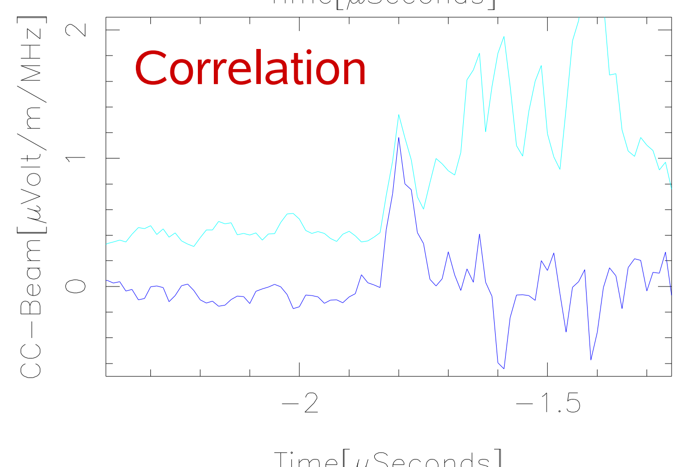
- filtered and time shifted data from single antennas
- beamformed data after correlation of all antennas
  - air shower pulse at -1.8µs
  - particle detector noise from -1.75µs to -1.3µs
  - Phasing ↔ Correlation







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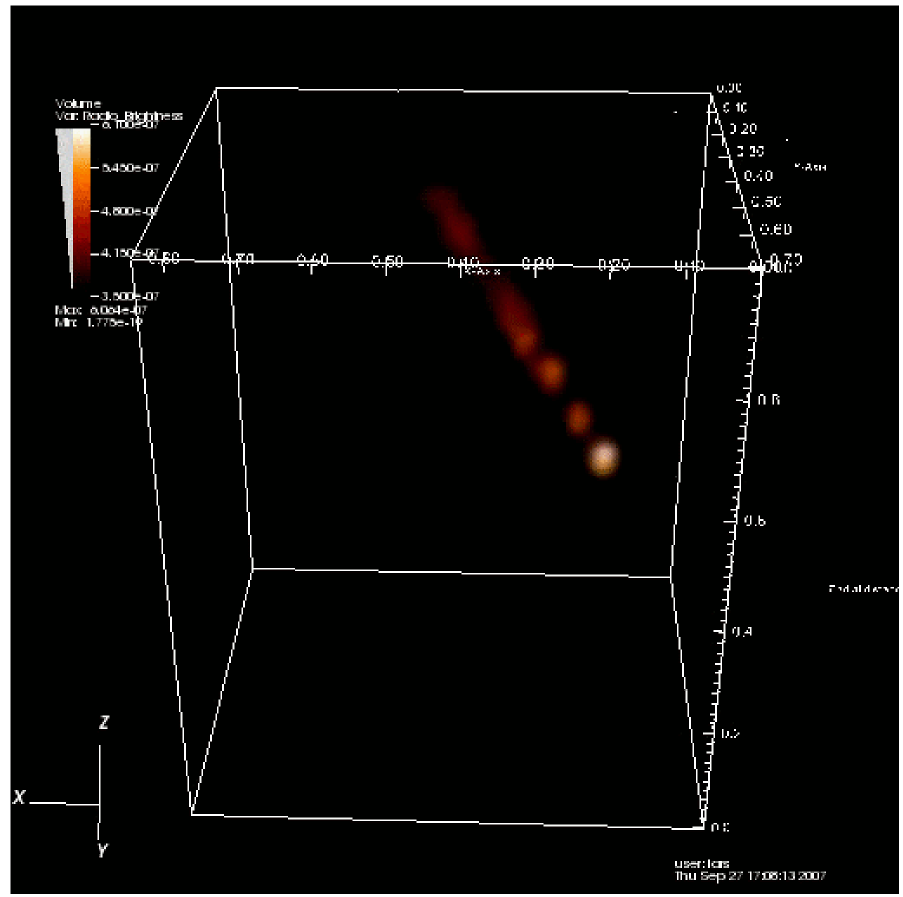
3d-Position Fitting

- find maximum pulse height in 3d space (azimuth, elevation, radius):
    1. starting point from KASCADE
    2. maximum on a small grid
    3. uphill-simplex algorithm



Example Event

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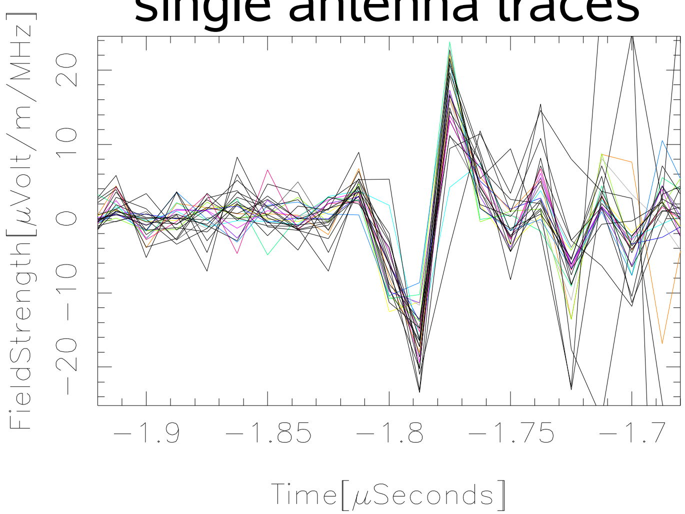
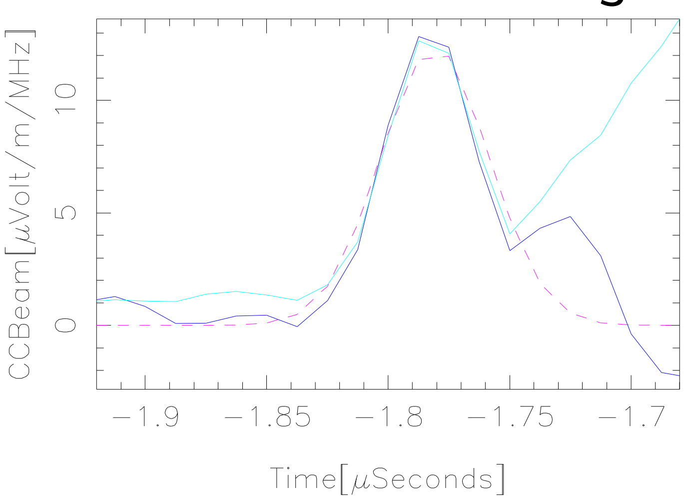
single antenna traces

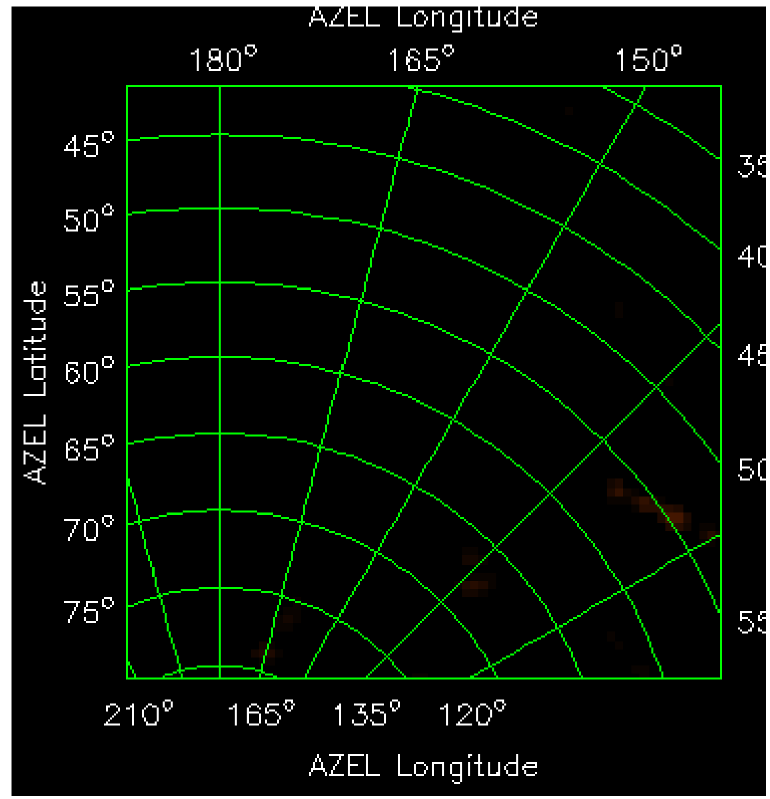


after beam-forming



animated skymap

- time resolution: 12.5 ns
- no cleaning → side lobes



Radio Pulse Height Parametrisation

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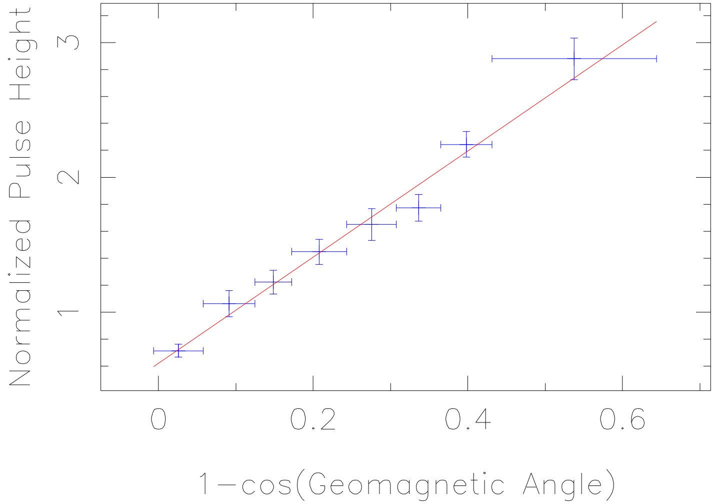
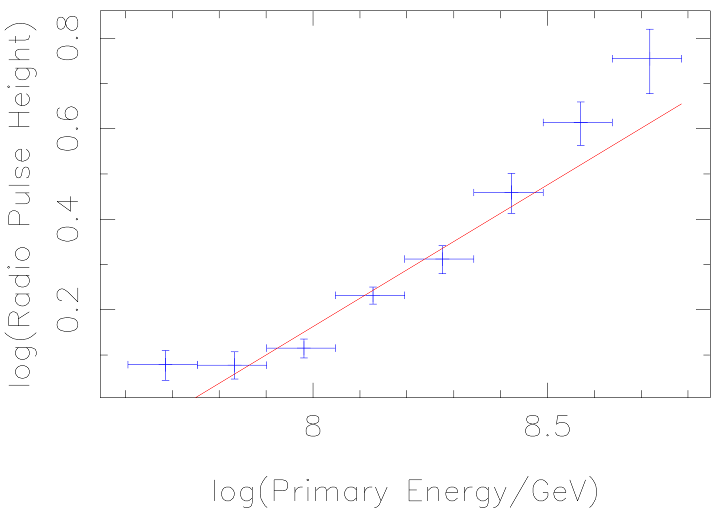


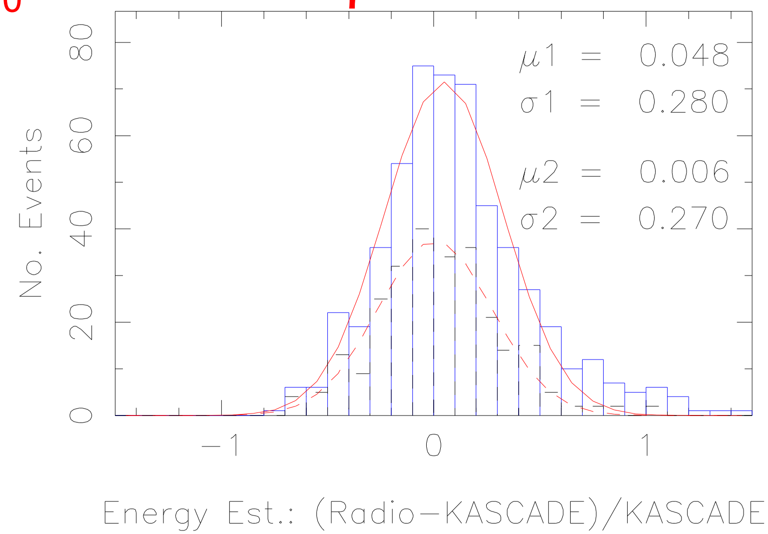
comparison with KASCADE data leads to parameterization formula:

$$\varepsilon_{EW} = A \cdot (B - \cos(\alpha)) \cdot \cos(\theta) \cdot \exp(R/R_0) \cdot (E/10^{17}\,\mathrm{eV})^{\gamma}\ [\mu\mathrm{V/m\ MHz}]$$

With: $A = 11 \pm 1$ $B = 1.16 \pm 0.025$

$R_0 = 236 \pm 81$ $\gamma = 0.95 \pm 0.04$





Horneffer et al. (LOPES coll.) ICRC(2007) Merida

Preparing the Future

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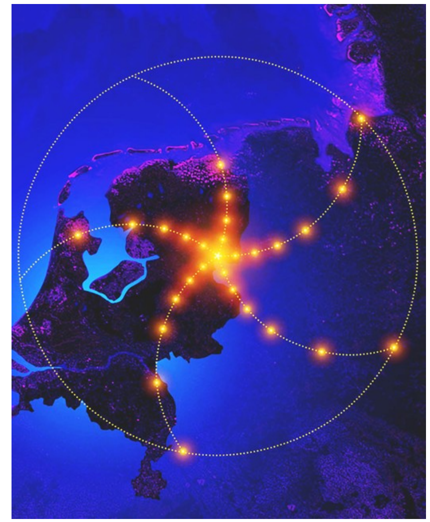
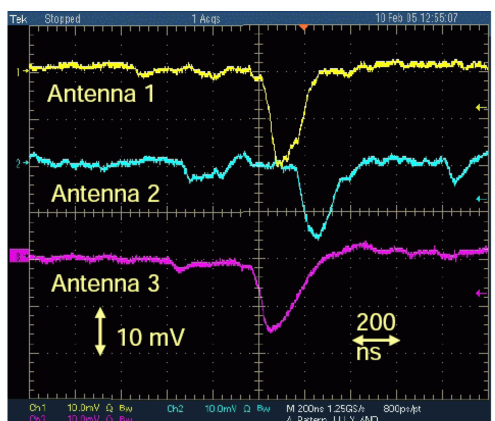
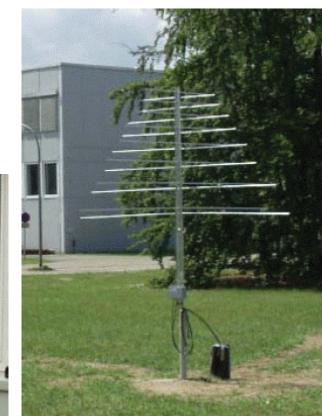
- LOFAR:
  - high sensitivity
  - excellent calibration
  - multi level radio trigger



- Radio@Auger
  - autonomous antennas
  - self triggering





- Simulations!!!

Summary

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- cosmic ray air showers emit short radio pulses
  - have been measured in the 1960ies and 1970ies
- with fast ADCs and fast computers one can store and process the whole waveform information
  - digital RFI suppression, e.g., by flagging in Fourier space
  - beam forming suppresses incoherent noise and noise form other directions
- LOPES was the first experiment to detect air shower radio pulses with this technology

LOPES Collaboration

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