



Max-Planck-Institut  
für  
Radioastronomie

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# Detection of Radio Pulses from Air Showers with LOPES

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# Radio Emission from Air Showers

- air showers are known since 1965 to emit radio pulses
- summary by Allen in 1971 led to the following formula:

$$\epsilon_{\nu} = 20 \left( \frac{E_p}{10^{17} \text{eV}} \right) \sin \alpha \cos \theta \exp \left( \frac{-R}{R_0(\nu, \theta)} \right) \left[ \frac{\mu\text{V}}{\text{mMHz}} \right]$$

With:  $\epsilon_{\nu}$ : received Voltage per unit Bandwidth,  $E_p$ : primary particle energy,  $\alpha$ : angle to the geomagnetic field,  $\theta$ : zenith angle,  $R$ : distance to the shower axis and  $R_0$  ca. 110 m at 55 MHz.

- radiation probably due to geomagnetic emission process
- measuring the radio emission from air showers could give several benefits:
  - higher duty cycle than fluorescence telescopes
  - effective RFI suppression allows measuring in radio loud areas
  - data integrated over the shower evolution, can be complementary to particle detectors



# LOFAR

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- LOFAR is 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
- LOFAR will be a good tool to measure the radio emission from air showers

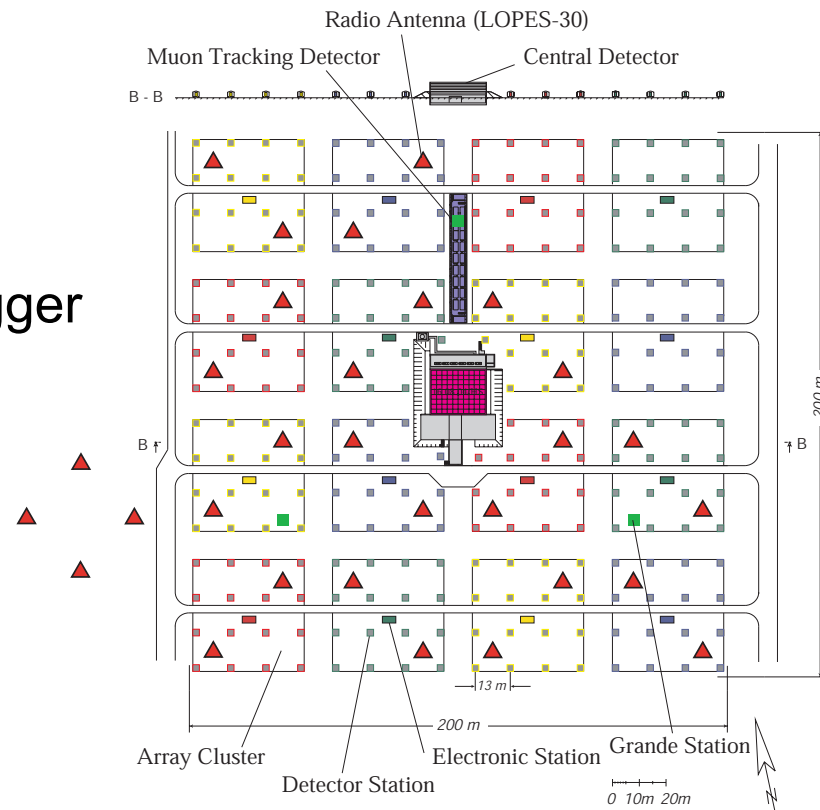




# LOPES

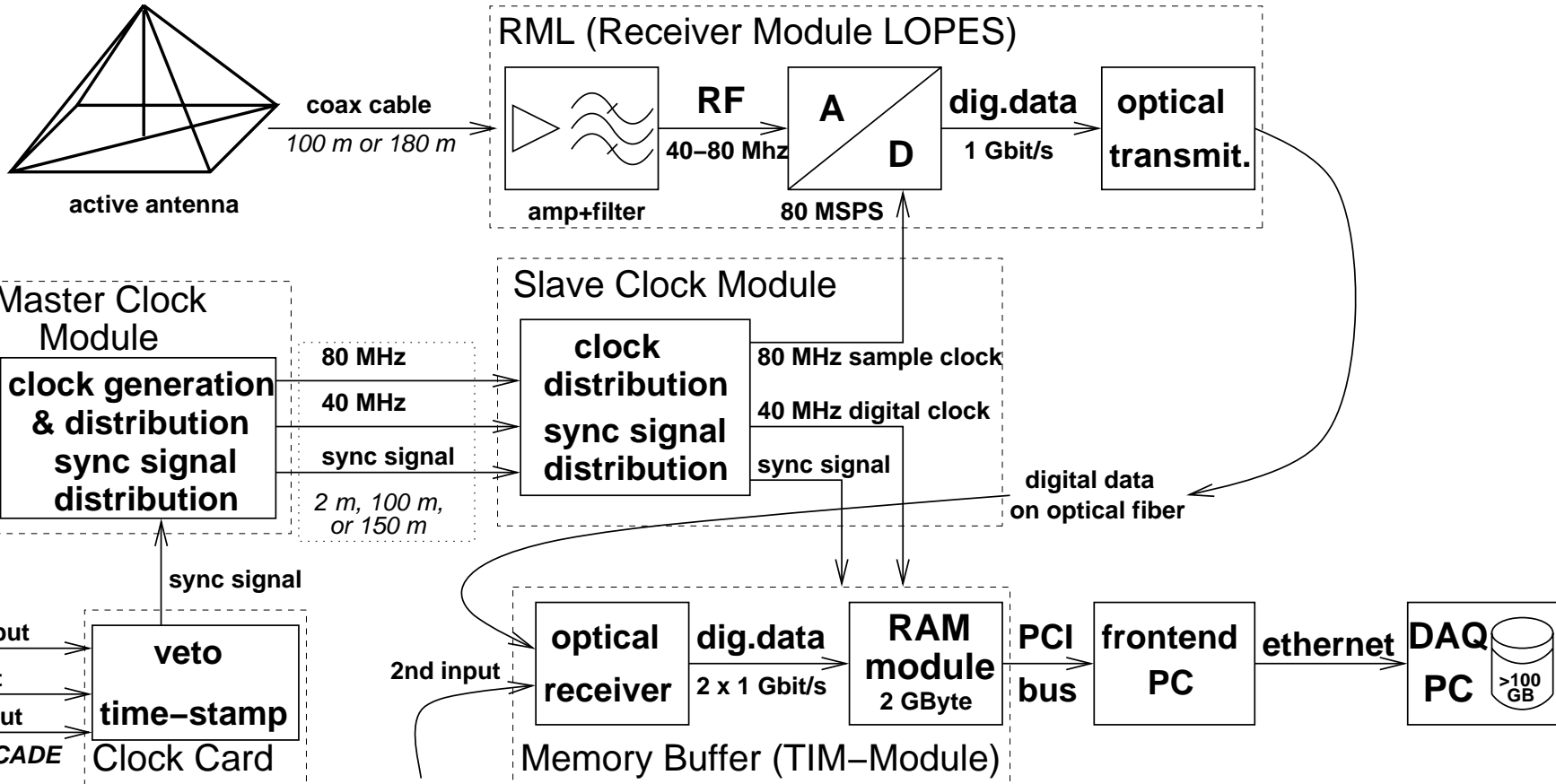
## LOFAR Prototype Station

- Goals:
  - develop techniques to measure the radio emission from air showers
  - determine the radiation mechanism of air showers
  - calibrate the radio data with theoretical and experimental values from an existing air shower array
- frequency range of 40 – 80 MHz
- 30 antennas running at KASCADE  
(10 antennas in first phase: LOPES10)
- triggered by large event (KASCADE) trigger  
(10 out of 16 array clusters)
- KASCADE provides starting points for LOPES air shower reconstruction
  - core position of the air shower
  - direction of the air shower
  - size of the air shower





# Hardware of LOPES





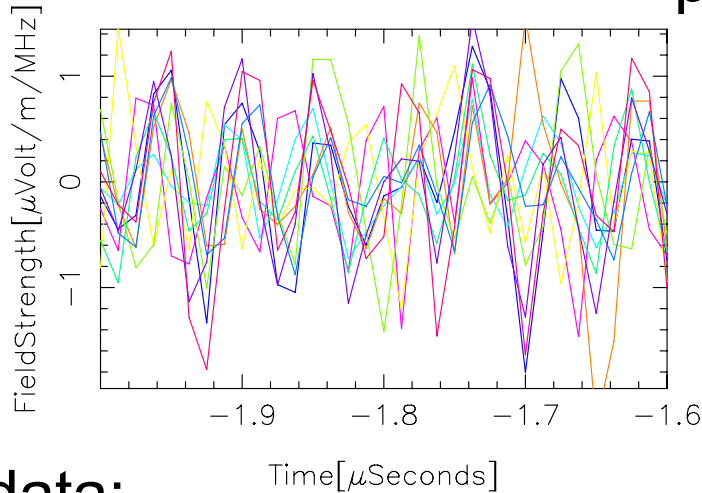
# Data Processing

- steps of the data processing:
  1. instrumental delay correction from TV-phases
  2. frequency dependent gain correction
  3. filtering of narrow band interference
  4. flagging of antennas
  5. correction of trigger & instrumental delay
  6. beam forming in the direction of the air shower
  7. optimizing radius of curvature
  8. quantification of peak parameters

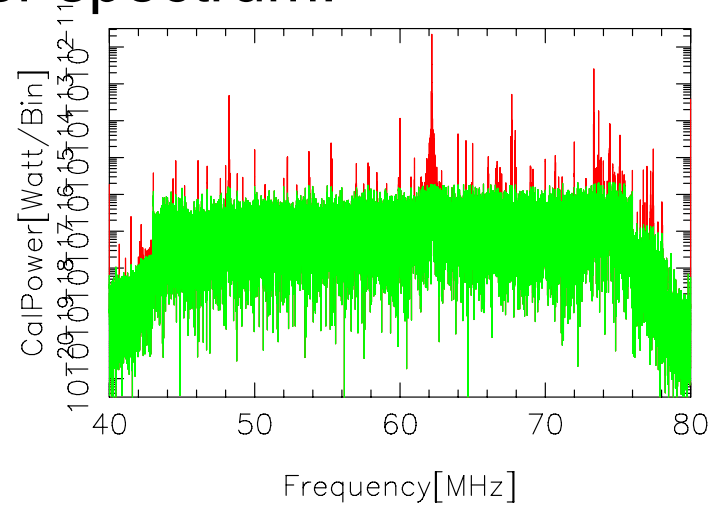


# Digital Filtering

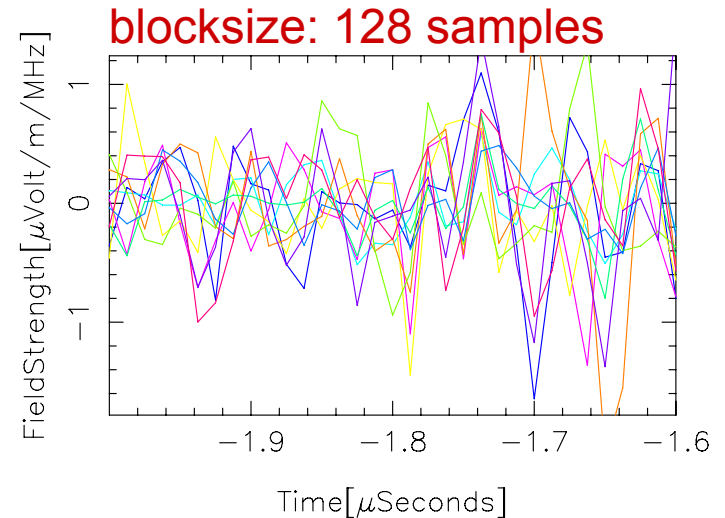
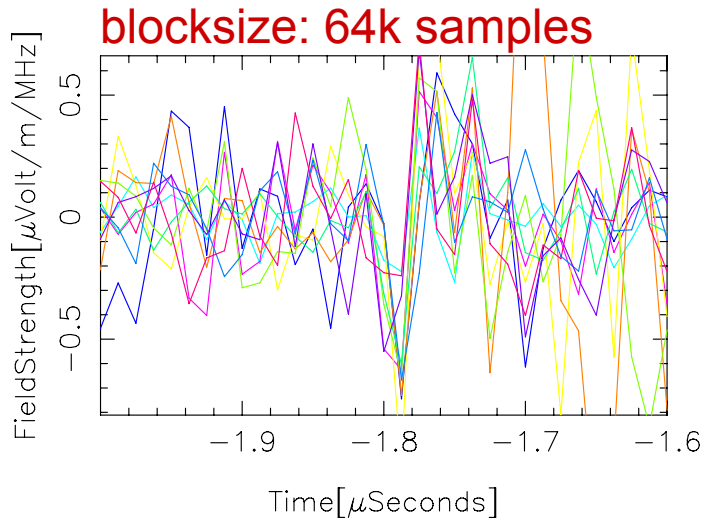
raw data:



power spectrum:



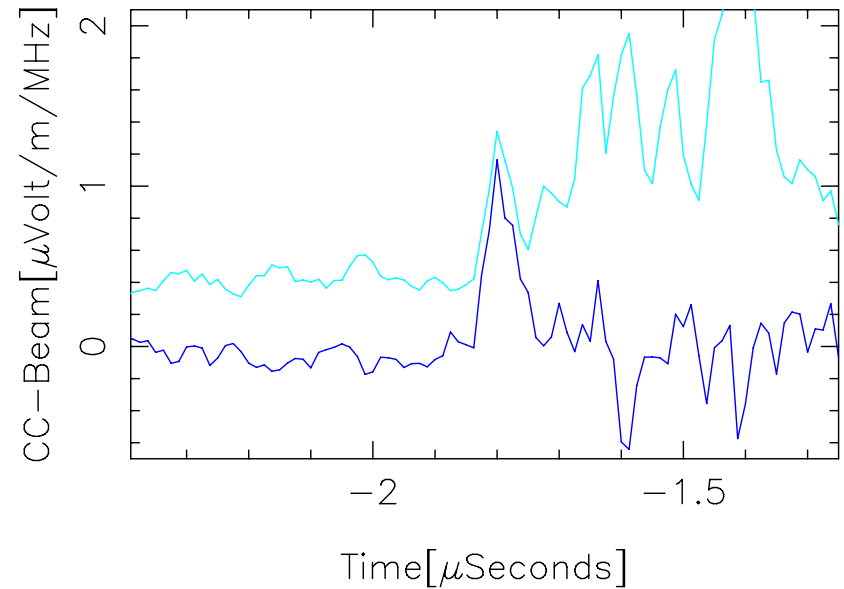
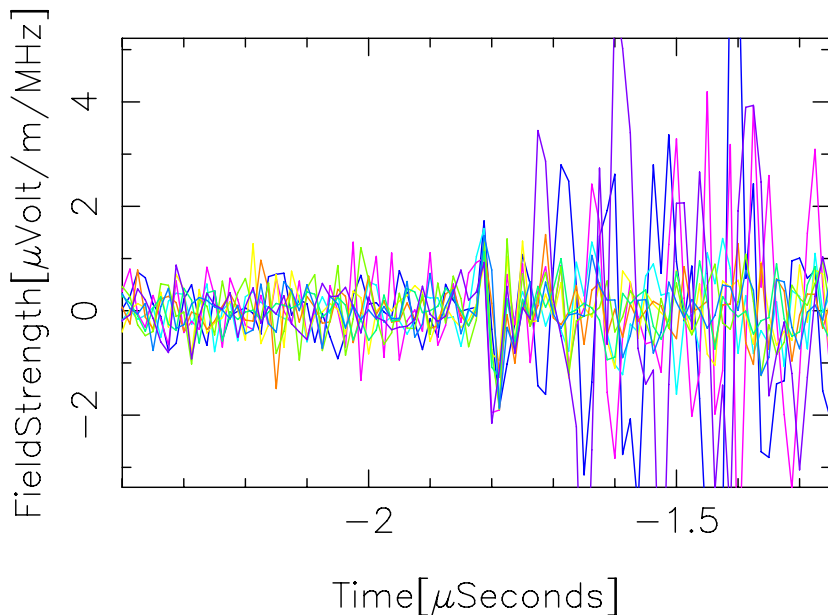
filtered data:





# Beam Forming

- filtered and time shifted data from single antennas
- beamformed data after correlation of all antennas
  - air shower pulse at  $-1.8\mu\text{s}$
  - particle detector noise from  $-1.75\mu\text{s}$  to  $-1.3\mu\text{s}$





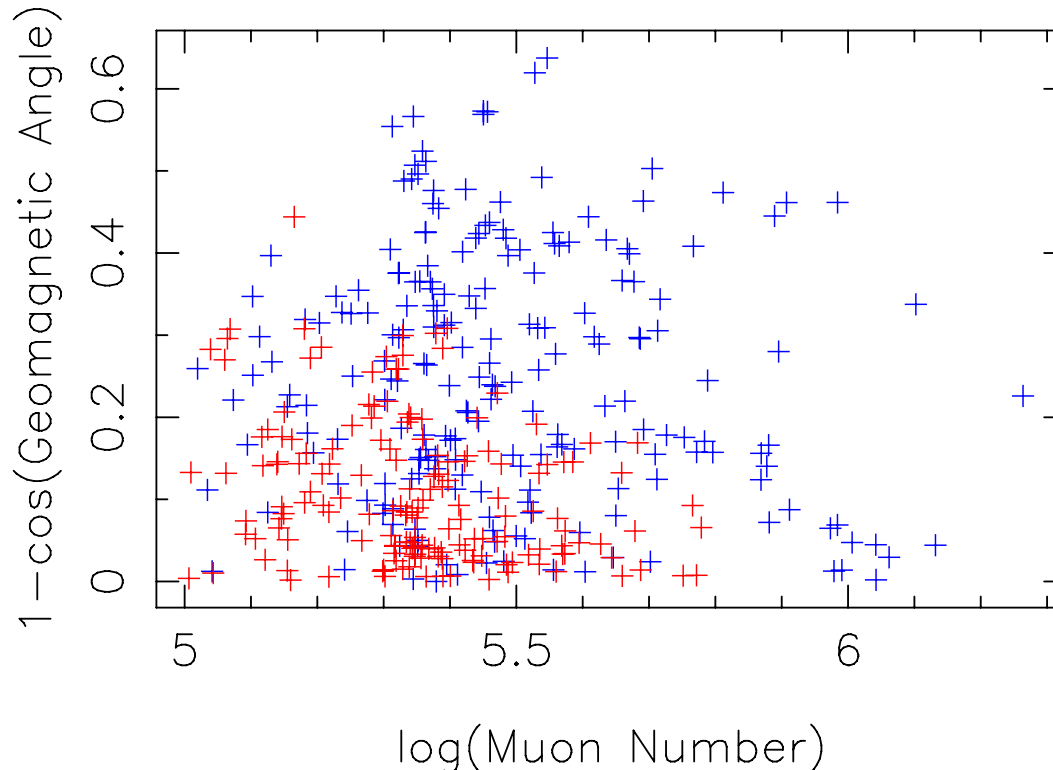
# LOPES10 Data

- LOPES10 ran from January to September 2004
  - 630 thousand events total
- used selection for further study:
  - KASCADE array processor didn't fail
  - distance of the core to the array center  $< 91\text{m}$
  - shower size (number of electrons)  $> 5e6$  **or**  
truncated muon number  $> 2e5$
  - zenith angle  $< 50$  deg
  - $\rightarrow$  375 events



# Detected Events

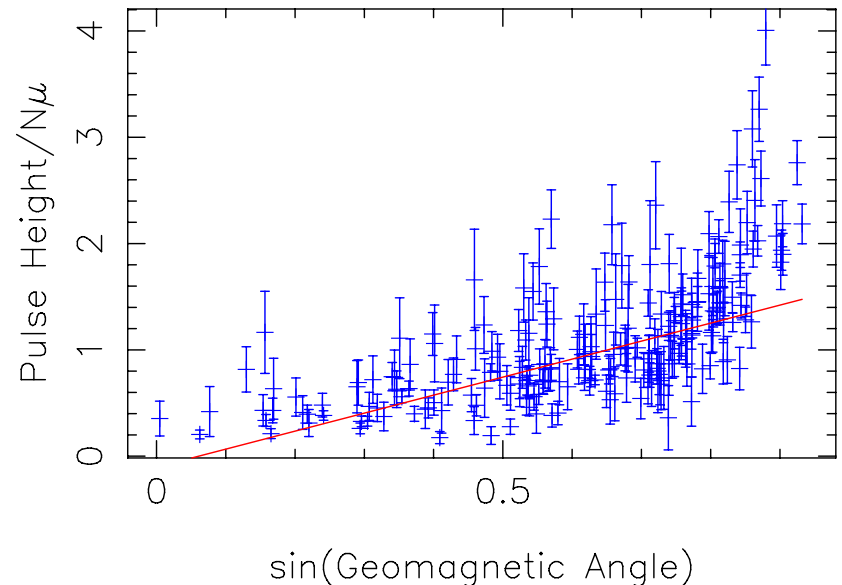
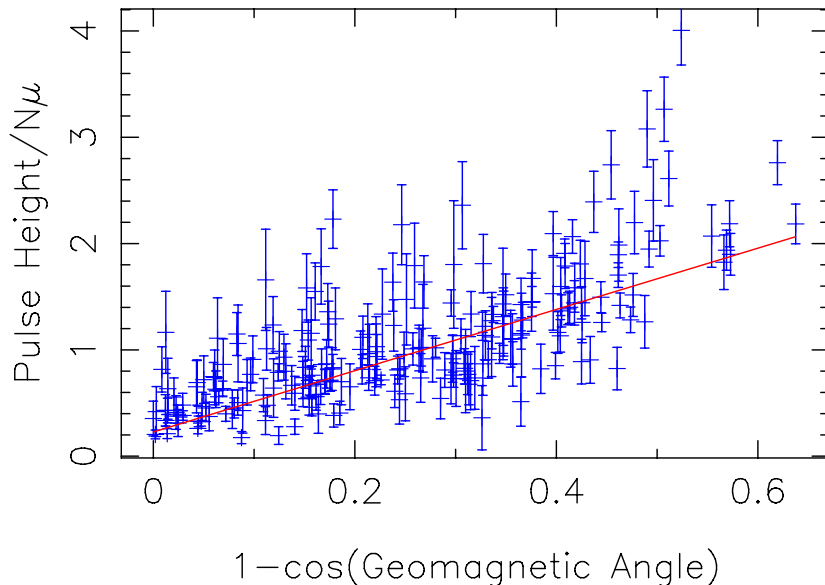
- detected air shower pulse in 213 out of 375 events
- fraction of “good” to “bad” events increases with increasing muon number and increasing geomagnetic angle
- → fraction also increases with zenith angle





# Dependencies: Geomagnetic Angle

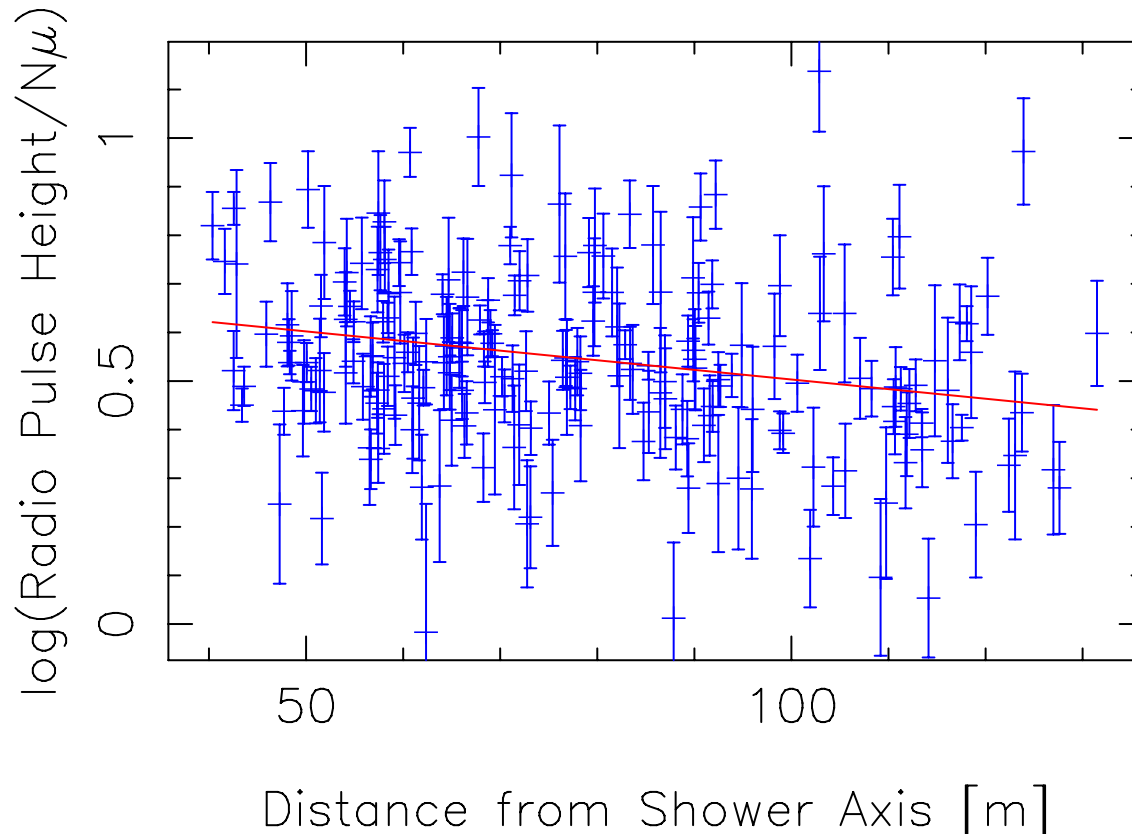
- divided pulse height by muon number
- fit results to the cosine and sine of the angle to the geomagnetic field
- got better fit to cosine than to sine





# Dependencies: Distance to Shower Center

- divided pulse height by muon number and by fit to  $\cos(\text{geomagnetic angle})$
- fit exponential decrease to distance

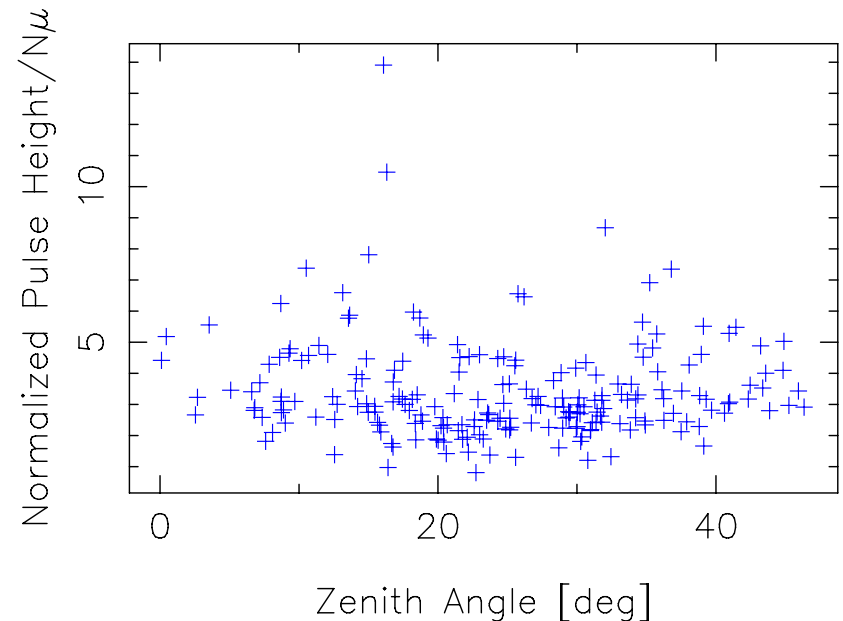
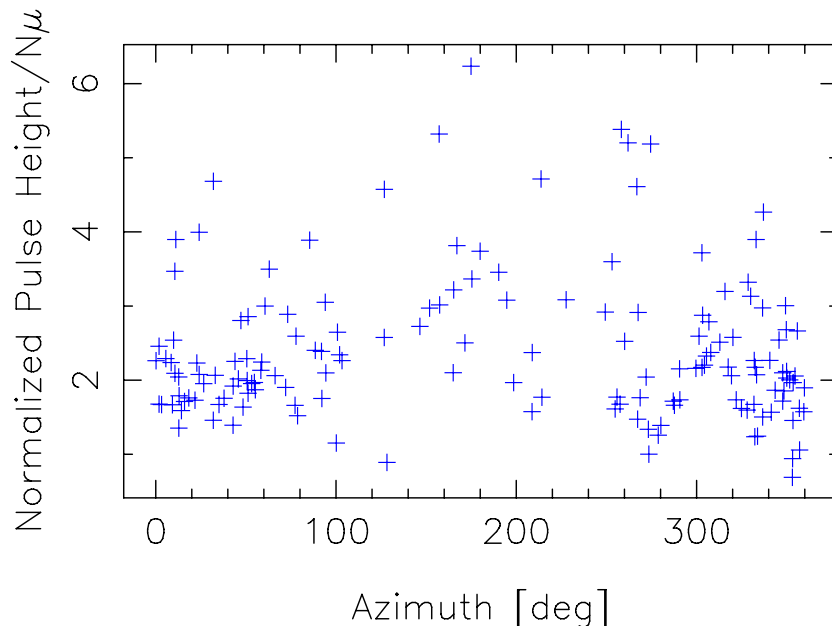




# Dependencies: Azimuth and Zenith Angle

- divided pulse height by the results from previous fits.
- no dependency on azimuth or zenith angle can be seen

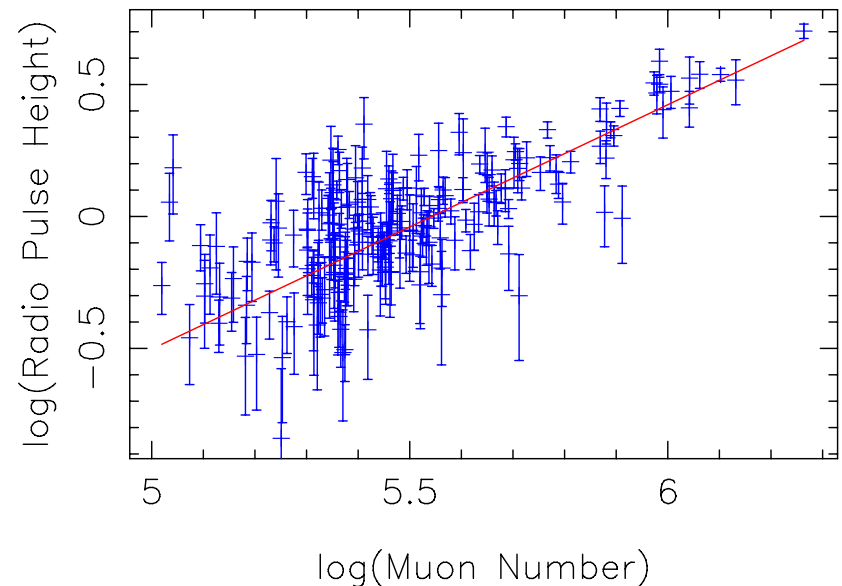
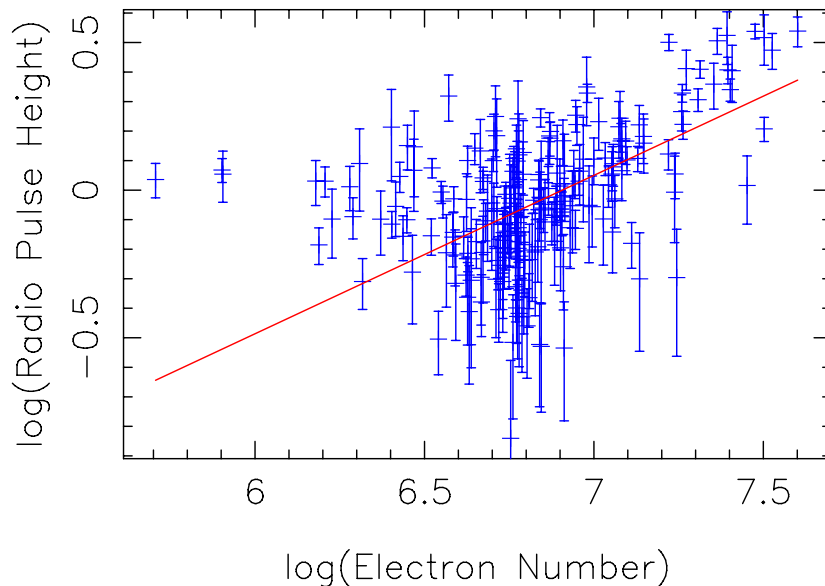
(events with  $ZE > 17$  degree)





# Dependencies: Size, $N_{\mu\text{trunc}}$ and Energy

- divided pulse height by the results from previous fits
- only little dependency on electron number
- power law is a good fit for muon number





# Summary

- LOPES is able to measure radio pulses from air showers
- with digital filtering and beam forming these radio pulses can be measured even in a radio loud environment
- radio pulse height depends on the geomagnetic angle
- radio pulse height correlates well with  $N\mu$  and not so well with  $N_e$
- radio can give useful complementary information
  - additional value for energy and mass determination
  - independent direction measurement
- todo:
  - trigger algorithm for LOFAR
  - polarization measurements
  - detailed comparison to theory