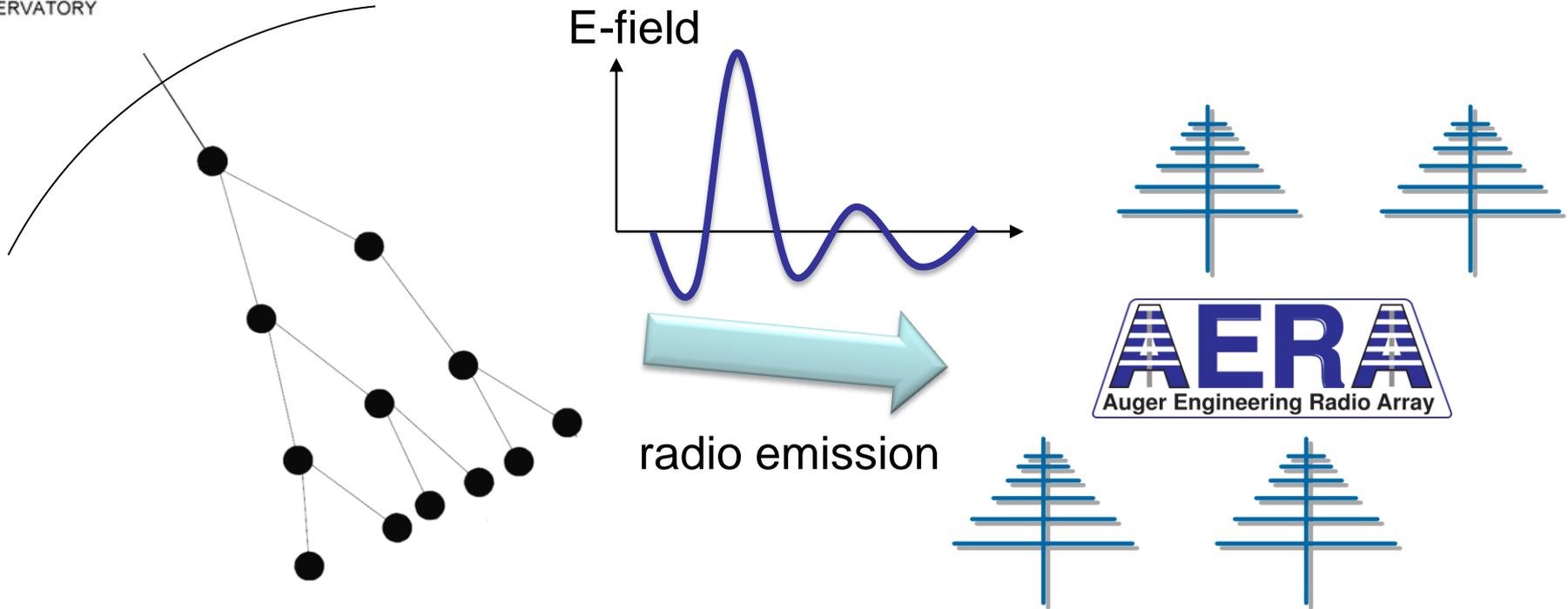




Detection of High Energy Cosmic Rays with the Auger Engineering Radio Array

PIERRE
AUGER
OBSERVATORY



Raphael Krause for the Pierre Auger Collaboration

Vienna Conference on Instrumentation 2016

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Content

■ overview

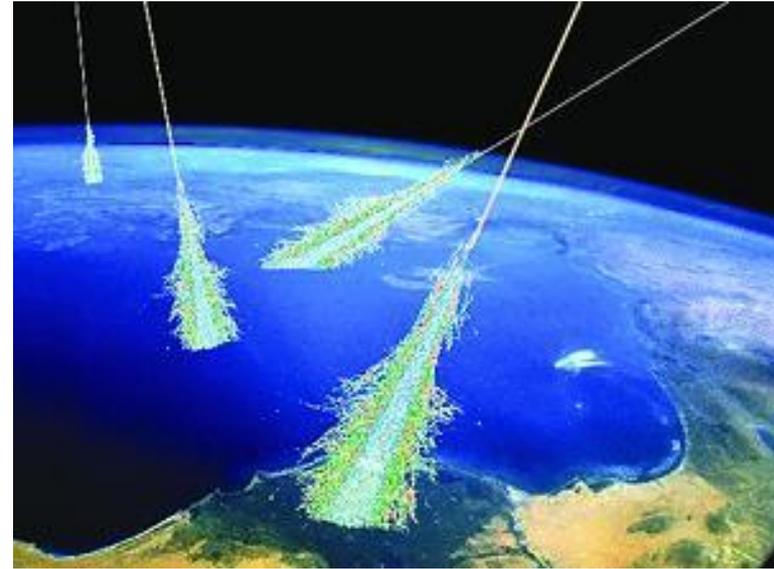
- Pierre Auger Observatory
- Auger Engineering Radio Array
- Radio Stations of AERA

■ AERA calibrations

- antenna response calibration
- time calibration

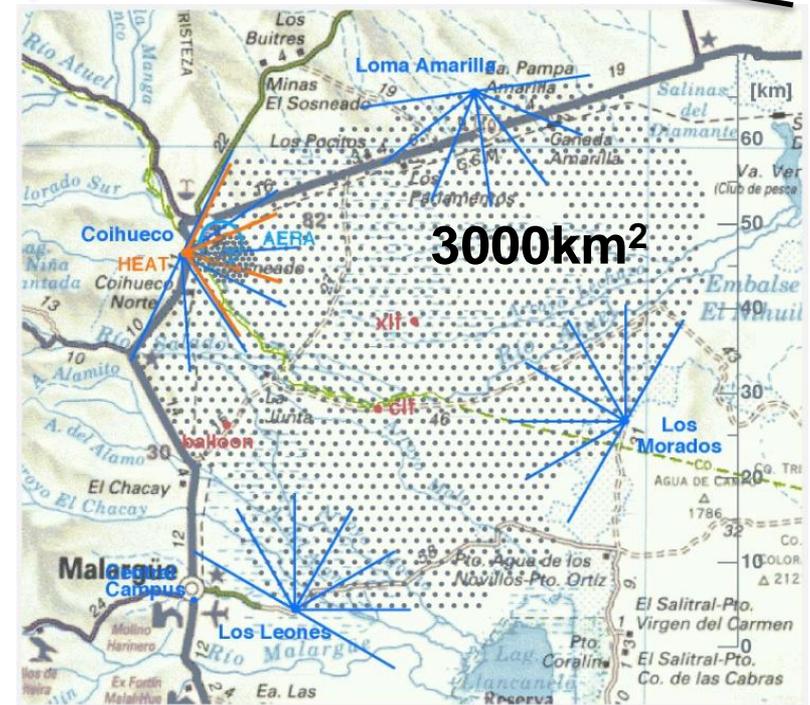
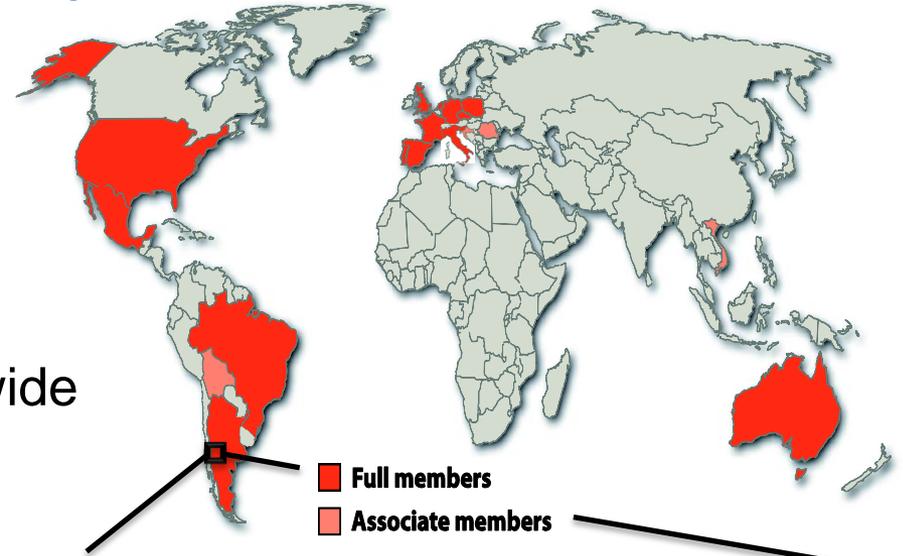
■ AERA physics results

- radio emission processes of extensive air showers
- measurement of radiation energy
- cosmic ray energy reconstruction

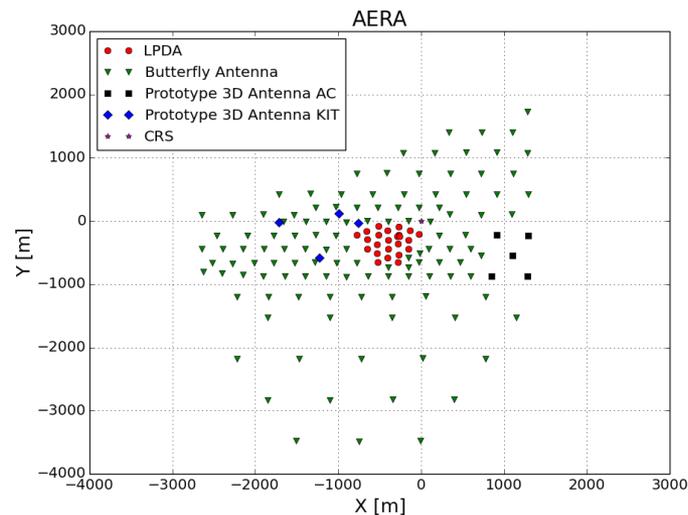
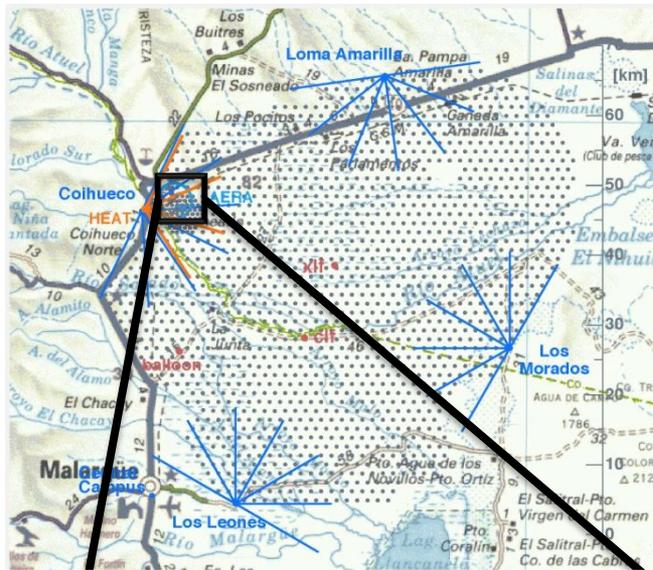


Pierre Auger Observatory

- located near Malargüe, Argentina
- largest cosmic ray experiment worldwide
- energy range: $E > 10^{17}$ eV
- data taking since 2004
- baseline detector:
 - 1660 surface detectors (SD)
 - duty cycle ~100%
 - 27 fluorescence detectors (FD)
 - duty cycle ~14%



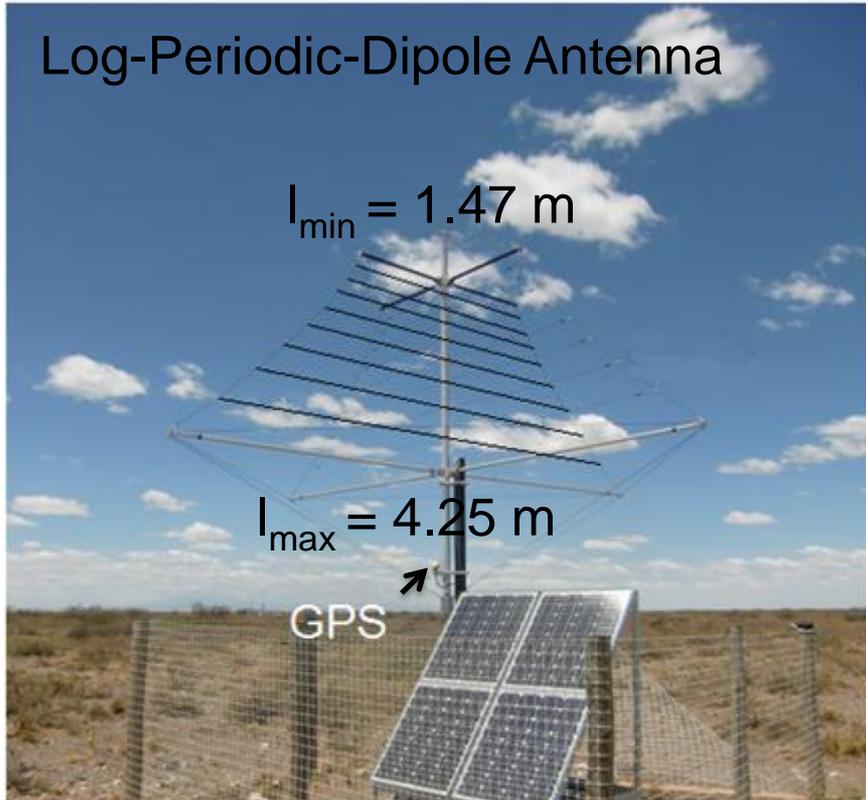
Auger Engineering Radio Array



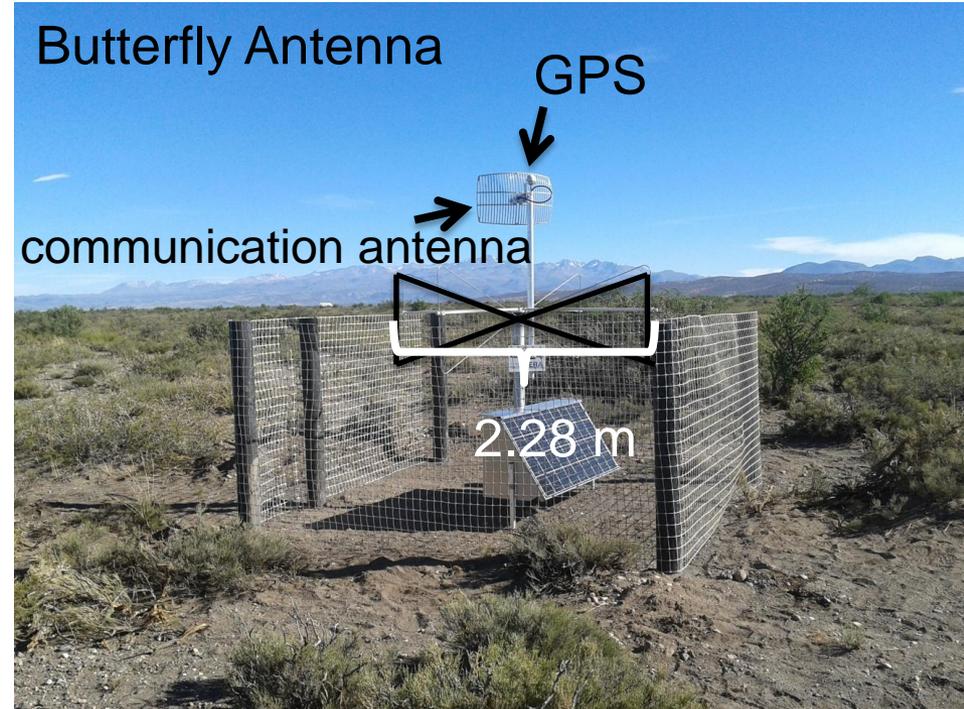
- lateral and longitudinal shower information
 - duty cycle ~100%
- coincident measurements with other Auger detectors
- 153 radio stations on 17km²
- grid spacing:
 - 144m (2011)
 - 250m, 375m (2013)
 - 750m (2015)
- determine cosmic ray properties:
 - arrival direction
 - energy
 - chemical composition
- energy range: $E > 10^{17}$ eV

AERA Radio Stations

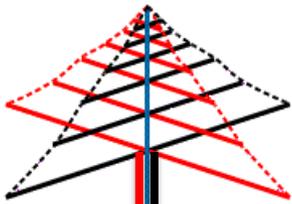
Log-Periodic-Dipole Antenna



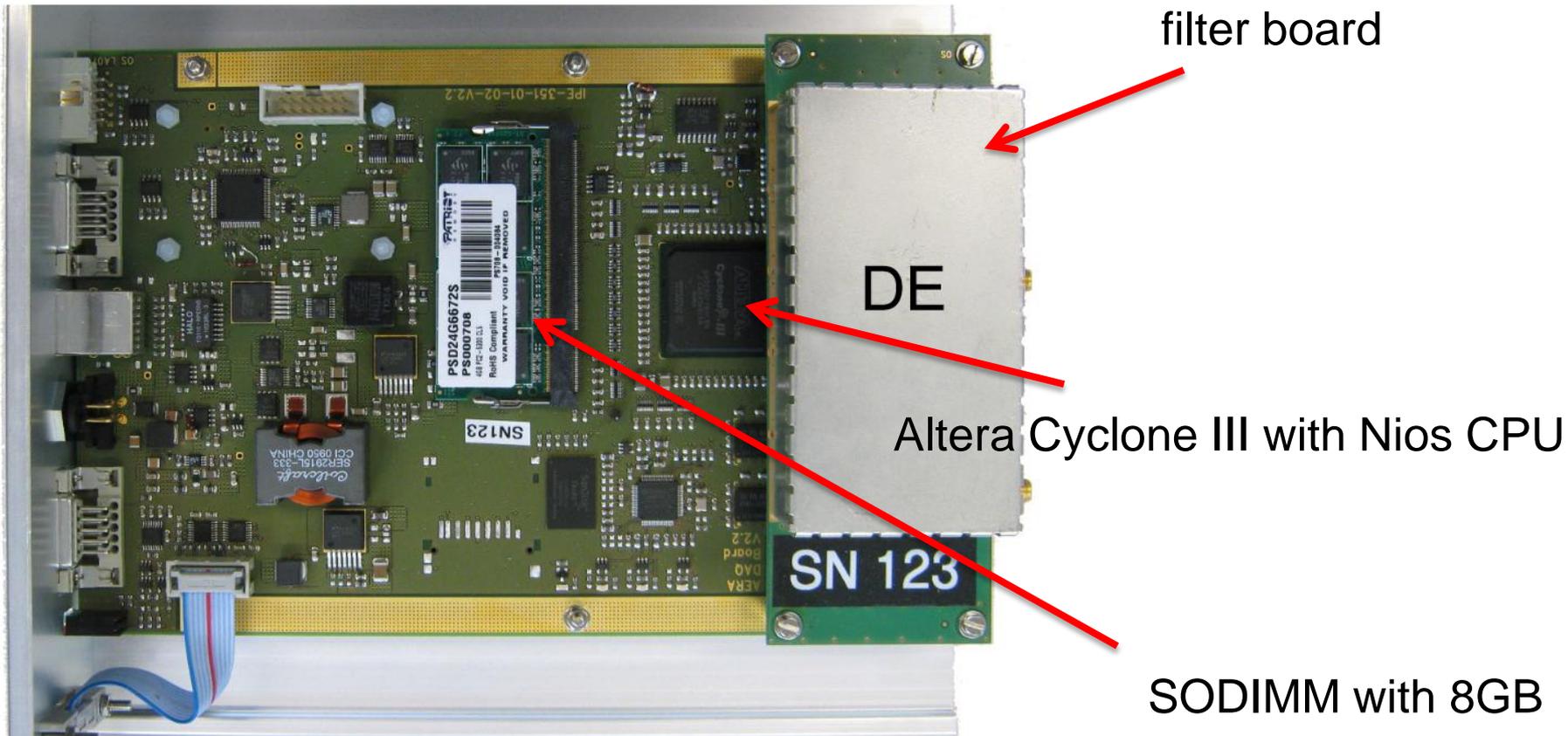
Butterfly Antenna



- 2 different radio station types
- NS and EW polarized antenna
- antenna alignment:
 - to magnetic north with precision $< 1^\circ$
- bandwidth: 30MHz - 80MHz
- autonomous radio station
- power consumption: $\sim 10\text{W}$



Digitizer

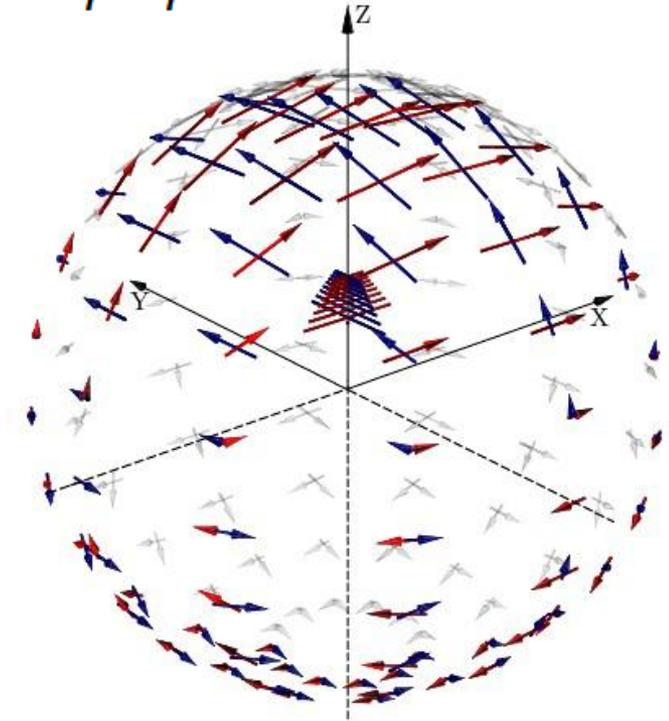
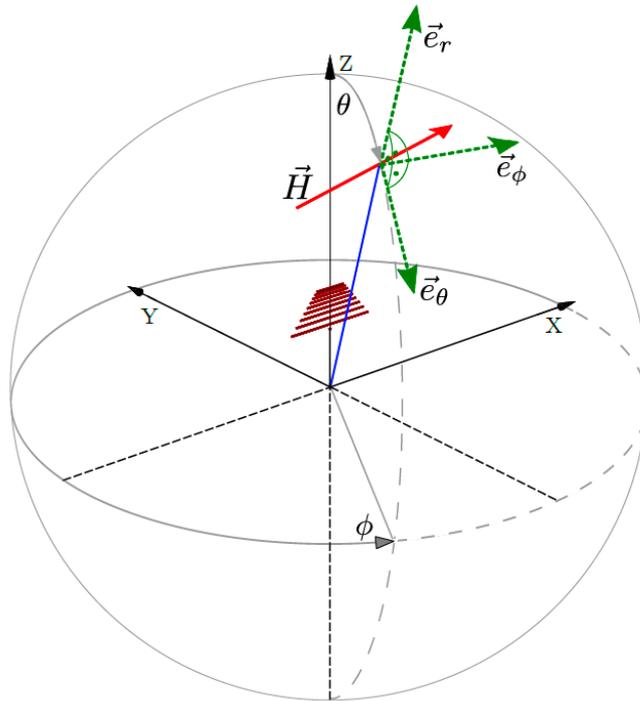


- self and external trigger
- 12bit ADC, 2x low + 2x high gain
- digitizer sampling rate: 180MHz

Vector Effective Length

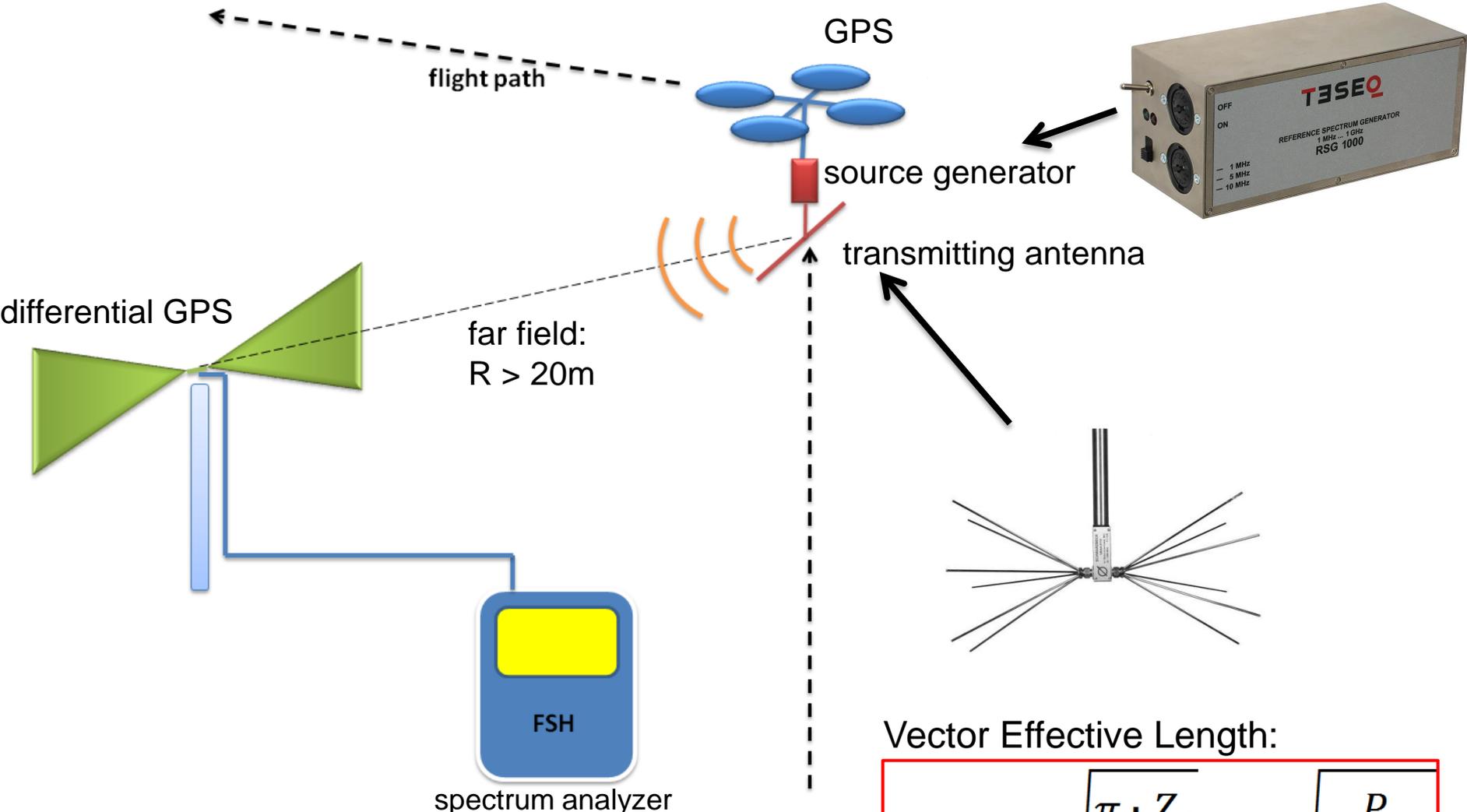
$$U(f, \theta, \varphi) = \vec{H}(f, \theta, \varphi) \cdot \vec{E}(f, \theta, \varphi)$$

$$\vec{H} = H_{\theta} \vec{e}_{\theta} + H_{\varphi} \vec{e}_{\varphi}$$



- H: relation of voltage to incoming e-field
- horizontal antenna most sensitive to zenith direction

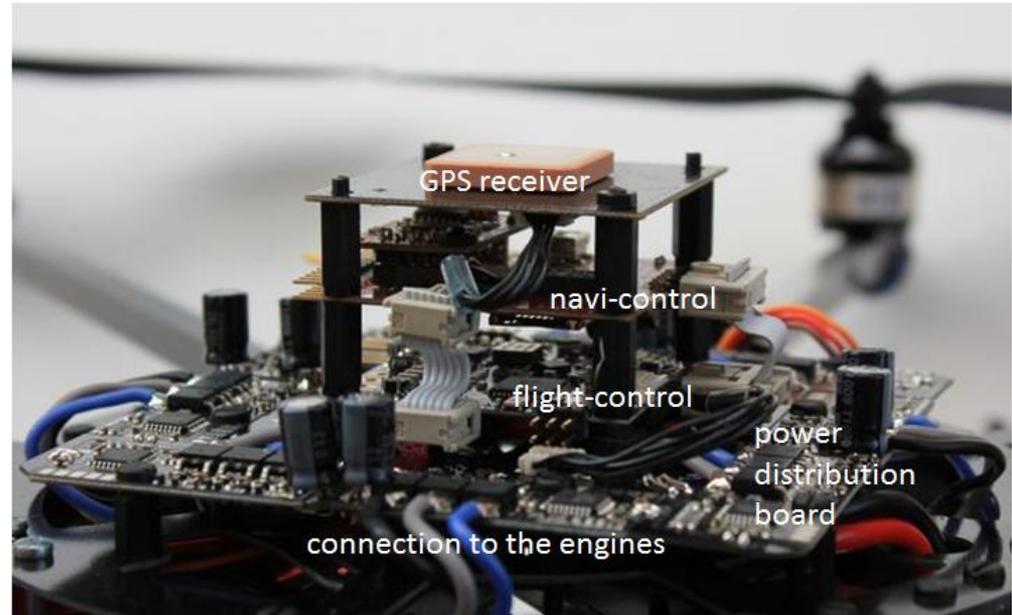
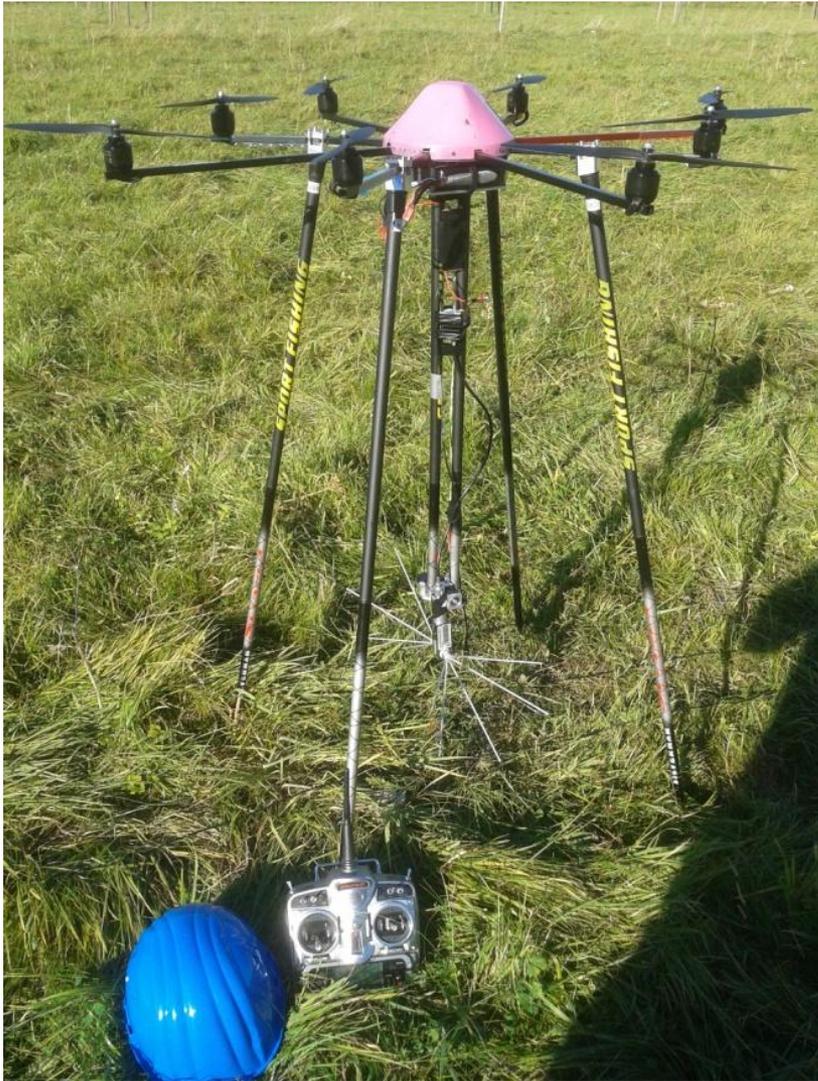
Setup of Antenna Response Calibration



Vector Effective Length:

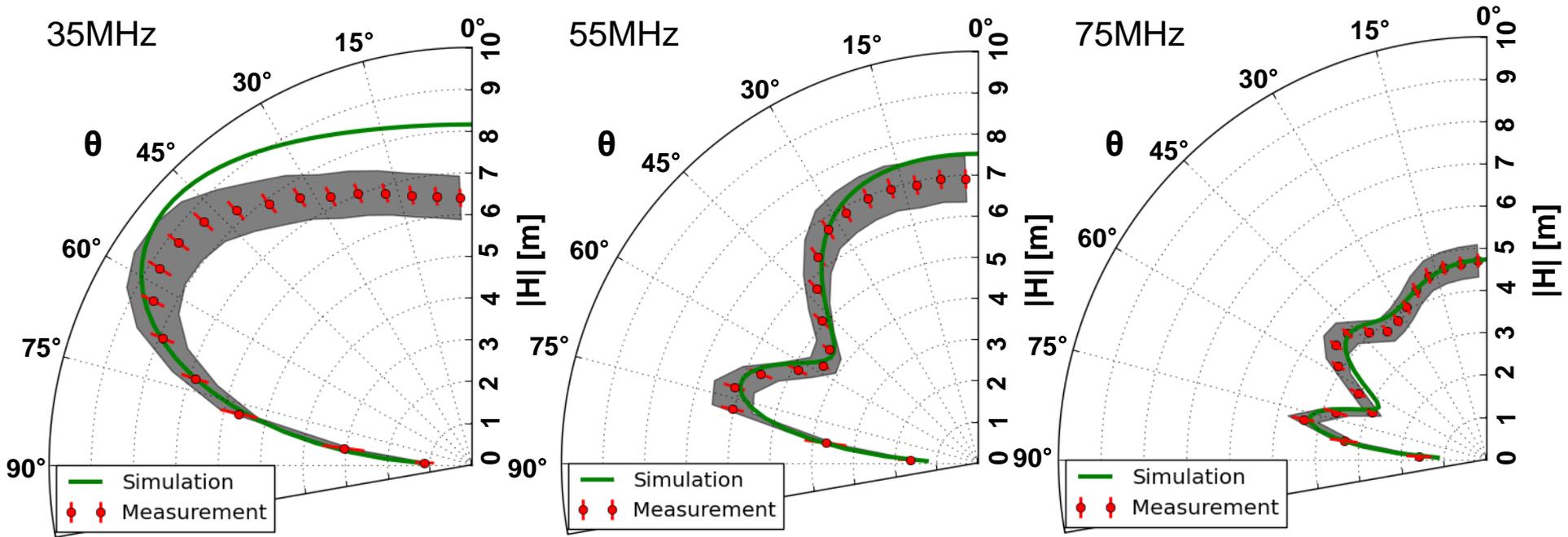
$$|H| = 2 \cdot \sqrt{\frac{\pi \cdot Z_A}{Z_0}} \cdot R \cdot \sqrt{\frac{P_r}{G_t \cdot P_t}}$$

Octocopter

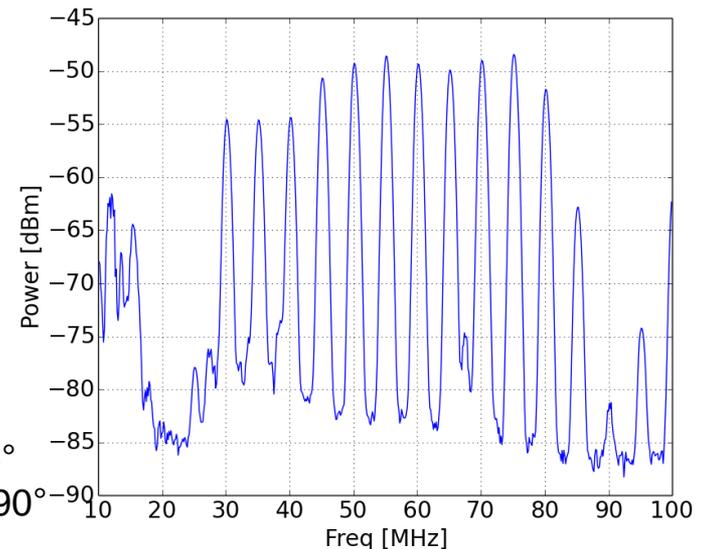


- power: 6600 mAh Lipo 13-16V
- payload: ~2000g
- mass: 2545g (including 715g accumulator)
- flight time: 25min/9min (wo/w payload)
- barometer → elevation
- gyroscope → inclination
- acceleration sensor → angular speed
- GPS → position

LPDA Vector Effective Length



- measurement and simulation in fair agreement at high frequencies
 - difference of the order of 10%
- measurement and simulation at small frequencies:
 - difference of the order of 25%



$R = 39.4\text{m}$
 zenith = 45°
 azimuth = 90°

AERA Time Calibration

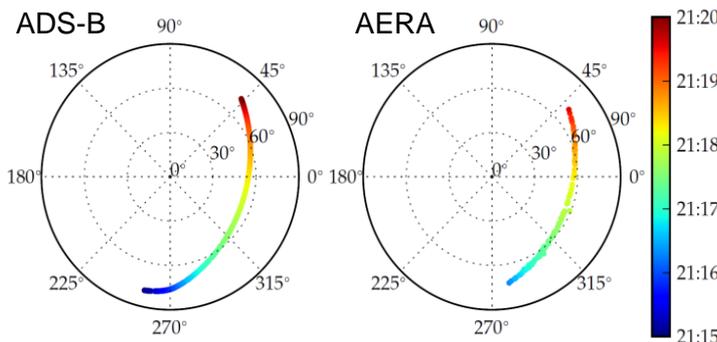
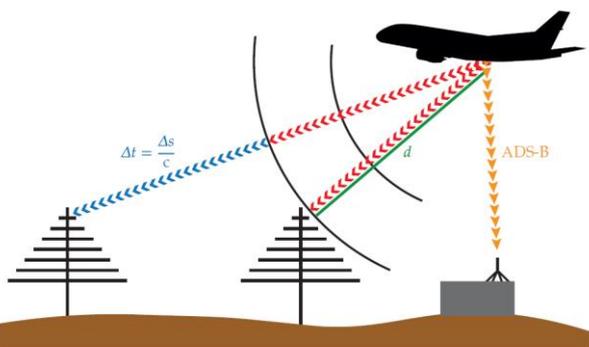
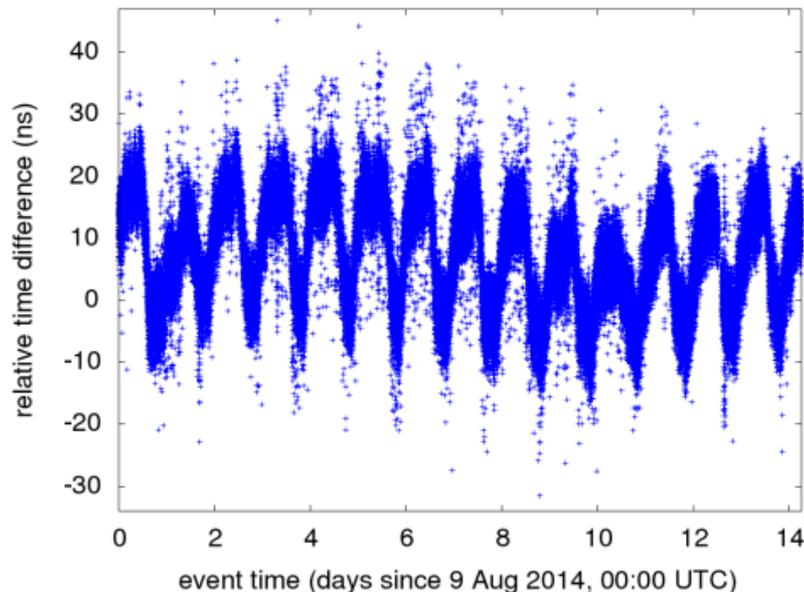
- time correction for GPS clock drifts
 - comparison of expected and measured time difference between two stations

- beacon method:

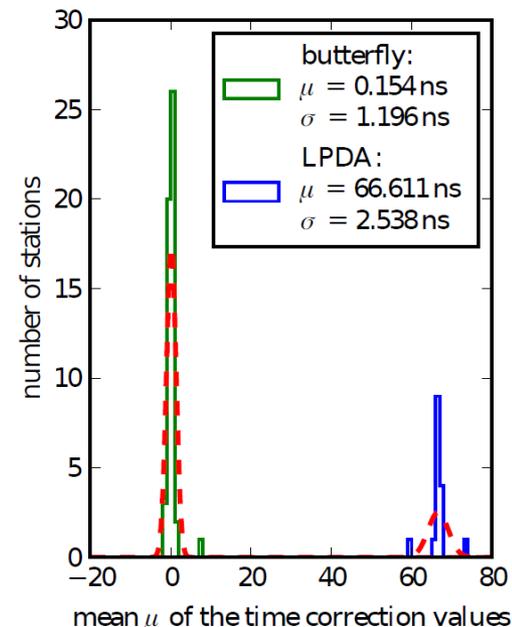
- horizontal NS-antenna
- frequencies:
 - 58.887MHz, 61.523MHz,
 - 68.555MHz, 71.191MHz

- air plane method:

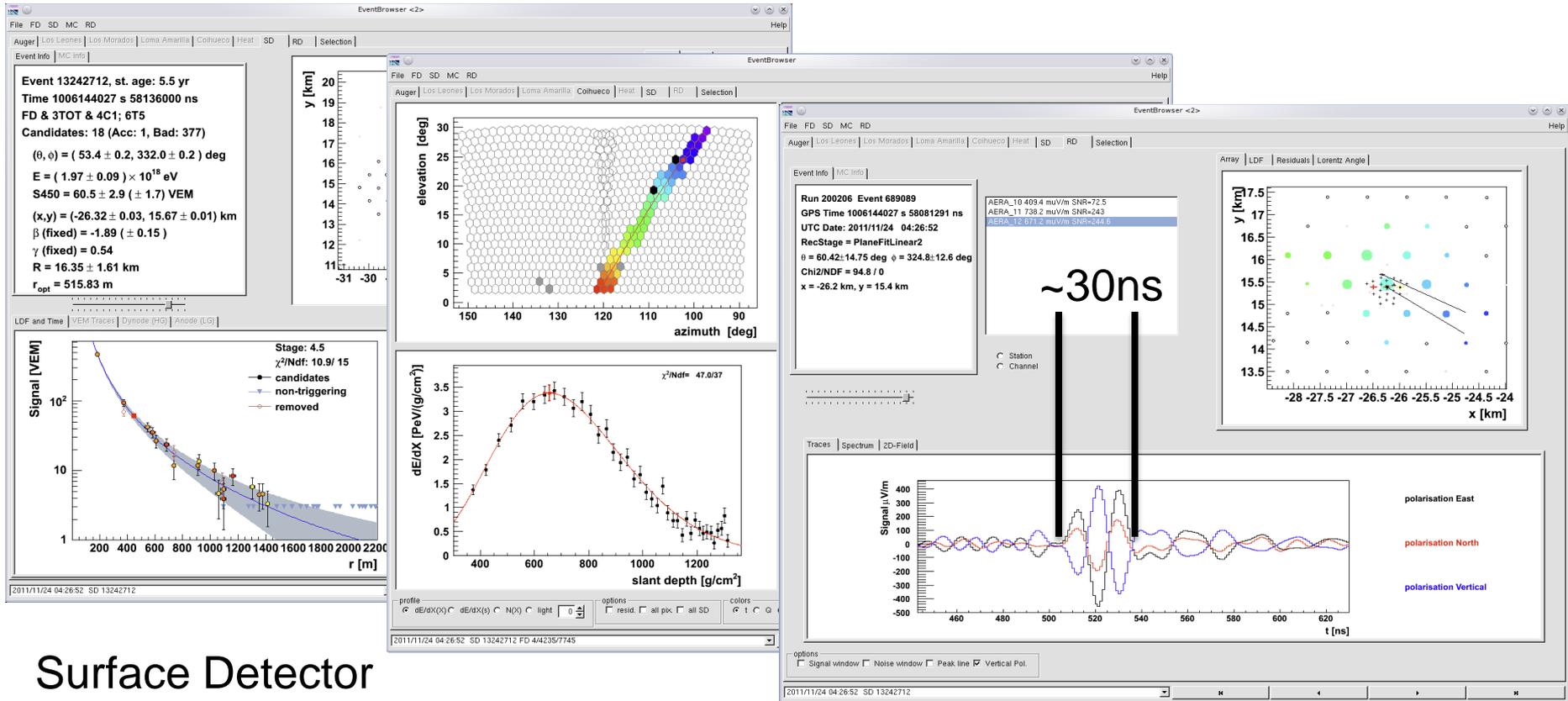
- ADS-B + radio signal from air planes



- combined time precision of $\sim 2\text{ns}$



In Coincidence Measured Events



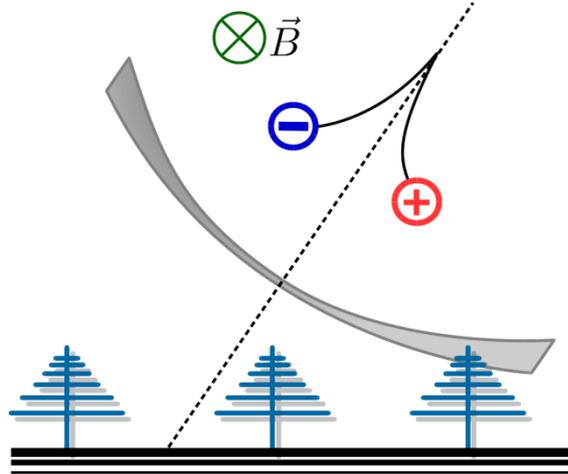
Surface Detector

Fluorescence Detector

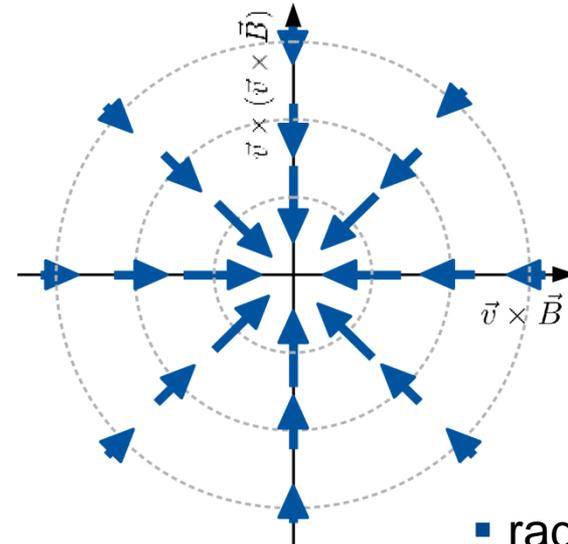
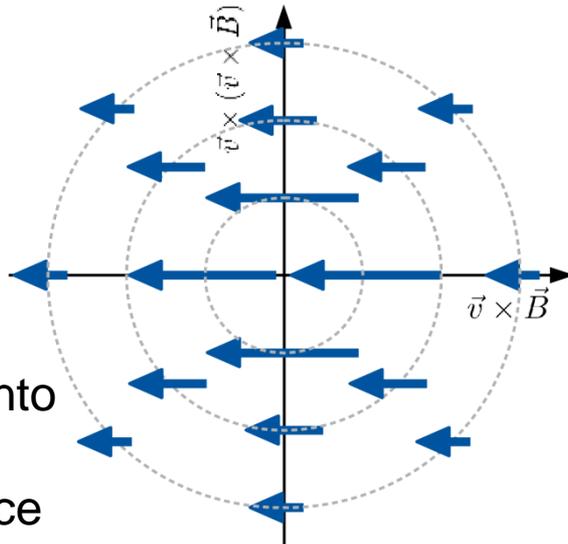
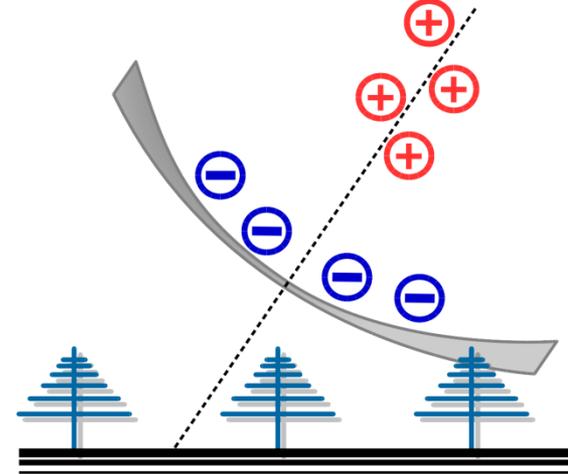
Radio Detector

Radio Emission in Extensive Air Showers

geomagnetic emission



charge excess emission



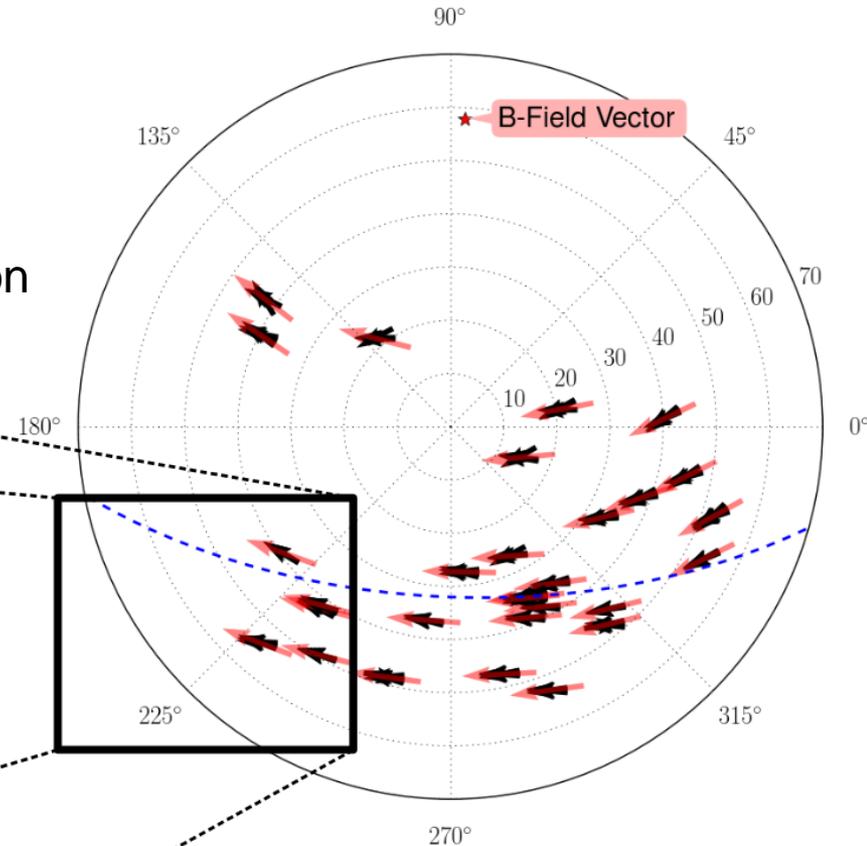
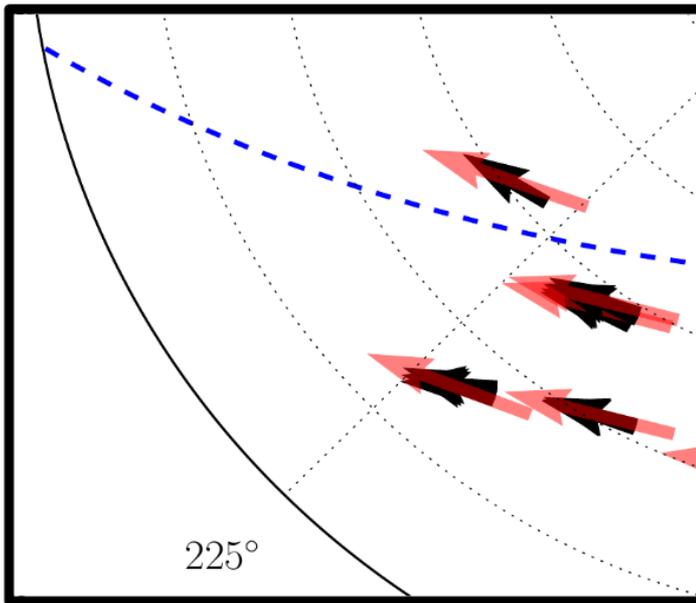
- polarized into direction of Lorentz force

- radially polarized towards shower axis

Electric Field Polarization

- black arrow:
 - measured polarization
 - at least 3 triggered stations
- red arrow:
 - expected from geomagnetic emission

$$\vec{E} \sim \vec{v} \times \vec{B}$$

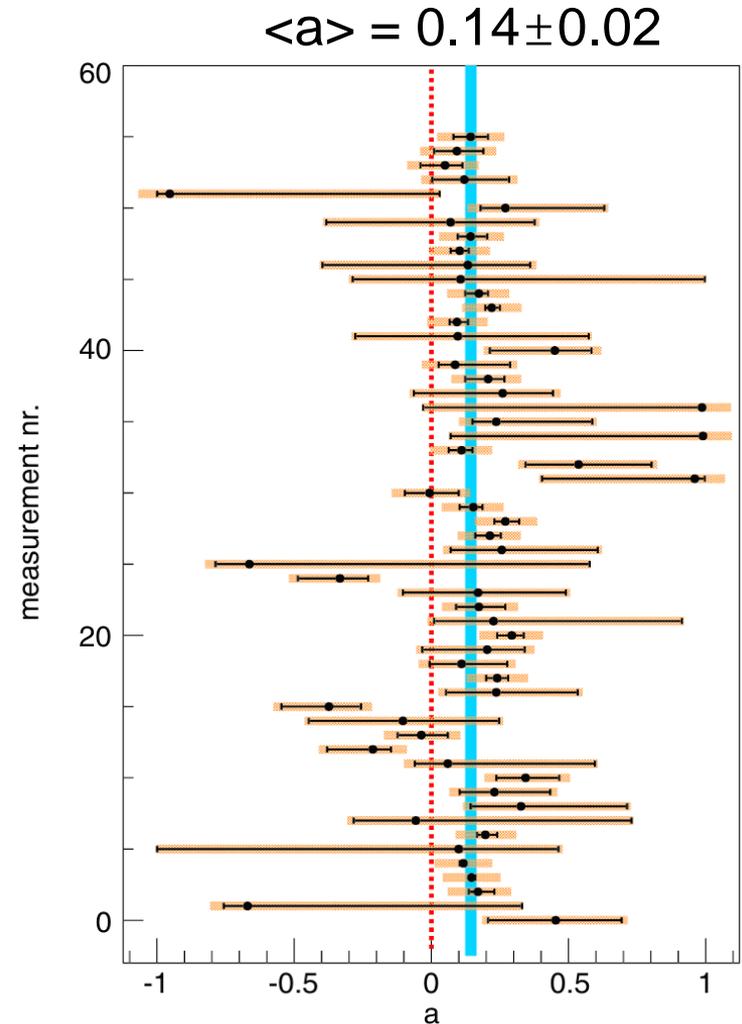
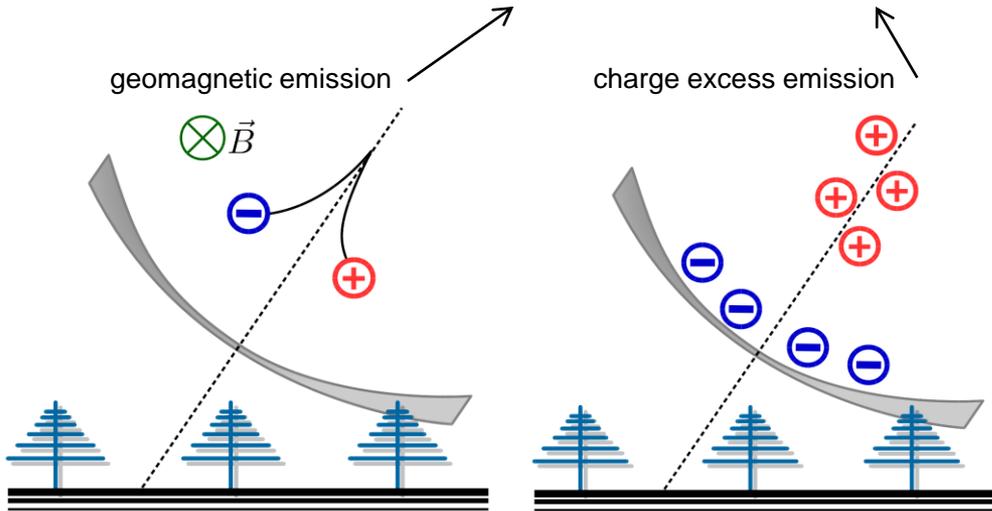


geomagnetic emission is
dominant emission
process

Second Order Emission Process

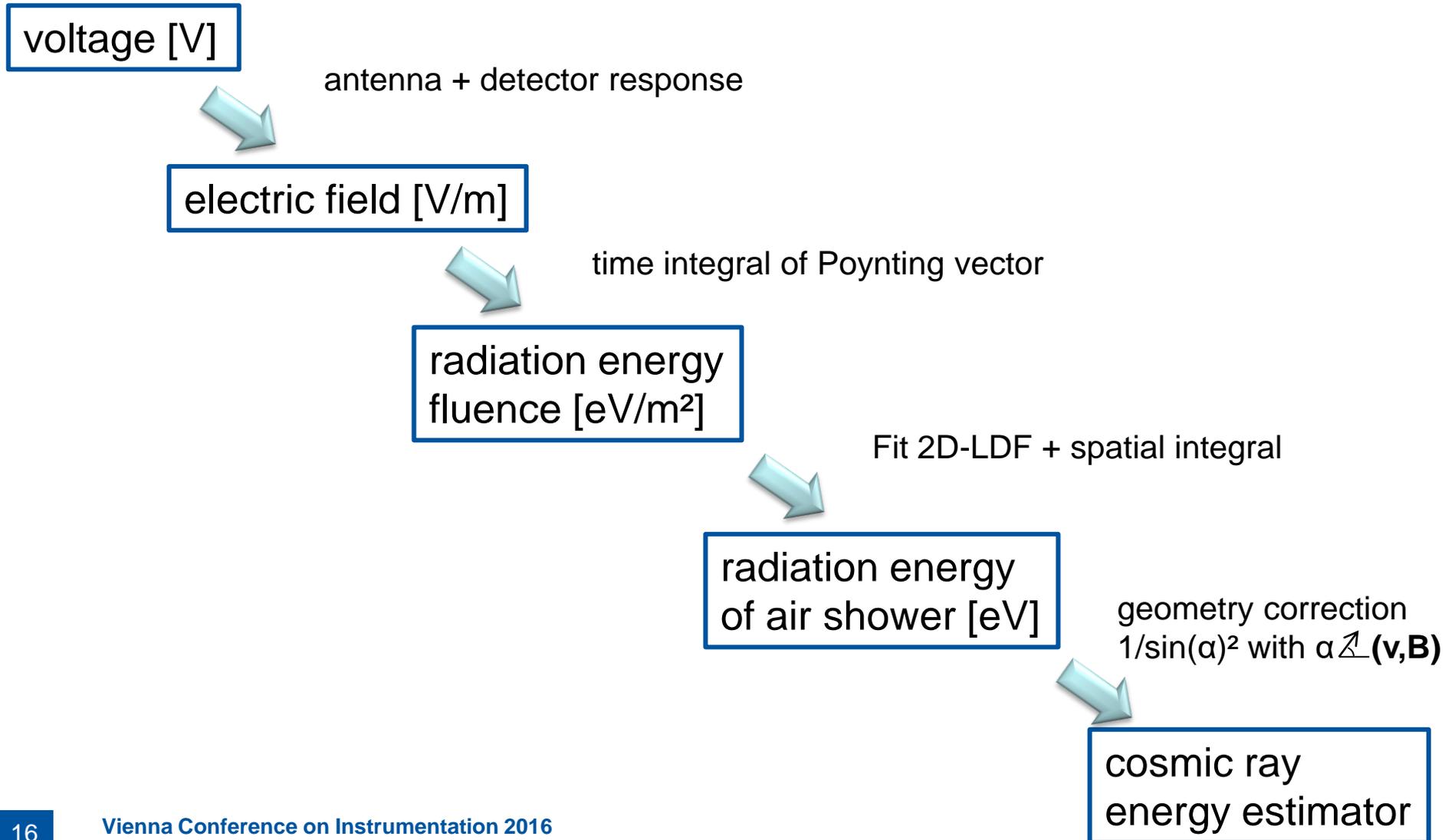
- pure geomagnetic radiation can not fully describe our data
- radial component, caused by a charge excess, is present

$$\vec{E} \sim \sin(\alpha) \cdot \vec{e}_{GM} + a \cdot \vec{e}_{CE}$$

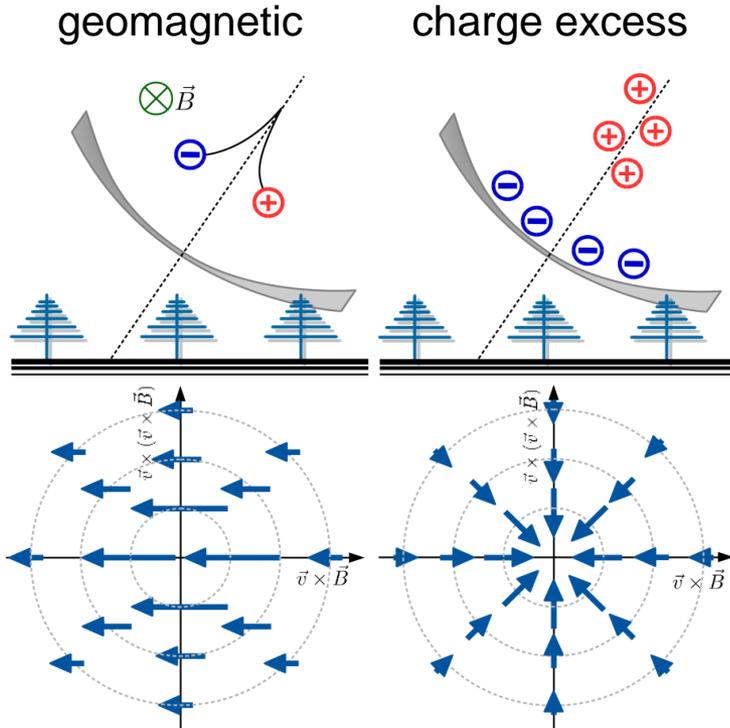


A. Aab et al., Phys. Rev. D 89, 052002, 2014

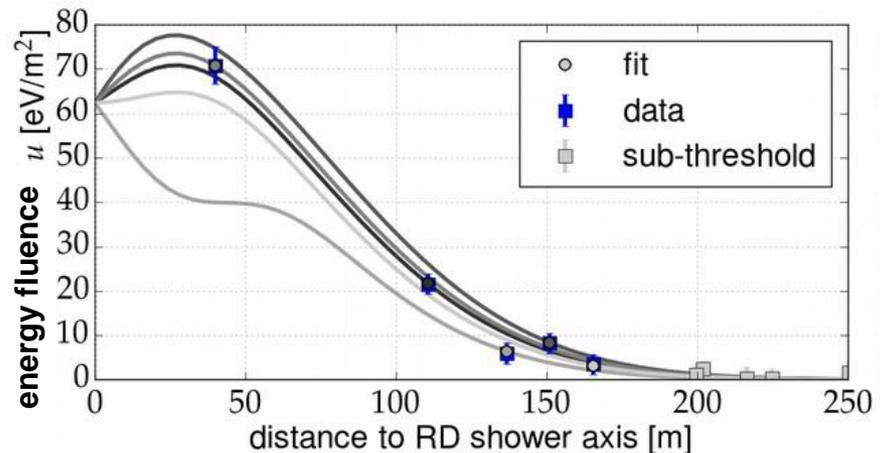
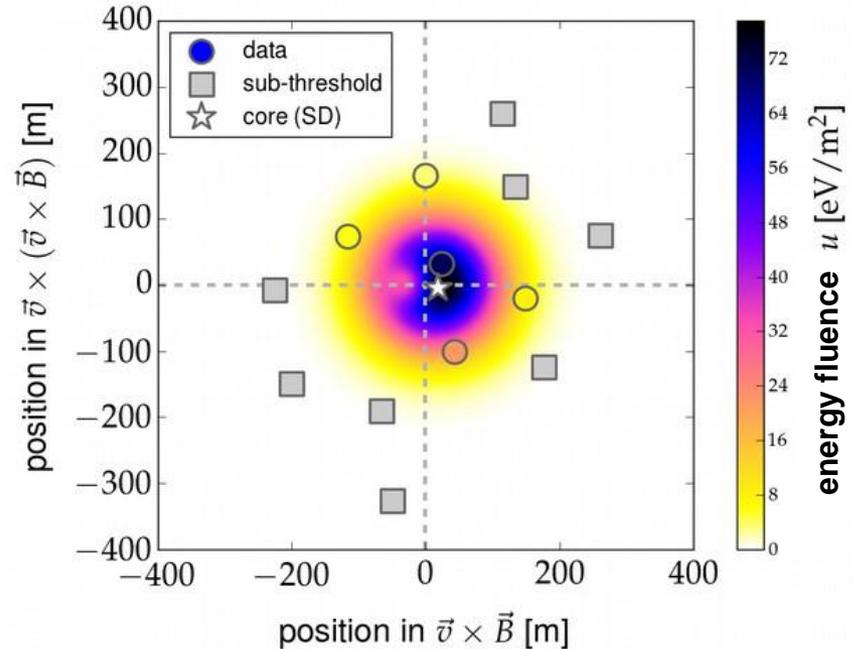
From Voltage To Cosmic Ray Energy



Radiation Energy Fluence

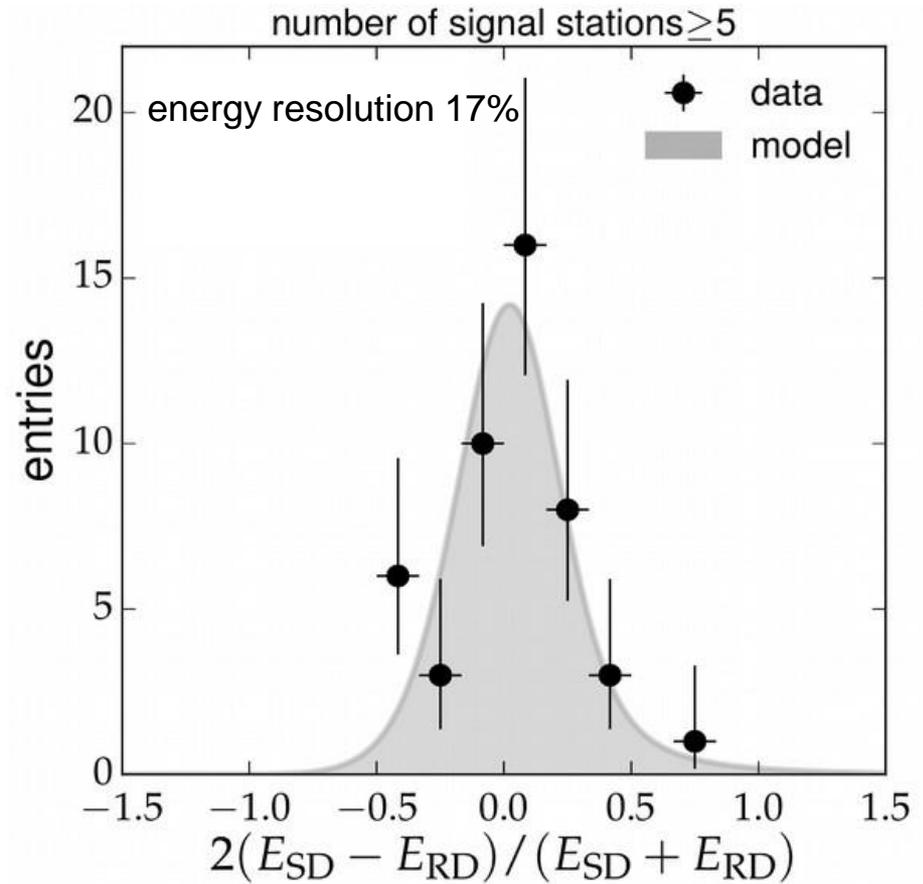
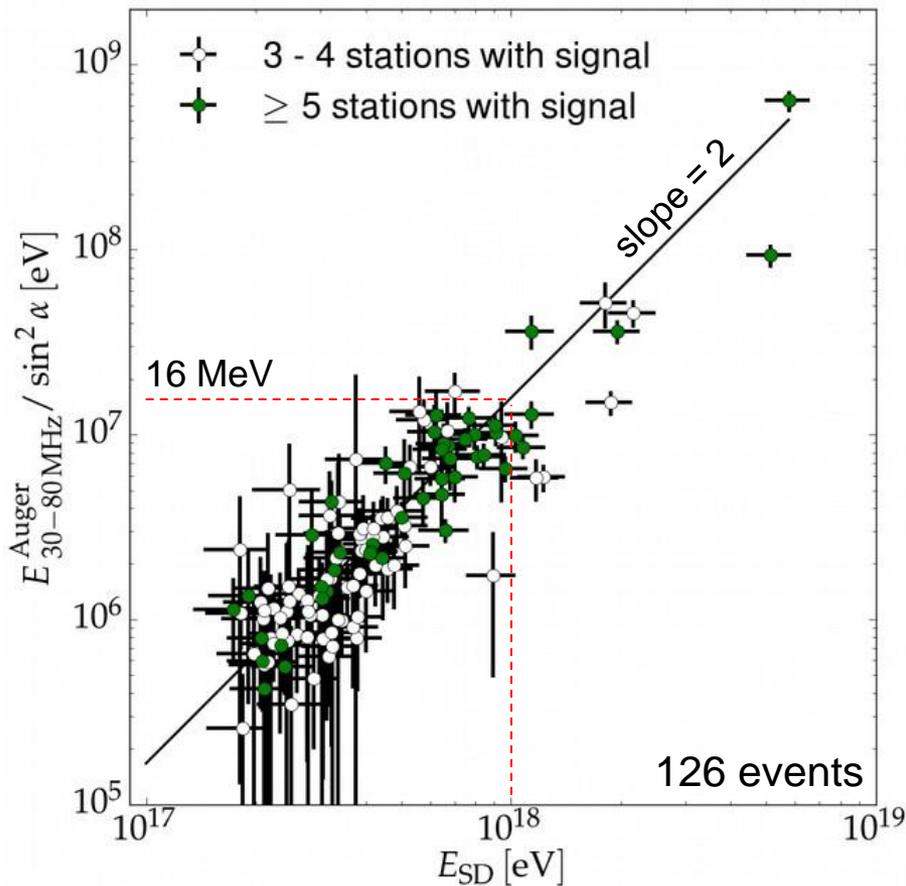


- polarized into direction of Lorentz force
- radially polarized towards shower axis



Radio Energy Estimator

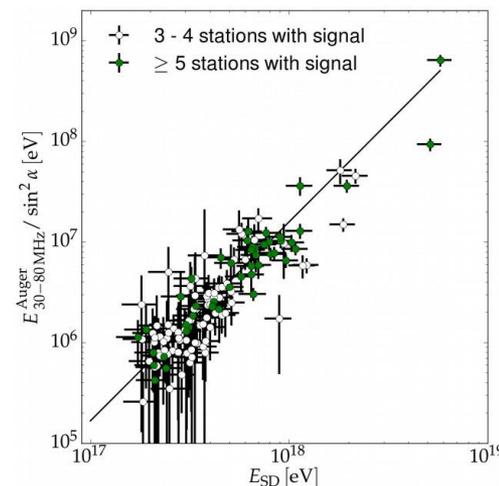
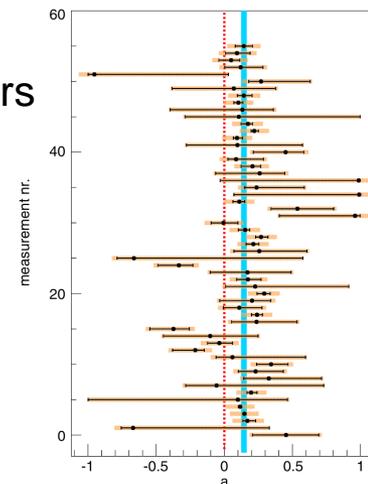
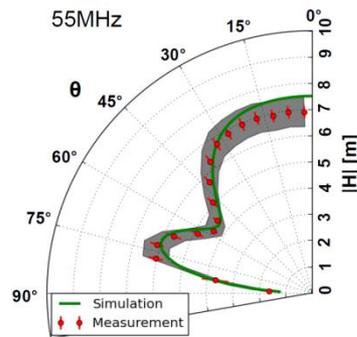
- LPDA stations
- coincidences with surface detector
- zenith angle $< 55^\circ$



- $\sim 16 \text{ MeV}$ radiation energy for a 1 EeV cosmic ray

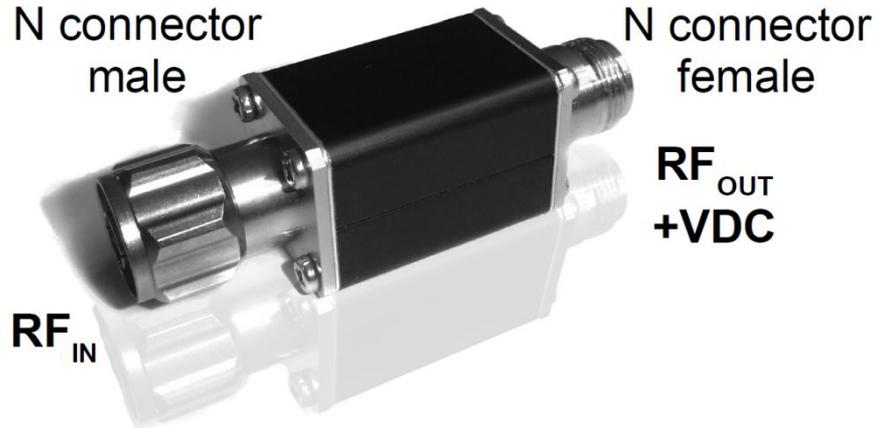
Summary

- Pierre Auger Observatory:
 - well calibrated environment for development of future detector technologies
- Auger Engineering Radio Array
 - largest experiment to measure radio emission of extensive air showers
 - several approaches to calibrate antennas
 - radio emission in extensive air showers:
 - geomagnetic emission (dominant)
 - charge excess emission (measured to 14% on average)
 - radiation energy of air showers measured
 - cosmic ray energy resolution 17%
- in progress
 - new precise calibration
 - data analysis of 17km² array
 - reconstruction of shower maximum to get information about the chemical composition of UHECRs
 - R&D to further improve radio detection
 - third polarization
 - inclined showers



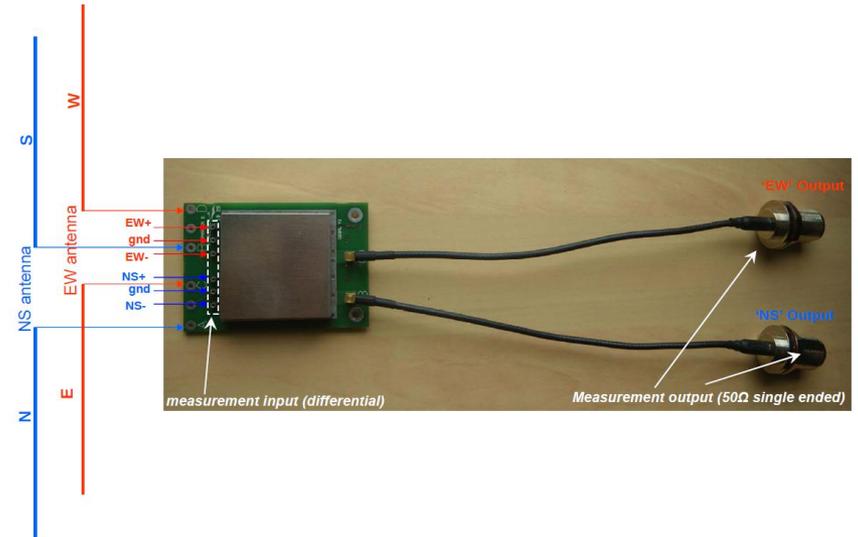
Backup

Low-Noise Amplifier



LPDA:

- frequency range: 30MHz – 80MHz
- gain: 19dB (typ)
- phantom powered
- power supply: 6V
- current consumption: $25mA \pm 1.5mA$



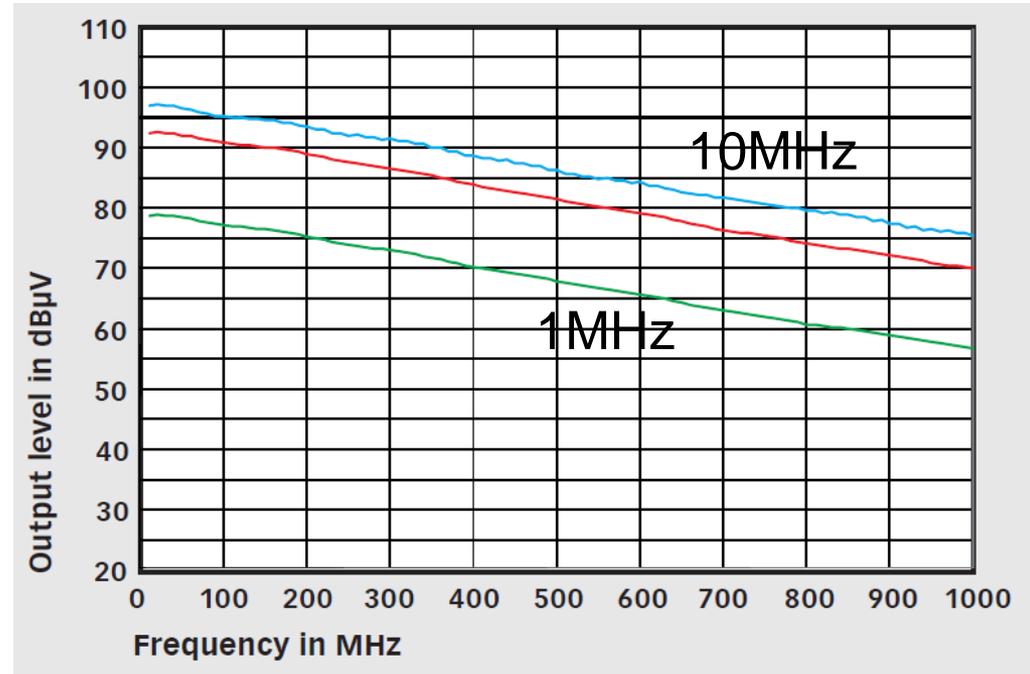
Butterfly Antenna:

- frequency range: 30MHz – 200MHz
- gain: 30dB (typ)
- phantom powered
- power supply: 6V
- current consumption: $50mA \pm 2mA$

Reference Spectrum Generator (RSG)



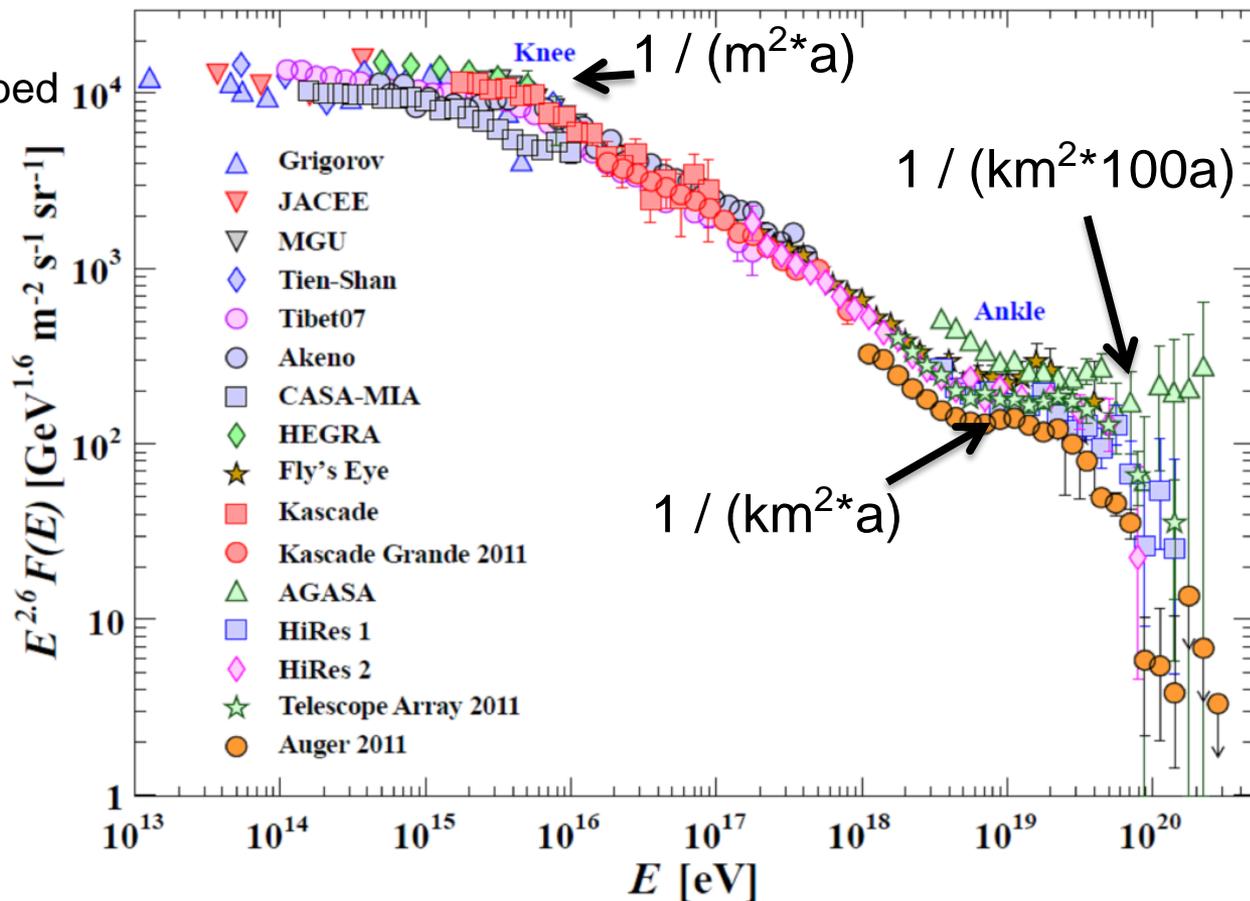
dimensions (W/H/D) in cm: 6/6/17.5
weight: ~580g



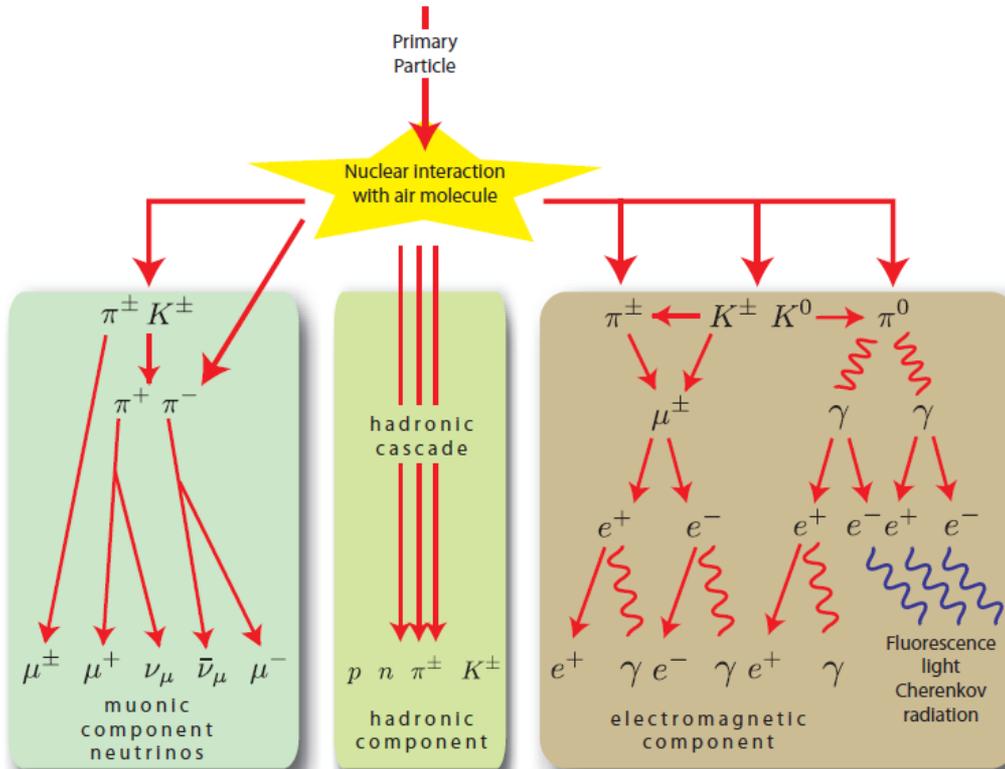
frequency range: 1MHz – 1000MHz
comb spacing: 1MHz, 5MHz or 10MHz
max power: ~ 97dBµV = -10dBm

Cosmic Ray Energy Spectrum

- spectrum can be partly described by a power law: $F \sim E^{-\gamma}$
- UHECR events are very rare
- no direct measurement of UHECRs
- large ground-based experiments are needed
- measurement of secondary particles produced in extensive air showers

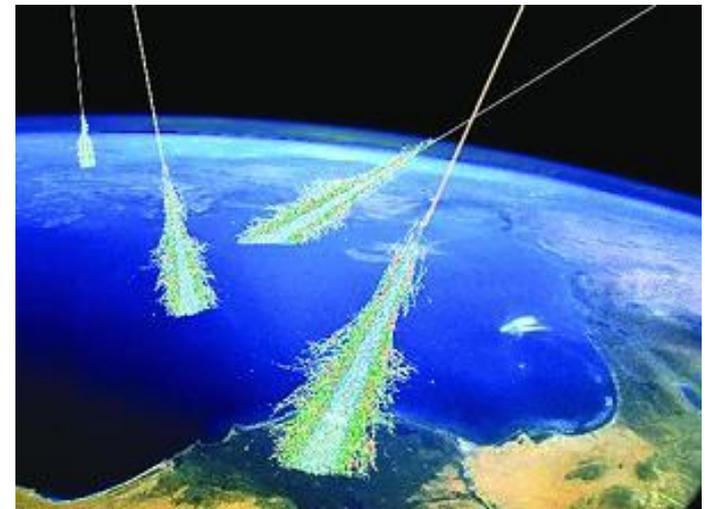


Extensive Air Showers



atmosphere corresponds to
a large calorimeter

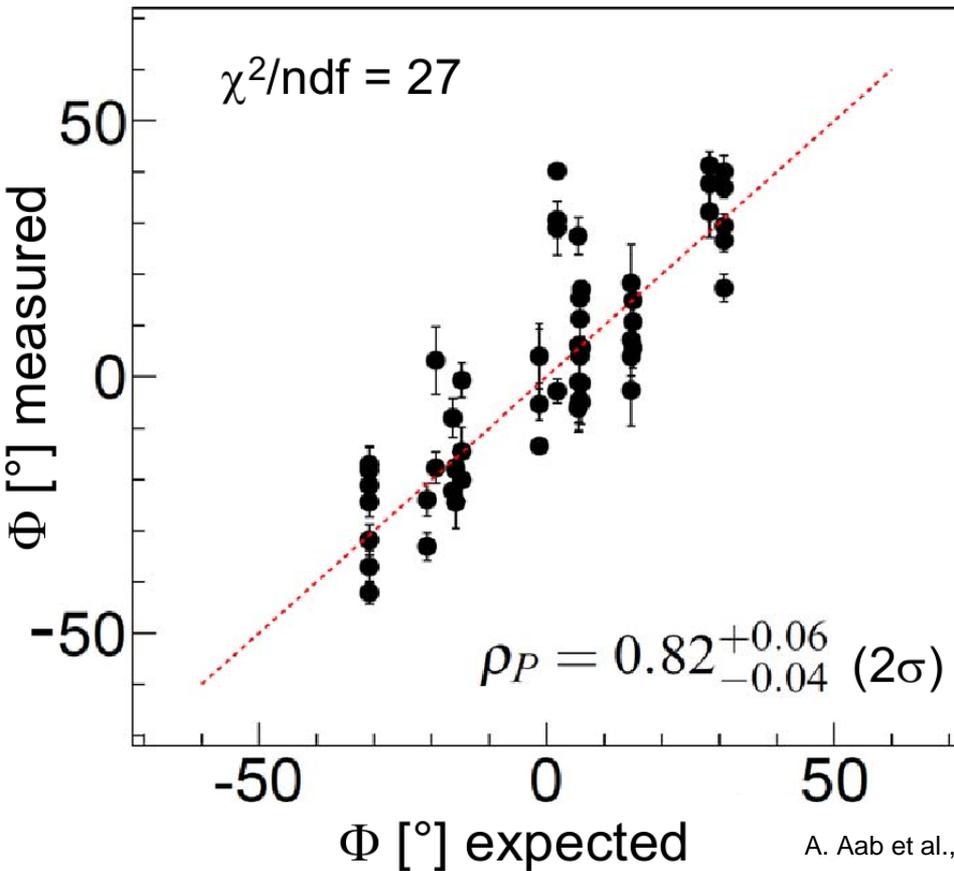
- interaction between UHECRs and air molecules
- Extensive Air Showers (EAS): muonic, hadronic and el.mag. component



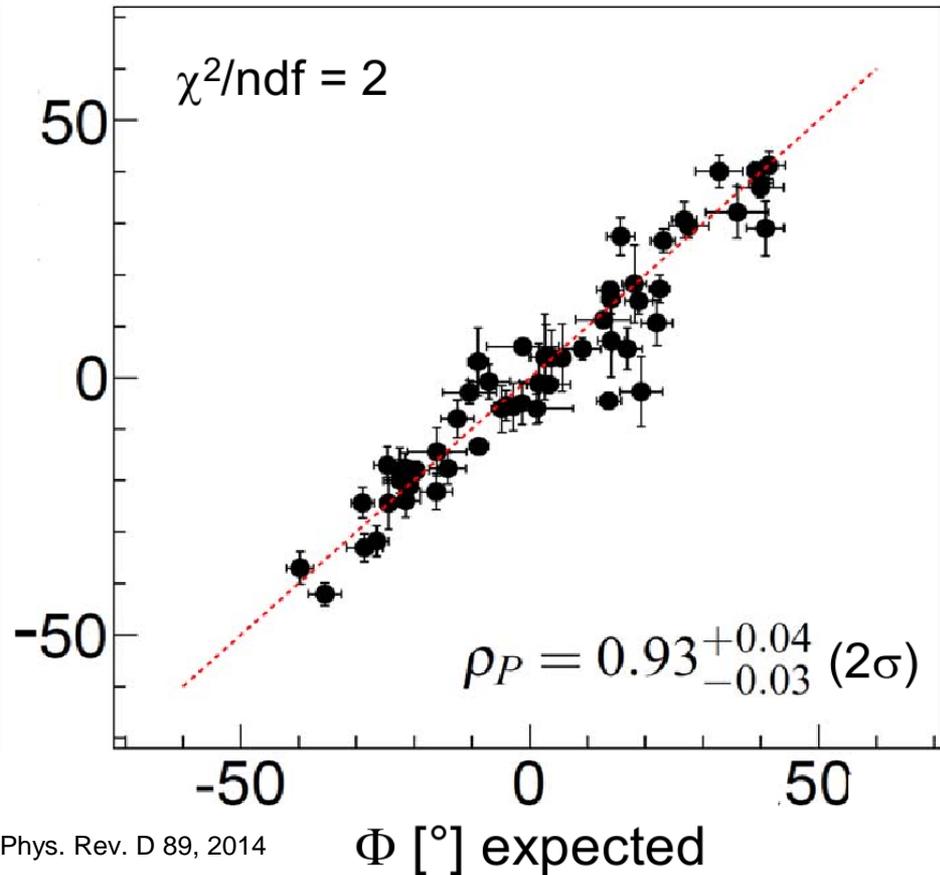
Second Order Emission Process

- adding a radial component clearly improves agreement

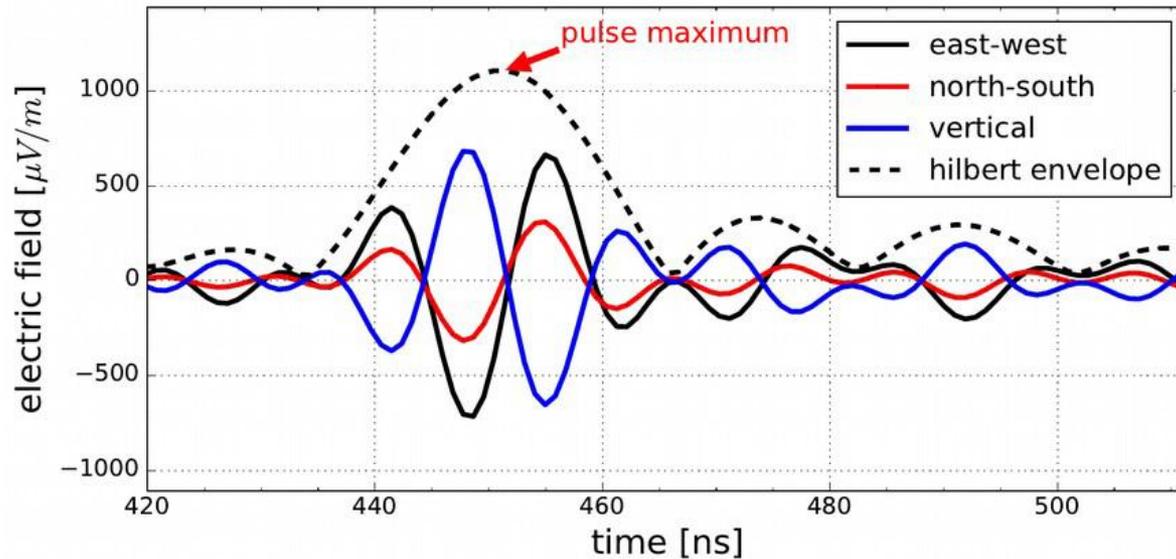
$a = 0$, pure geomagnetic



$a = 0.14$, geom. + radial



Energy Fluence



- window around maximum of Hilbert envelope

- energy fluence in eV/m²

- time integral of Poynting vector

- noise expectation subtracted

- $$u = \epsilon_0 c \left(\Delta t \sum_{t_1}^{t_2} |\vec{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\vec{E}(t_i)|^2 \right)$$

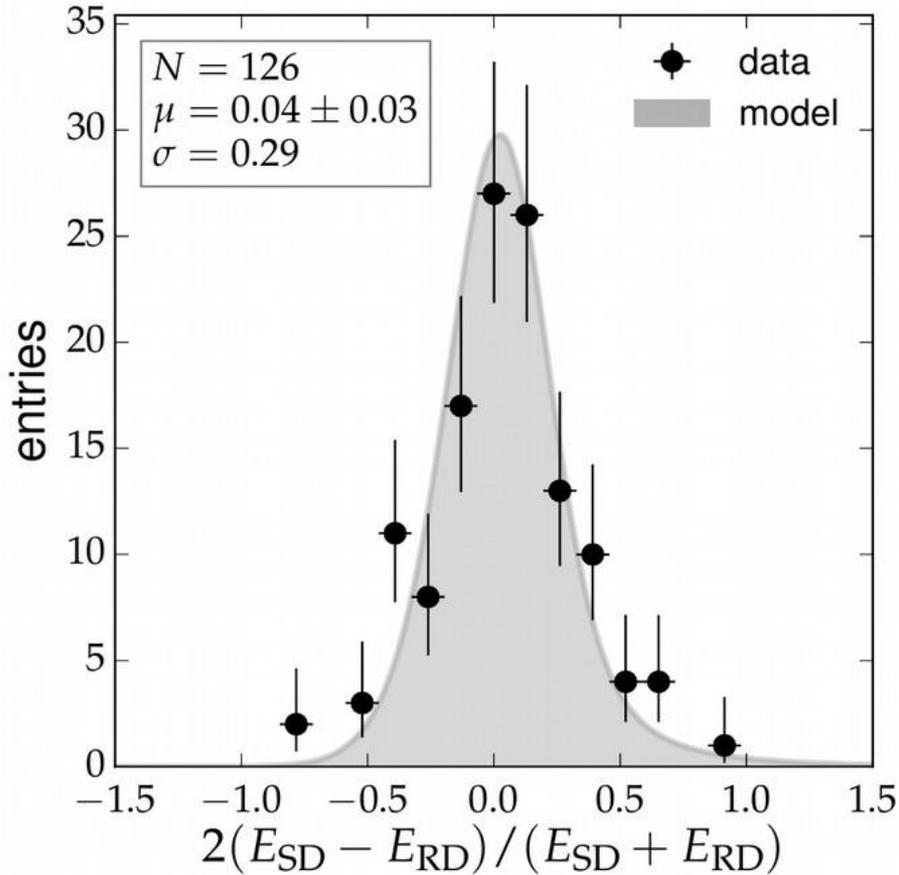
Energy Fluence Fit

$$f(\vec{r}) = A \left[\exp \left(\frac{-(\vec{r} + C_1 \vec{e}_{\vec{v} \times \vec{B}} - \vec{r}_{\text{core}})^2}{\sigma^2} \right) - C_0 \exp \left(\frac{-(\vec{r} + C_2 \vec{e}_{\vec{v} \times \vec{B}} - \vec{r}_{\text{core}})^2}{(C_3 e^{C_4 \sigma})^2} \right) \right]$$

- 3 or 4 stations: 2 parameters (A and σ)
- 5 or more stations: 4 parameters (A, σ , $r_{\text{core},x}$, $r_{\text{core},y}$)
- C: constants from CoReas simulations

Energy Resolution

energy resolution: 22%



energy resolution: 17%

