Precise time synchronisation of autonomous radio stations at the Pierre Auger Observatory

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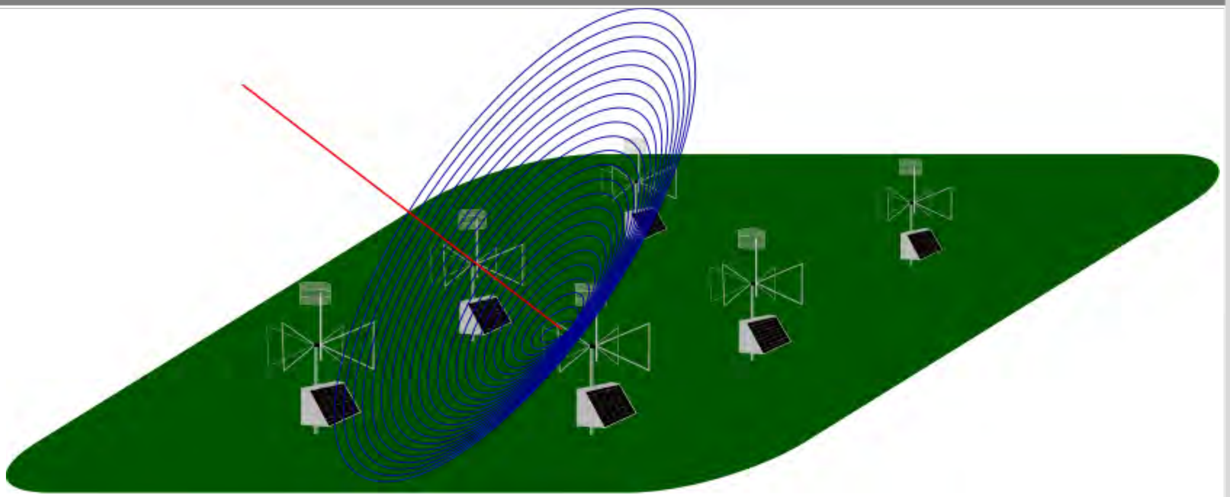
Outline:

- Motivation
- Pierre Auger Observatory
- Time Calibration
- Results



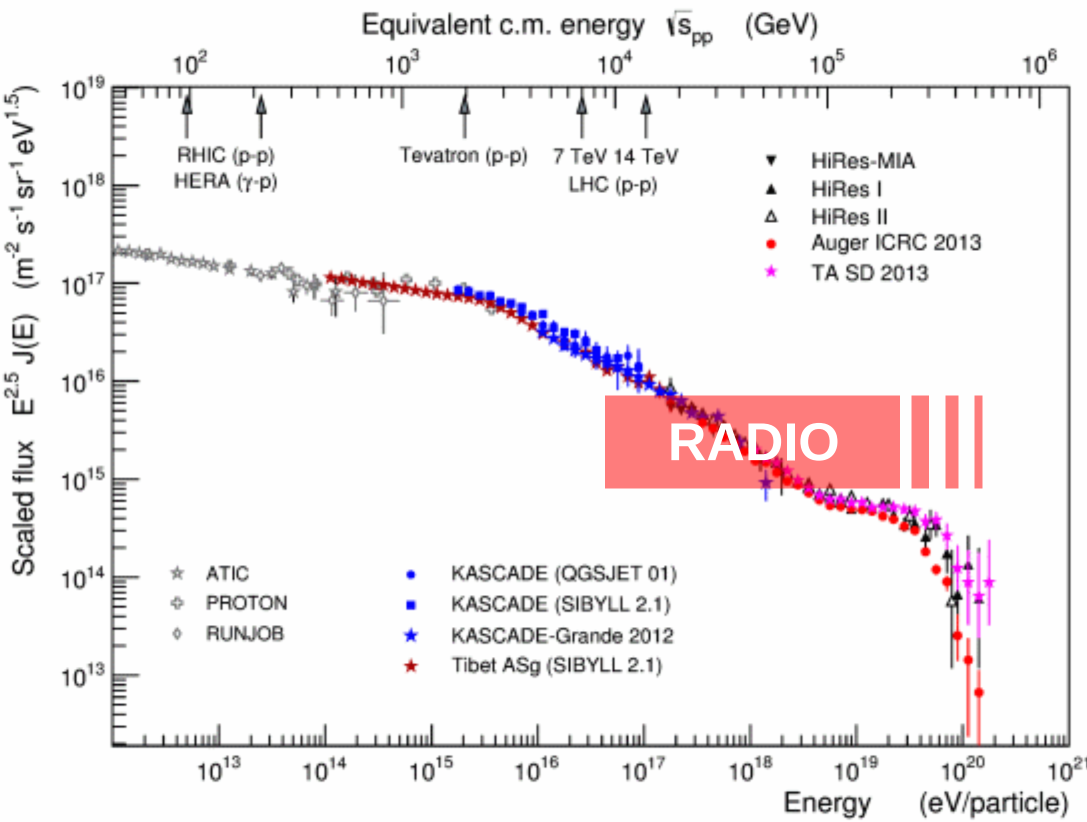
Take home message:

Time resolution < **2 ns**

Cosmic-ray physics

Karlsruhe Institute of Technology

Energy spectrum of cosmic rays



Plot by R. Engel & T. Huege

- Intriguing science questions:
  - Origin of cosmic rays
    → **10^{20} eV ?**
  - Acceleration mechanism?
- Answer requires measurements:
  - Direction
  - Energy
  - Composition
- We need large exposure
- We need precise calibration

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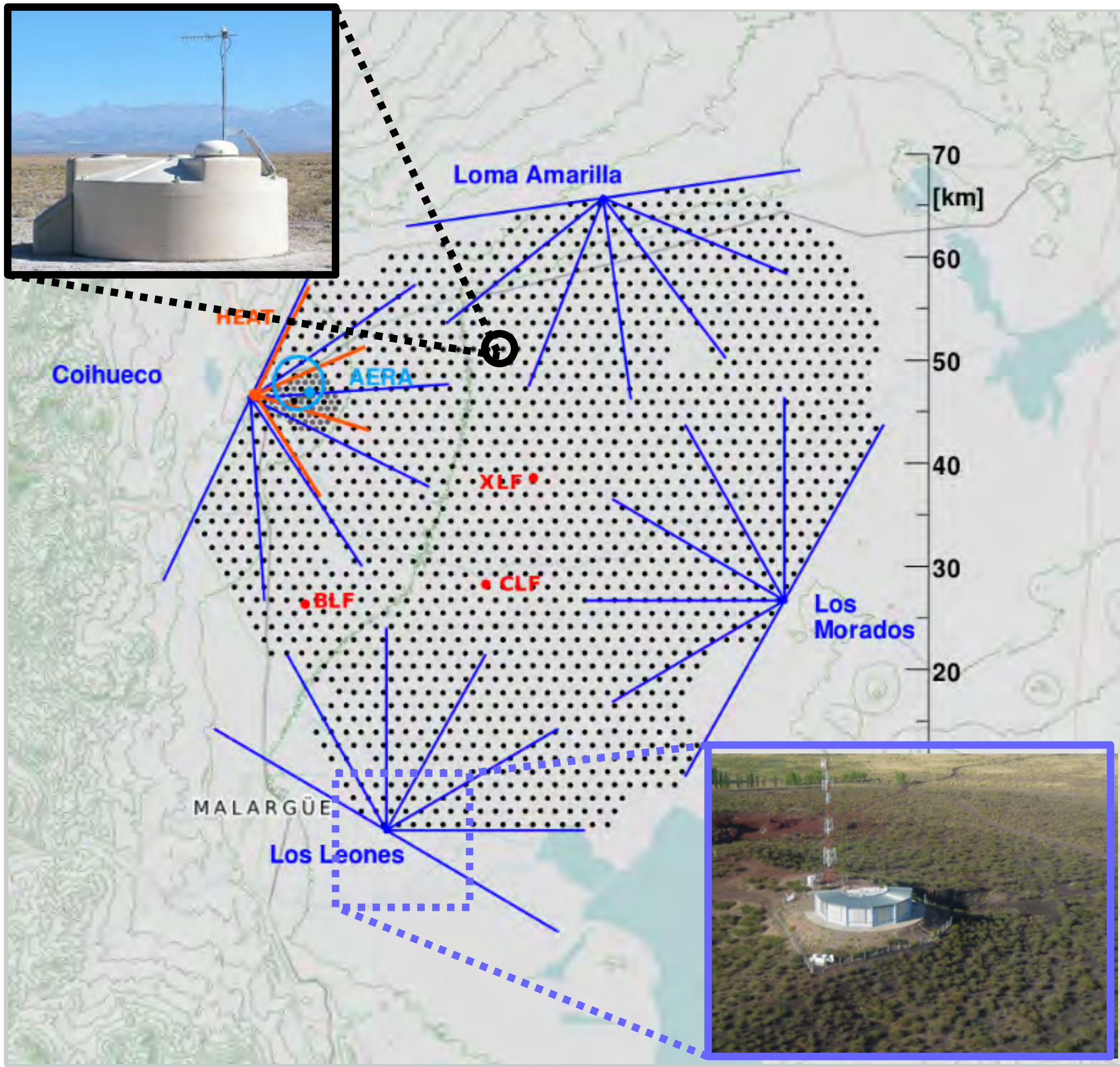
Pierre Auger Observatory

Layout of the Pierre Auger Observatory



Location: Argentina, Mendoza, Malargue

Surface Detectors (SD)
- 1660 Cherenkov tanks
- 100% duty cycle
- High angular resolution

Fluorescence Detector (FD)
- 27 telescopes
- 15% duty cycle
- Composition measurement

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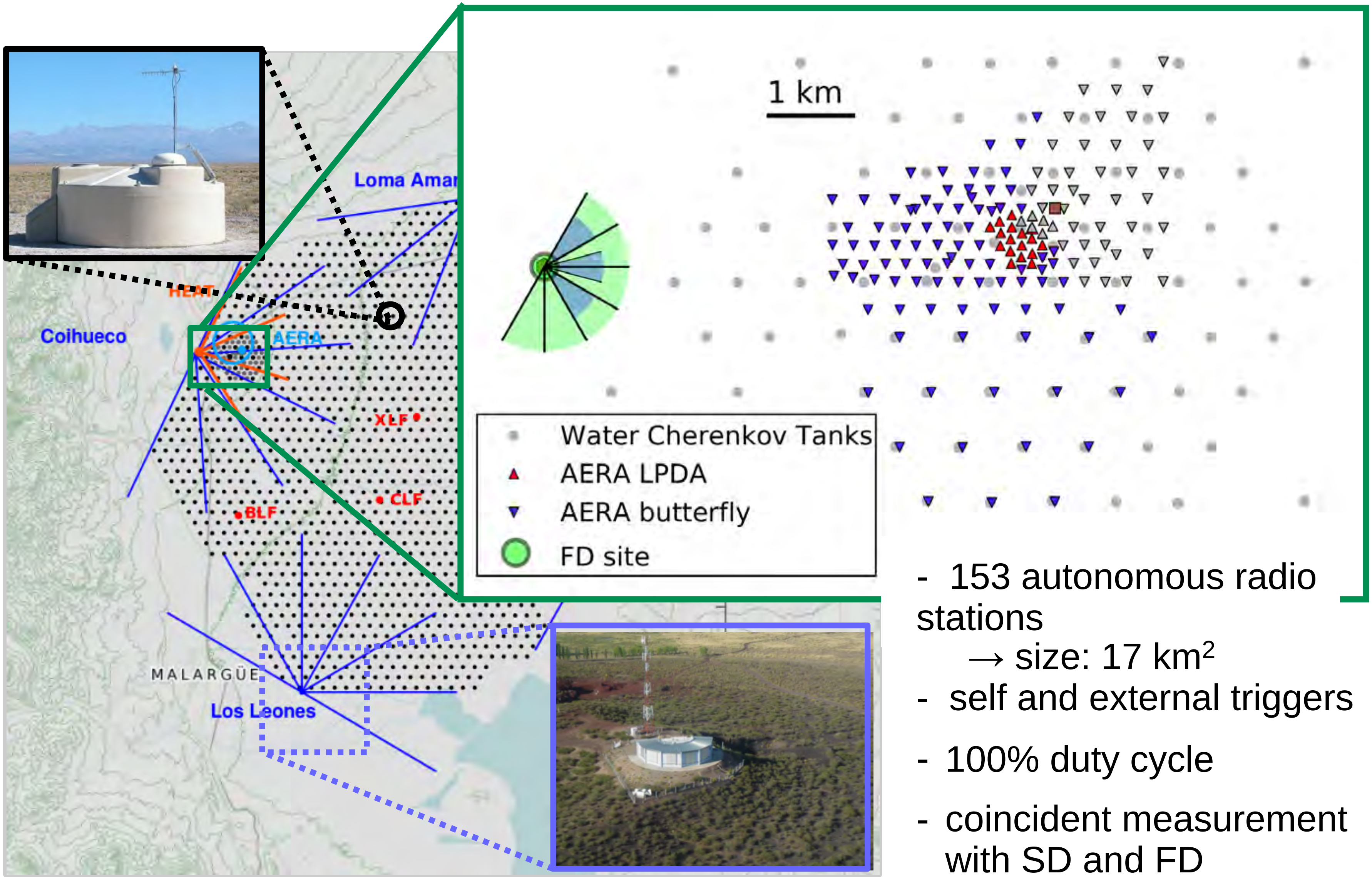
Auger Engineering Radio Array (AERA)



- 153 autonomous radio stations
  → size: 17 km^2
- self and external triggers
- 100% duty cycle
- coincident measurement with SD and FD

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AERA stations

Log-periodic dipole antenna (LPDA)

Butterfly antenna

- 1 GPS clock / station for timing
- Wireless communication antenna
- frequency range: 30-80 MHz
- Differential GPS: position accuracy better than 10 cm

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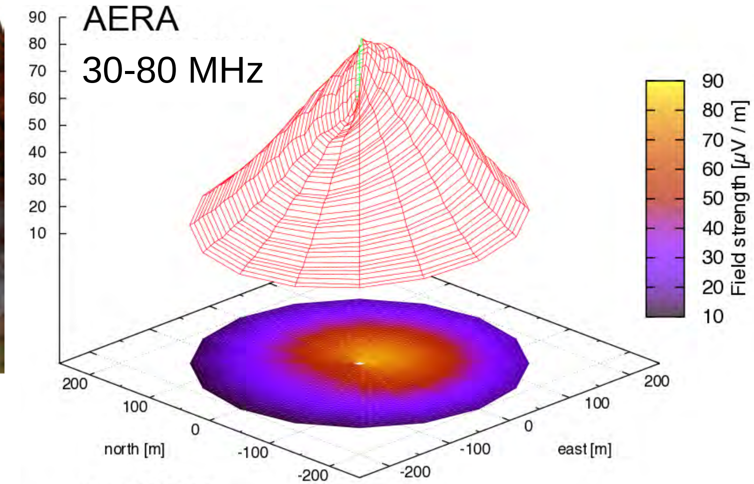
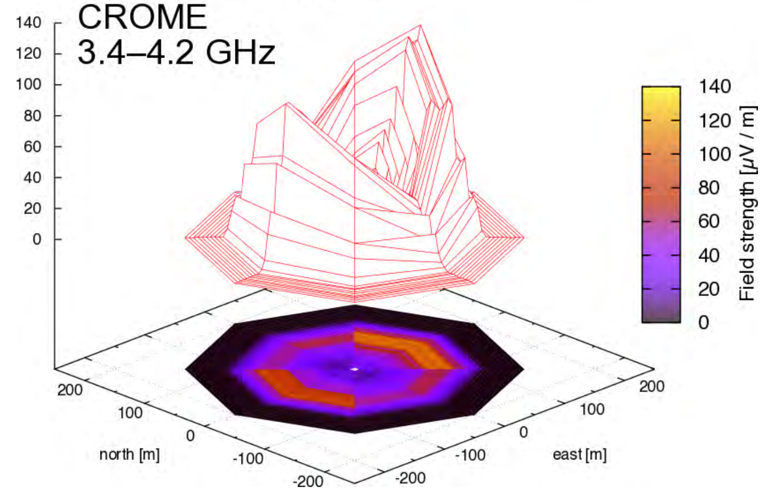
HAP supports of radio detection of cosmic rays

Tuna-Rex antenna

CROME antenna

simulated radio emission for different frequency ranges





- Objectives:
  - Scalability of cosmic-ray radio detectors to large arrays
  - Investigating radio detection in different frequency ranges
  - Initial investigation for radio antenna at South Pole (RASTA)

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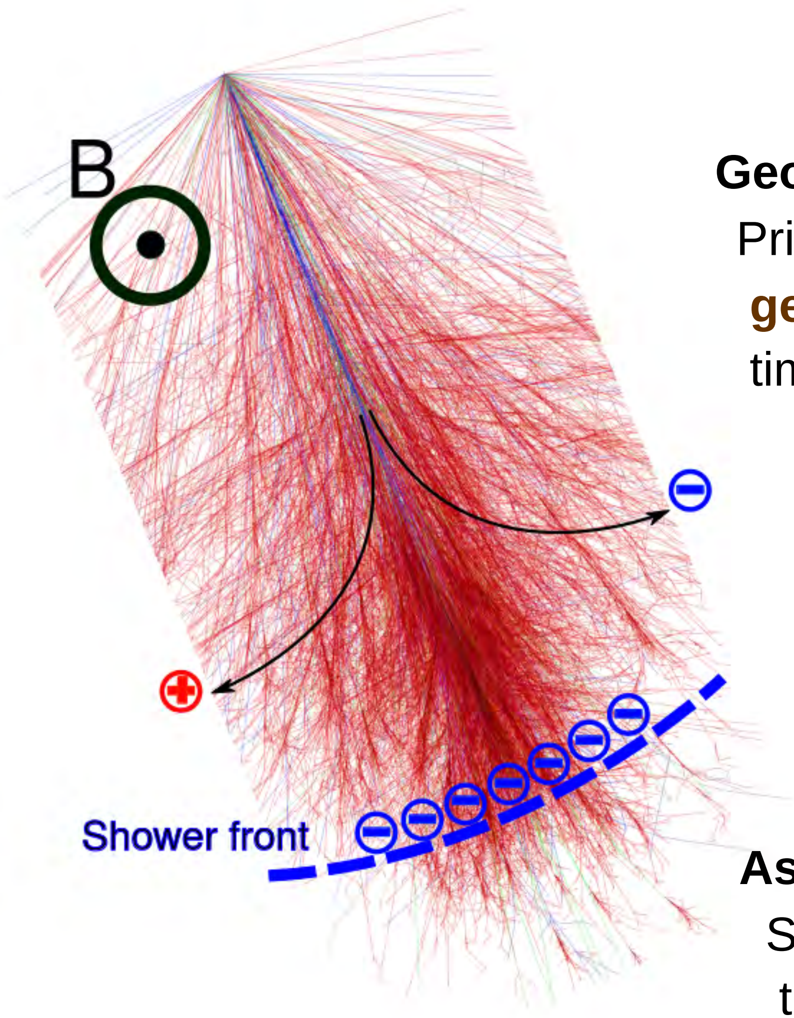
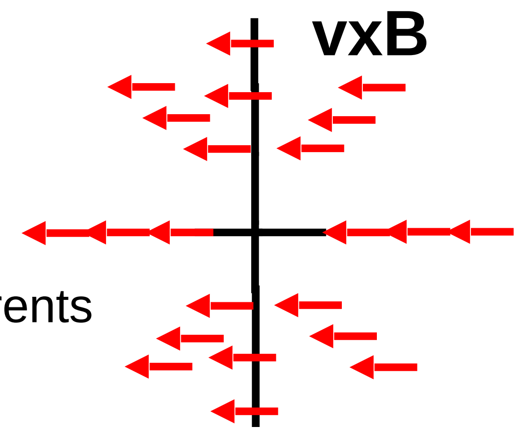
Radio emission mechanism

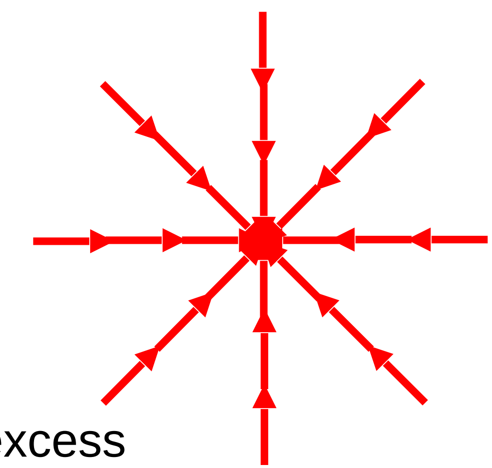




Geomagnetic effect

Primary effect:

geomagnetic field induces time-varying transverse currents



Askaryan effect

Secondary effect:

time-varying **net charge** excess

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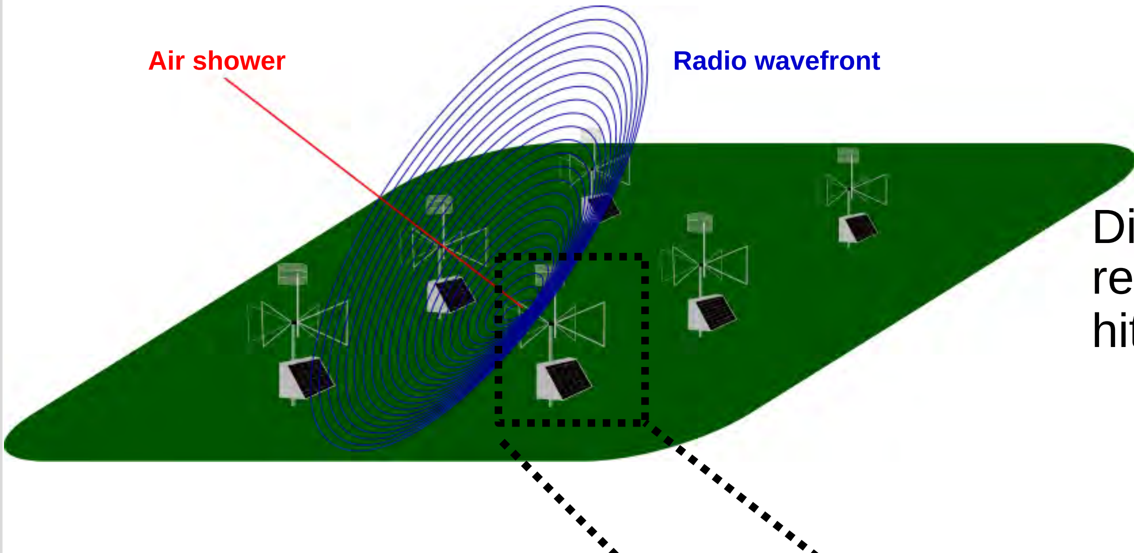
Radio detection principle

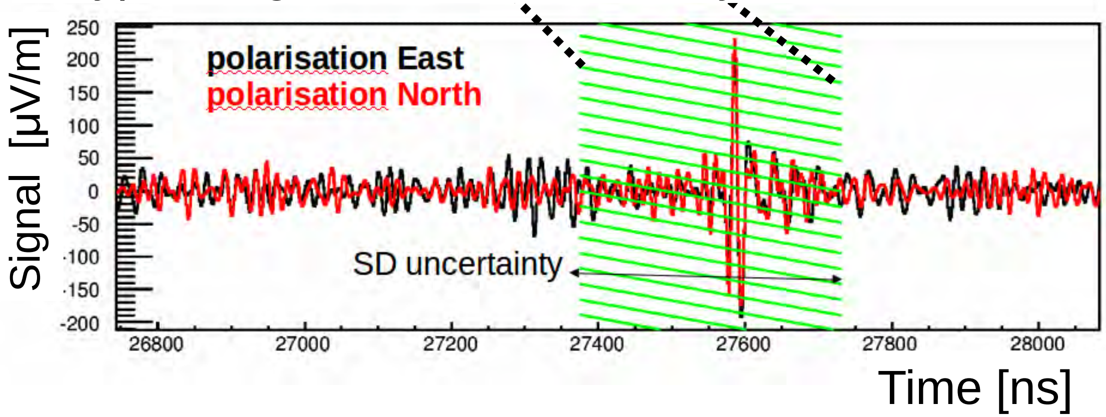
Karlsruhe Institute of Technology



Direction of **air shower** is reconstructed from **radio wavefront** hitting 2D array of **radio stations**

- Aims to measure:
  - In self and external trigger modes
  - Arrival direction
  - Energy
  - Mass composition
  - Radio interferometry

Typical signal trace recorded by radio stations



To exploit the full potential of radio measurement timing of **1 ns** is ideal

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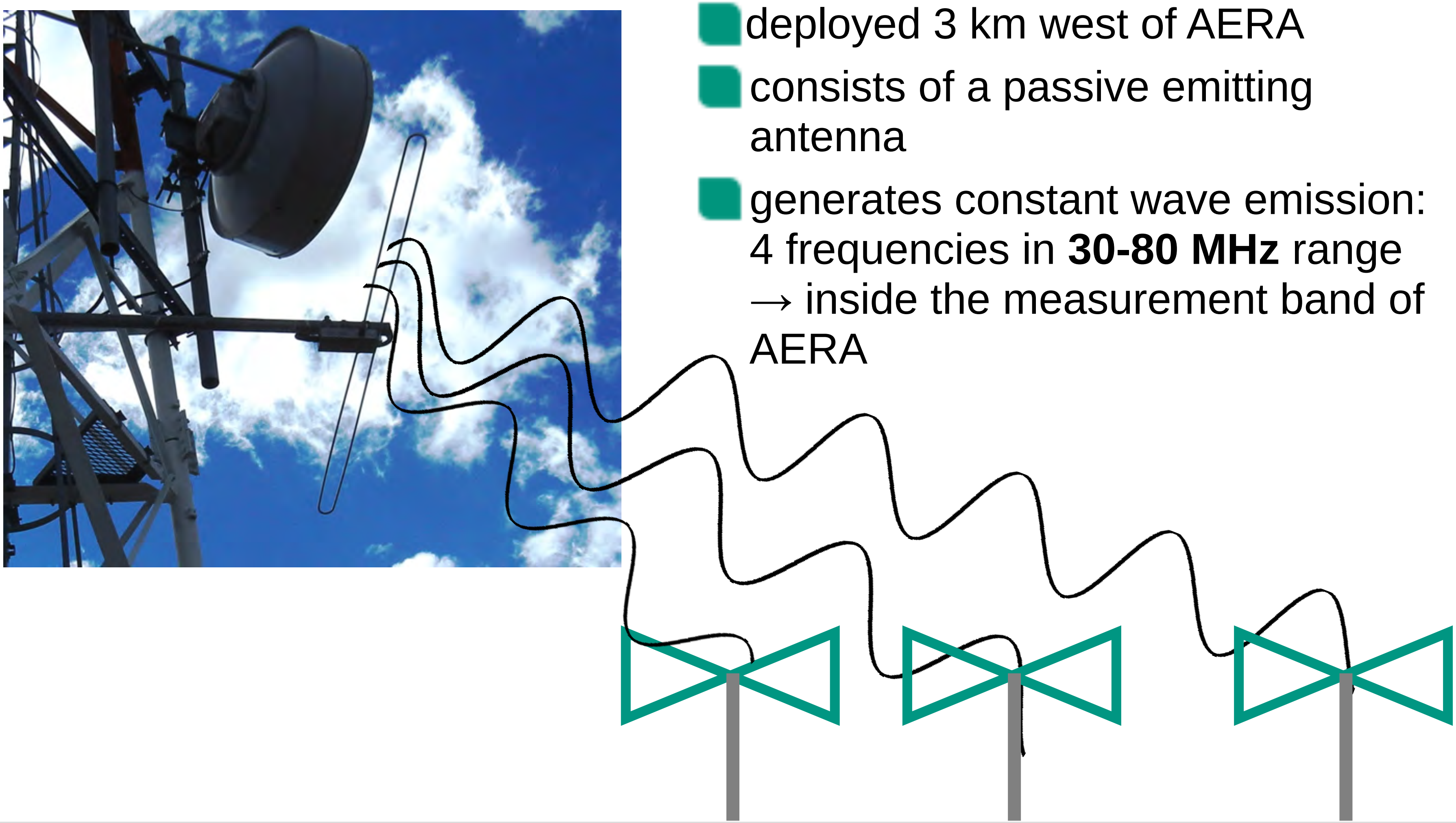
Time calibration of AERA

Beacon transmitter



- deployed 3 km west of AERA
- consists of a passive emitting antenna
- generates constant wave emission: 4 frequencies in **30-80 MHz** range → inside the measurement band of AERA

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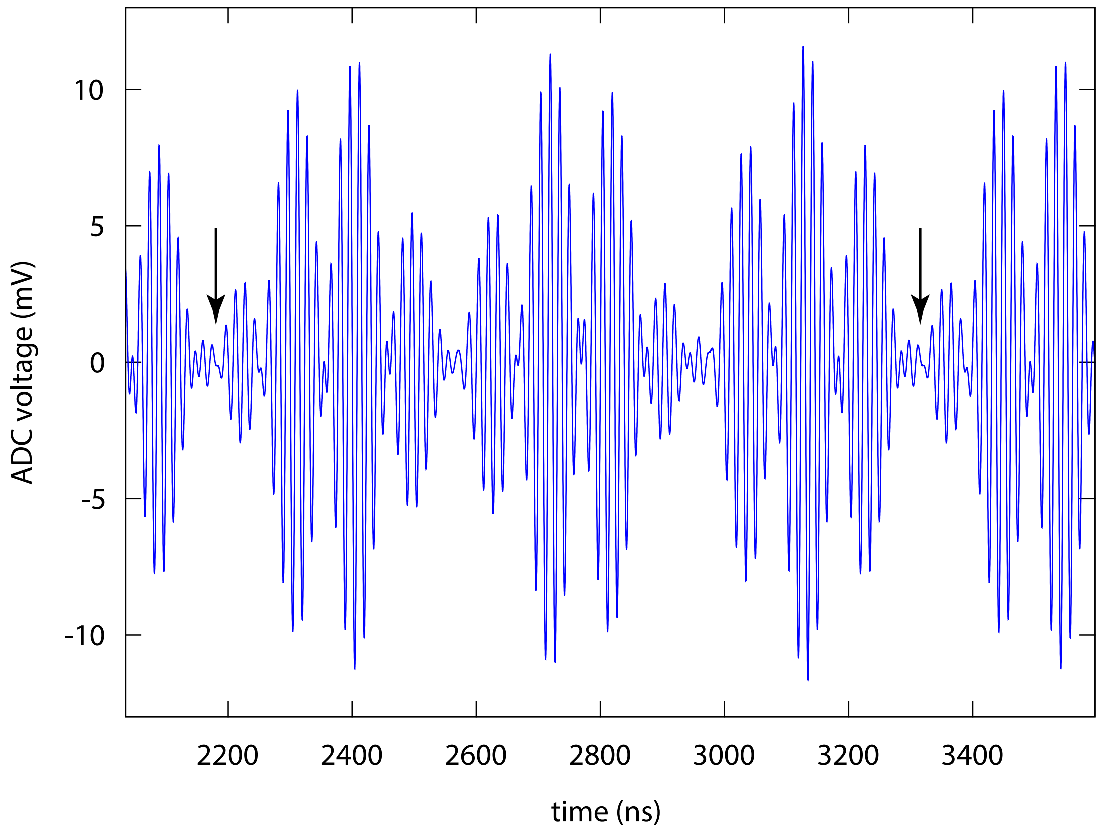
Principle of time calibration

Measured time trace of a typical beacon signal

- 4 sine waves beat repeats every 1.1 µs < AERA time trace length, i.e. 10 µs
- compare arrival time of beat with expected propagation time
- calculate relative time difference



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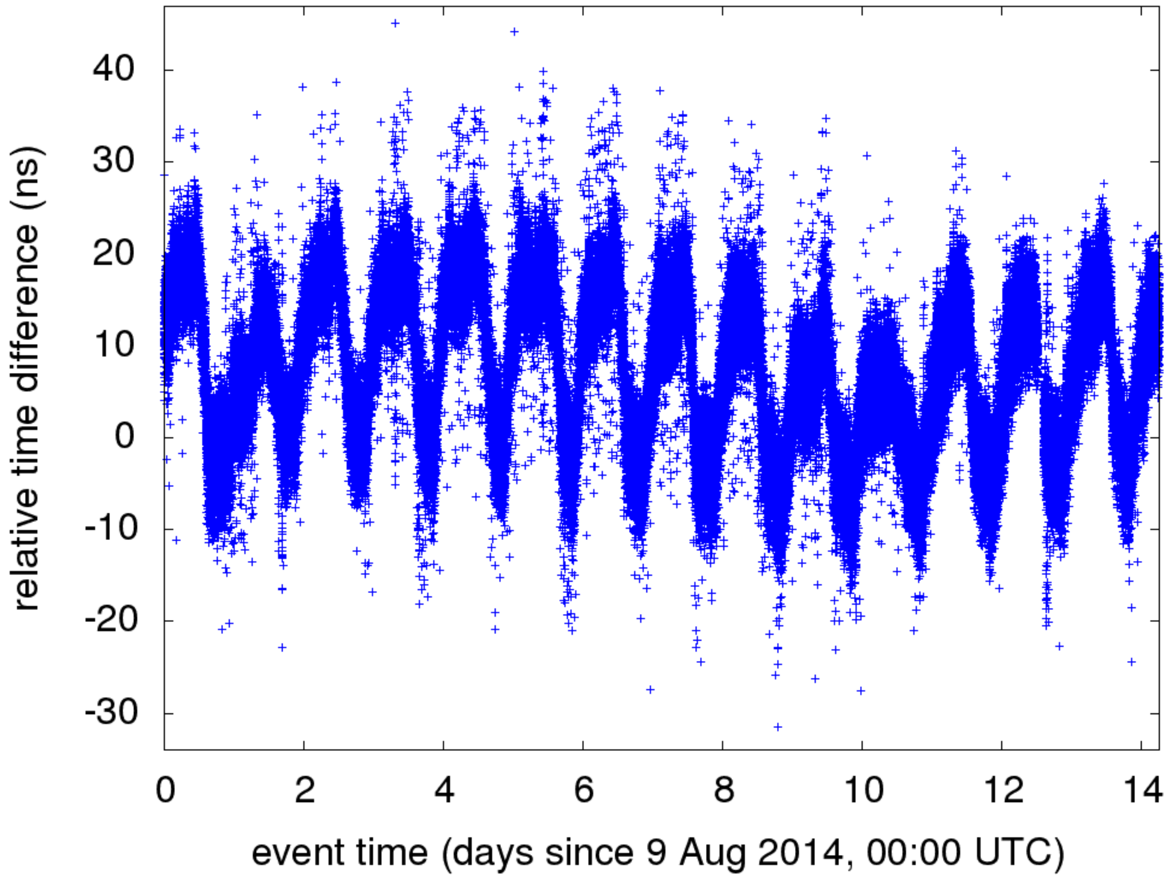
Performance of the time calibration

Typical time difference between radio stations



Strong fluctuations of a few 10 ns between stations: due to **GPS time offsets**?
Can beacon simply correct for this?
→ we need independent cross check

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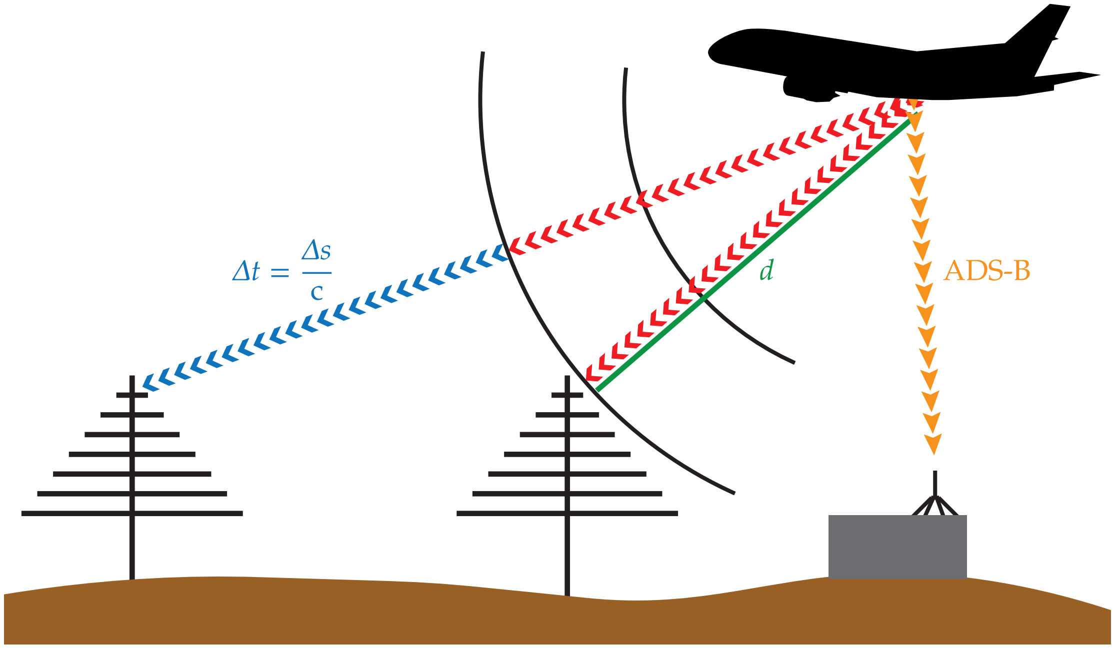
Airplane: independent method

- Some commercial airplanes send radio pulses which can be detected by AERA
- Airplanes also send ADS-B (Automatic Dependent Surveillance - Broadcast) data which can be used to determine their positions



→ estimate the pulse arrival time

→ cross check the time calibration of beacon method

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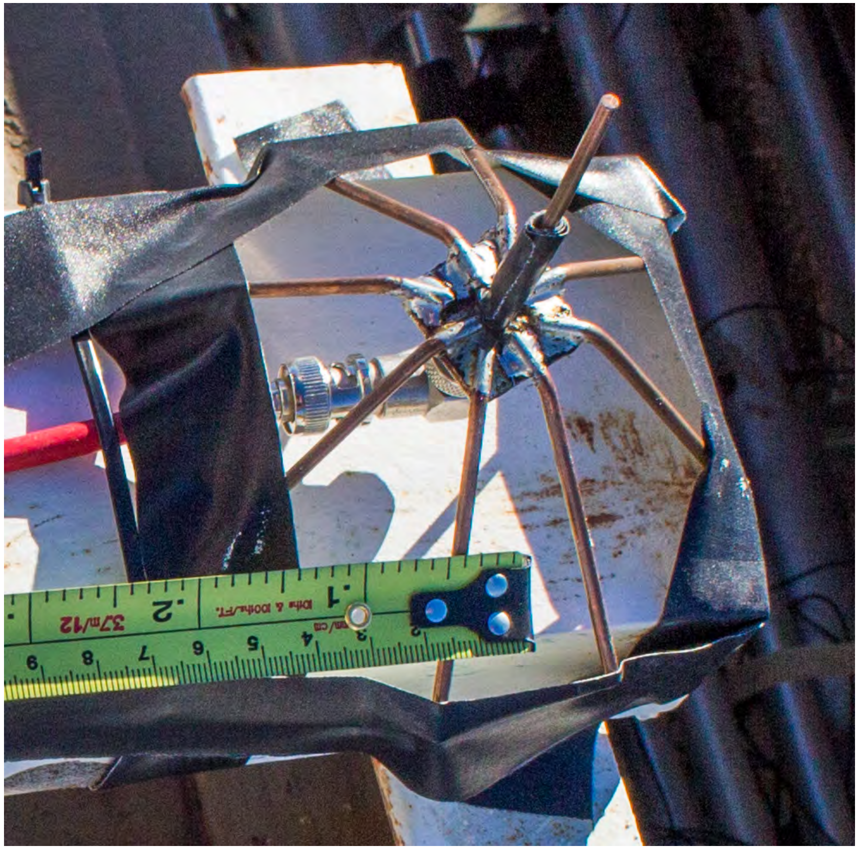
Determination of airplane position

ADS-B receiver antenna



- ADS-B transmitted at 1090 MHz
  at rate of 0.5 − 1 Hz
- contains information, e.g.
  latitude, longitude, altitude, heading
  and speed of the airplane
- can be received with equipments
  costing less than 20 USD

We deployed an ADS-B receiver antenna at the AERA field
→ range of detection 400 km

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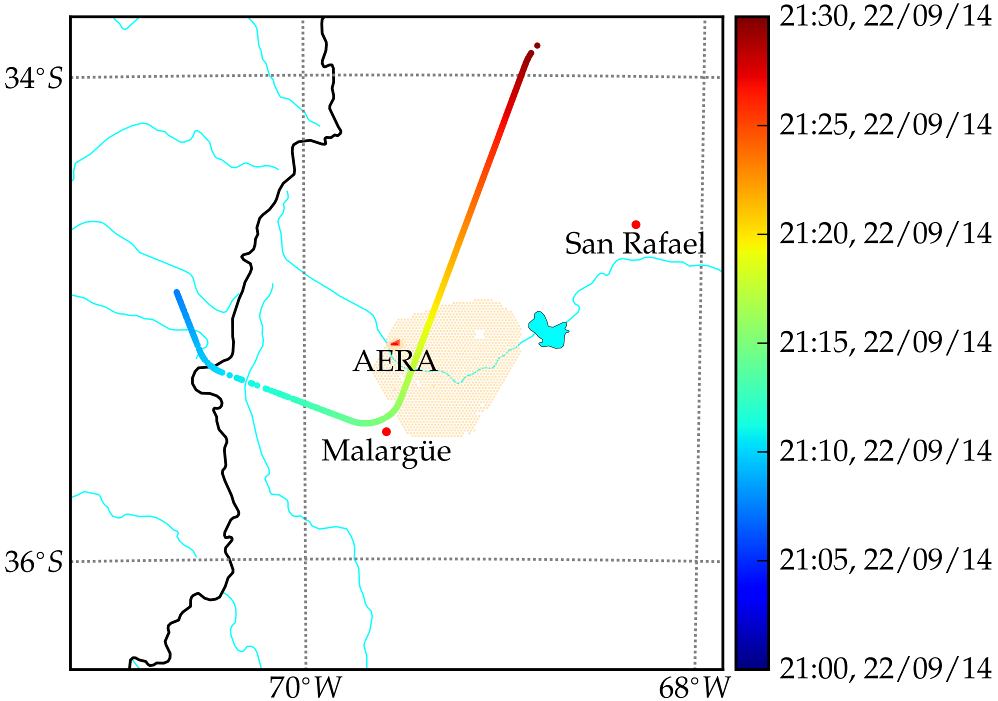
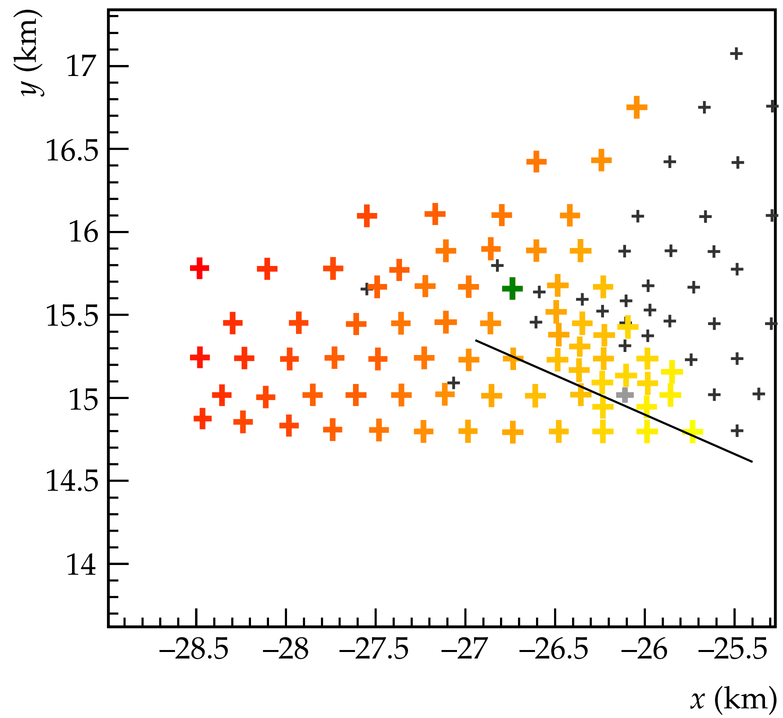
An example event

An airplane trajectory reconstructed from ADS-B data



The airplane pulse measured by AERA



By combining the real-time position information from ADS-B
and the radio pulses emitted by airplanes
→ **time offsets** between GPS clocks can be calculated

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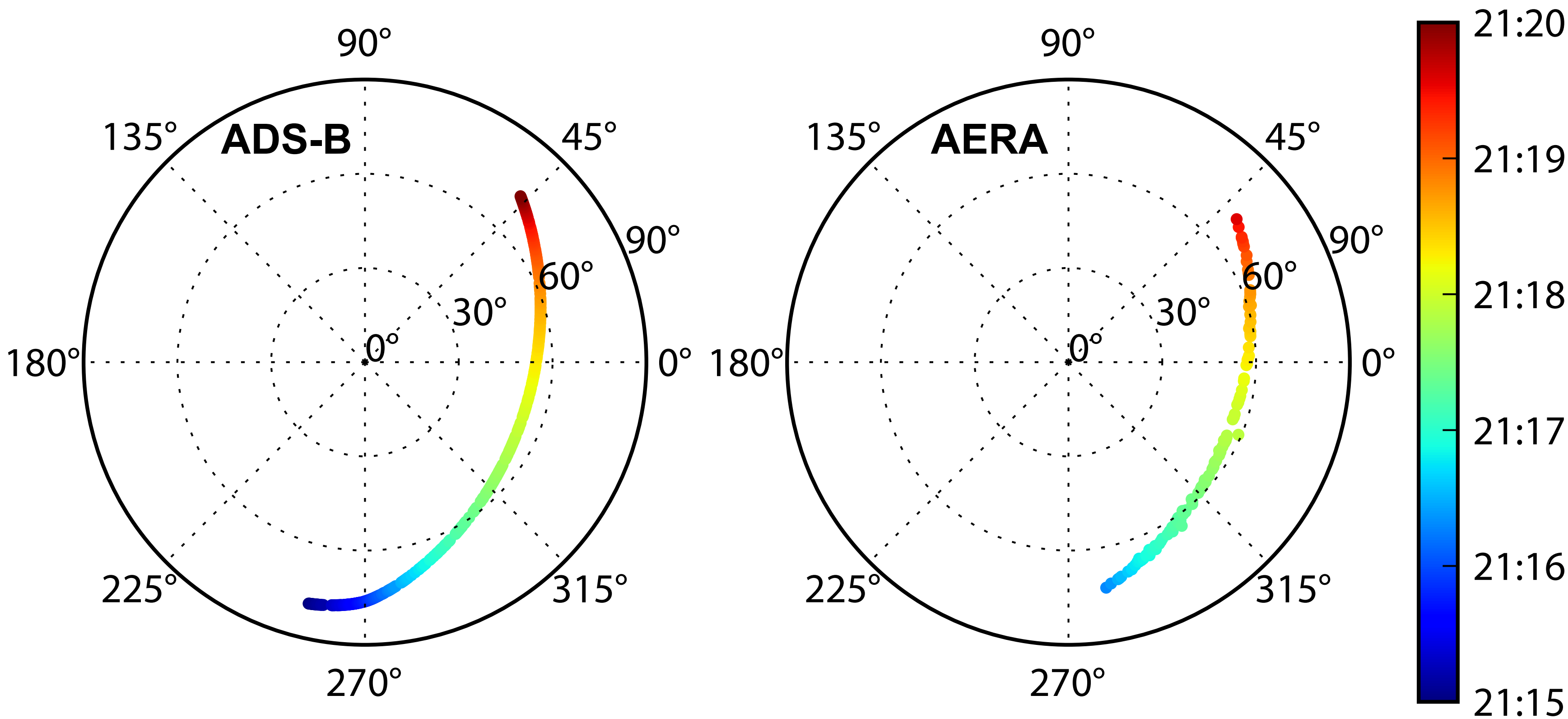
Comparison between ADS-B and AERA data



ADS-B and AERA reconstructed airplanes are highly correlated

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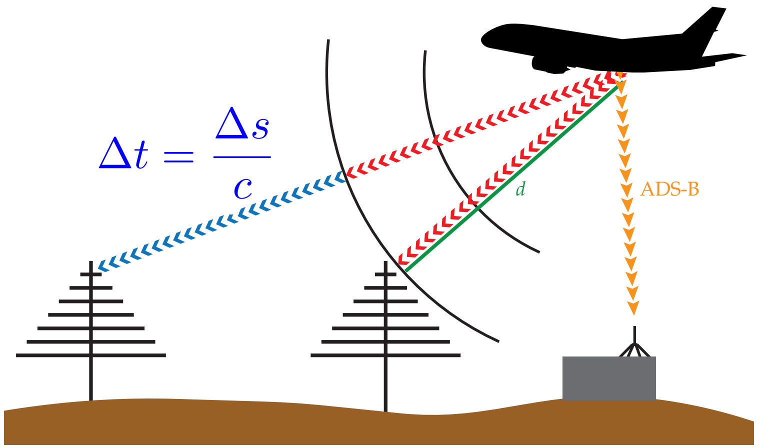
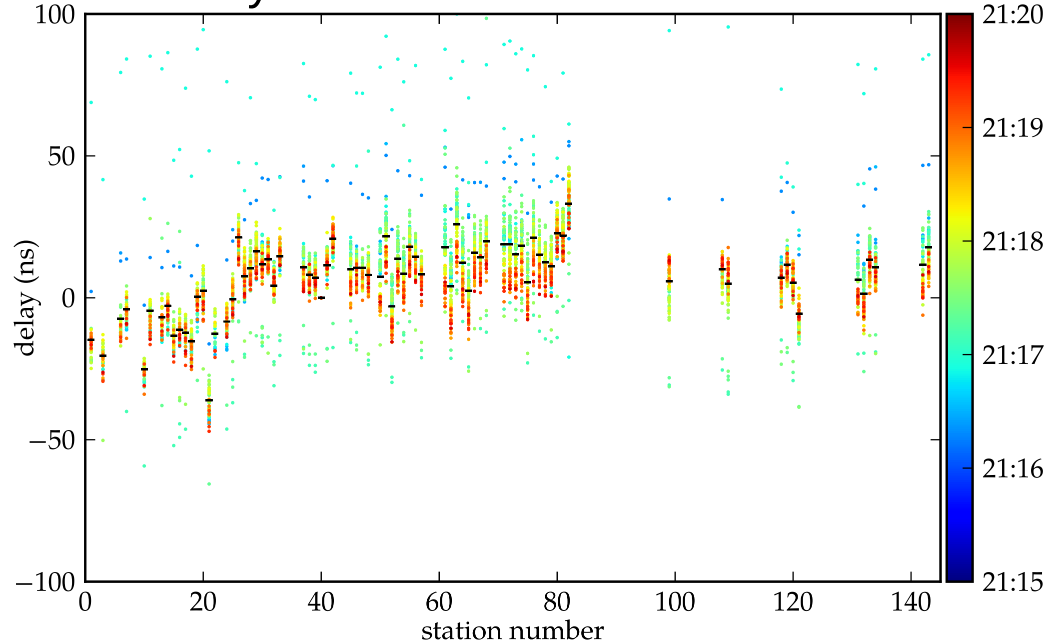
Performance of the airplane time calibration



Time delay as a function of radio station ID



Time delay:
Time difference between a reference station (40)
and other stations, corrected for expected propagation time Δt

Again strong time fluctuations between stations: due to **GPS time offsets**??
→ apply beacon correction

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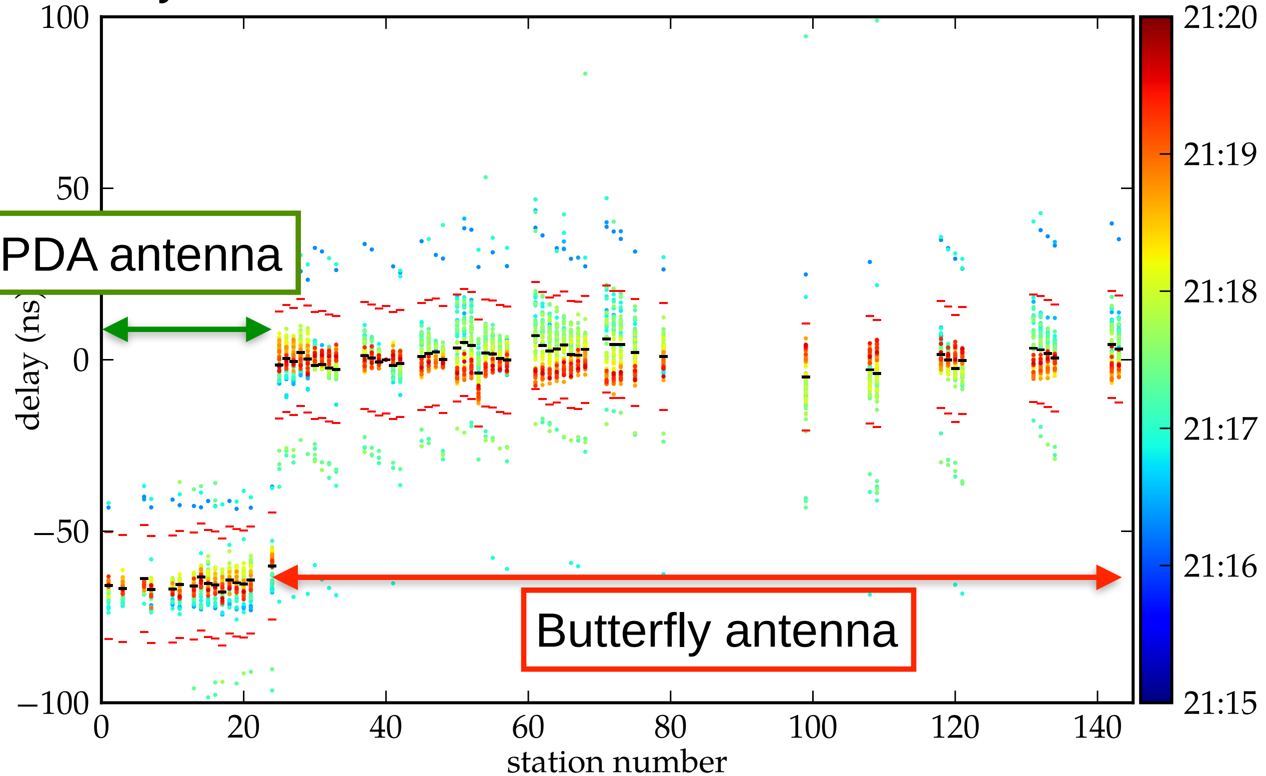
Combination of beacon calibration and airplane measurement

Time delay as a function of radio station ID after beacon correction



Different antenna response → different group delay

Mean time offsets over the course of several months are consistent within **2 ns**

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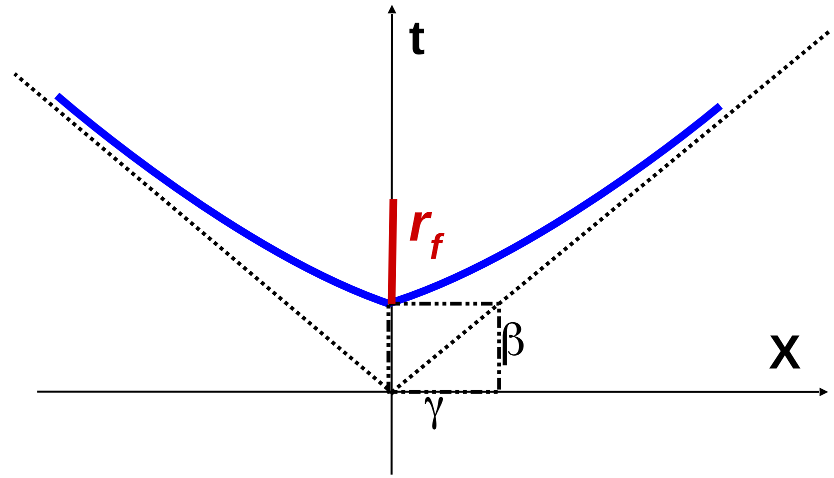
Reconstruction improvement

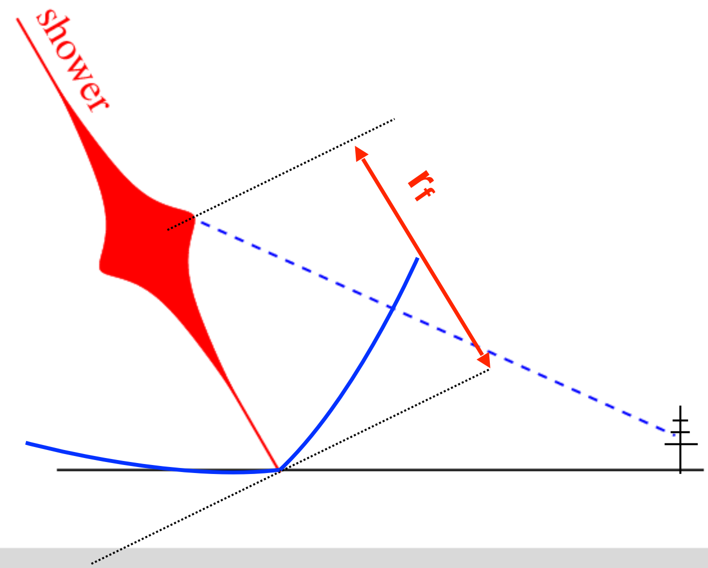
- The wavefront of radio emission is known to be of hyperbolic shape
- We fit a hyperbolic function

$$t = \beta \left(\sqrt{1 + x^2/\gamma^2} - 1 \right)$$

  to extrapolate radio pulse time measured by stations as a function of its distance to the shower axis
- Distance r_f *to focus is correlated to depth of shower maximum*
  $\rightarrow$ *composition measurement*

Hypothetical hyperbolic wavefront





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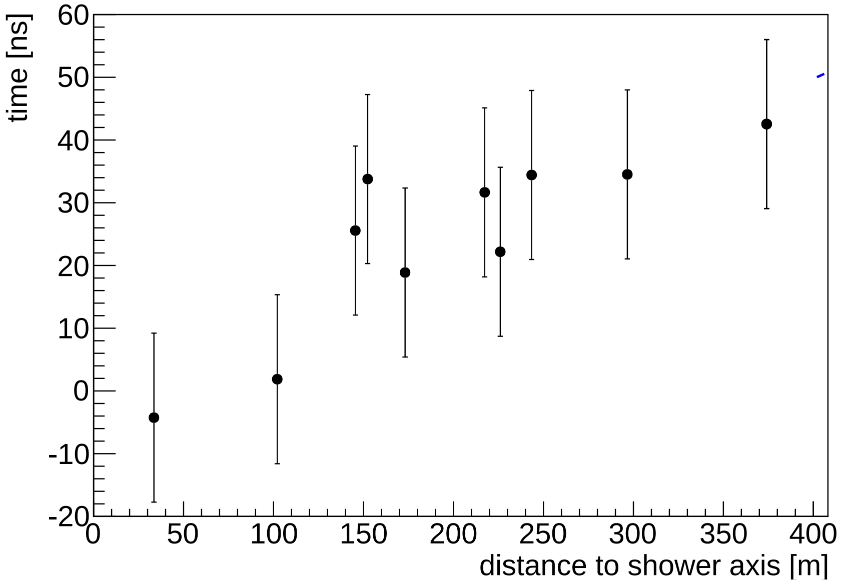
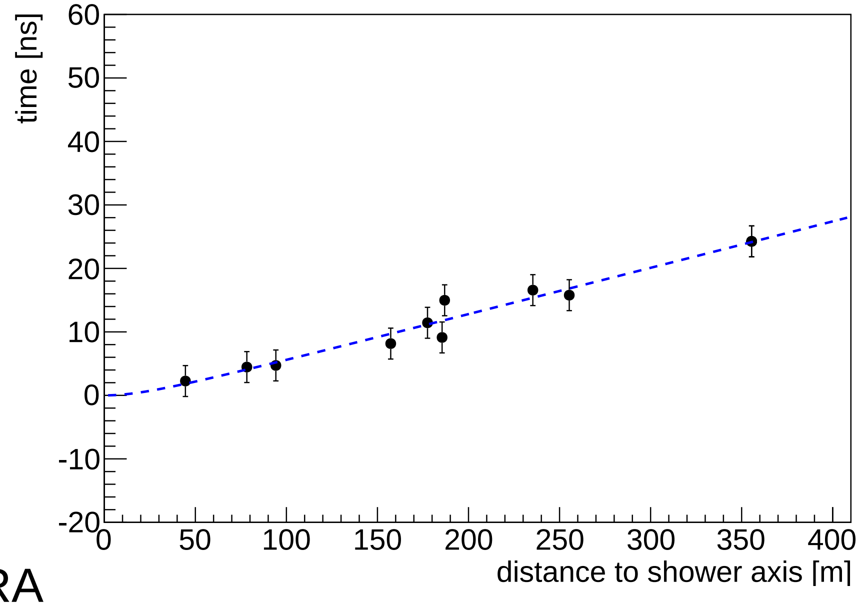
Measurement of radio wavefront

measured wavefront **before** beacon correction



measured wavefront **after** beacon correction



This event imply both antenna type of AERA

After beacon correction the spread between the antenna types are **suppressed**

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Summary

- Radio detection of cosmic rays provides complementary information on air shower physics
- Beacon provides a high precision timing calibration for autonomous radio detector
- We have cross-checked the beacon timing calibration with a novel method using the signal emitted from commercial airplanes:
  → 2 ns time precision
- The time calibration is already included in analysis

Outlook

- Collect more airplane events

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Spare slides

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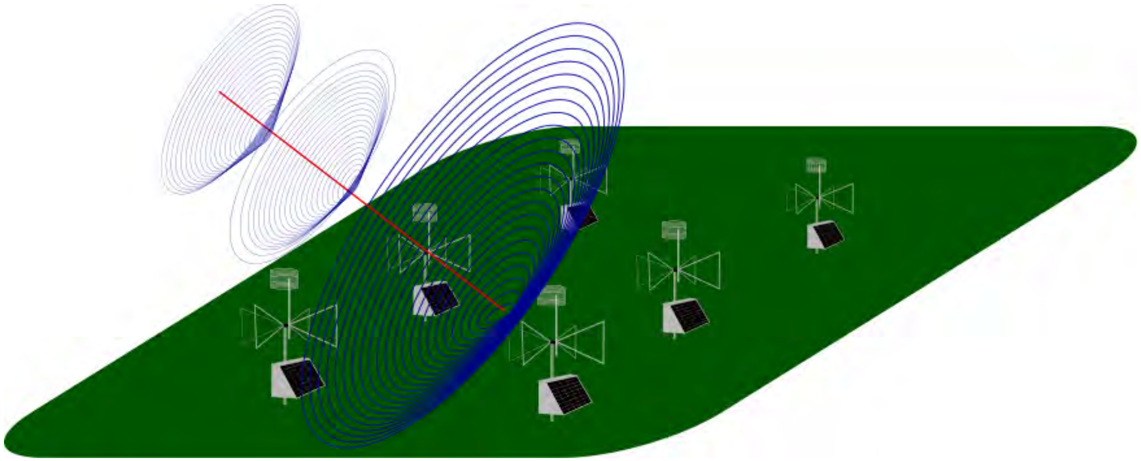
Physics objective of AERA

Artist's impression of radio wavefront measured by AERA

- Accurate measurements of:
  - Arrival direction
  - Energy
  - Mass composition
  - Radio interferometry



Shape of the wavefront measured on ground relates to the composition of cosmic rays

To exploit the full potential of radio measurement timing of 1 ns is needed

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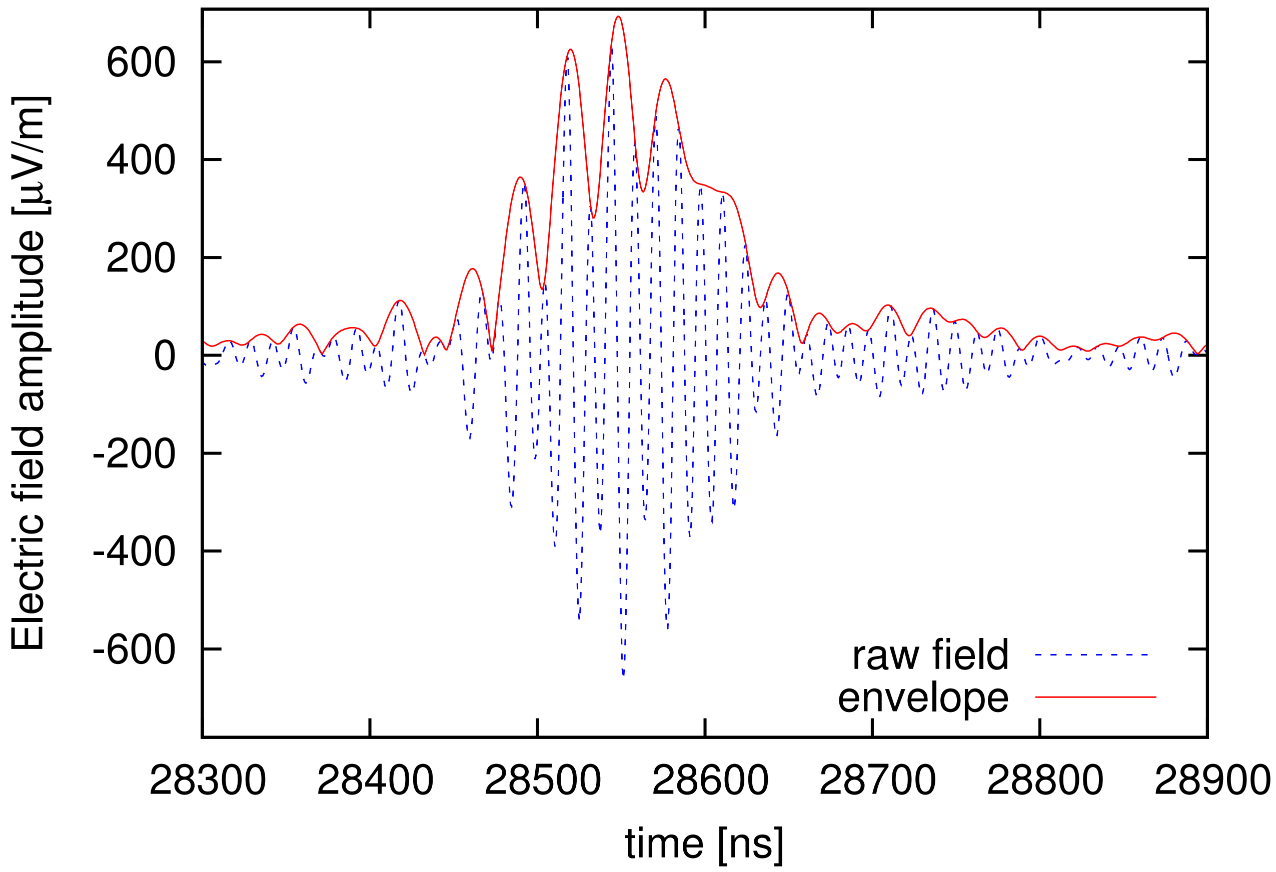
Typical airplane radio pulse measured by AERA stations



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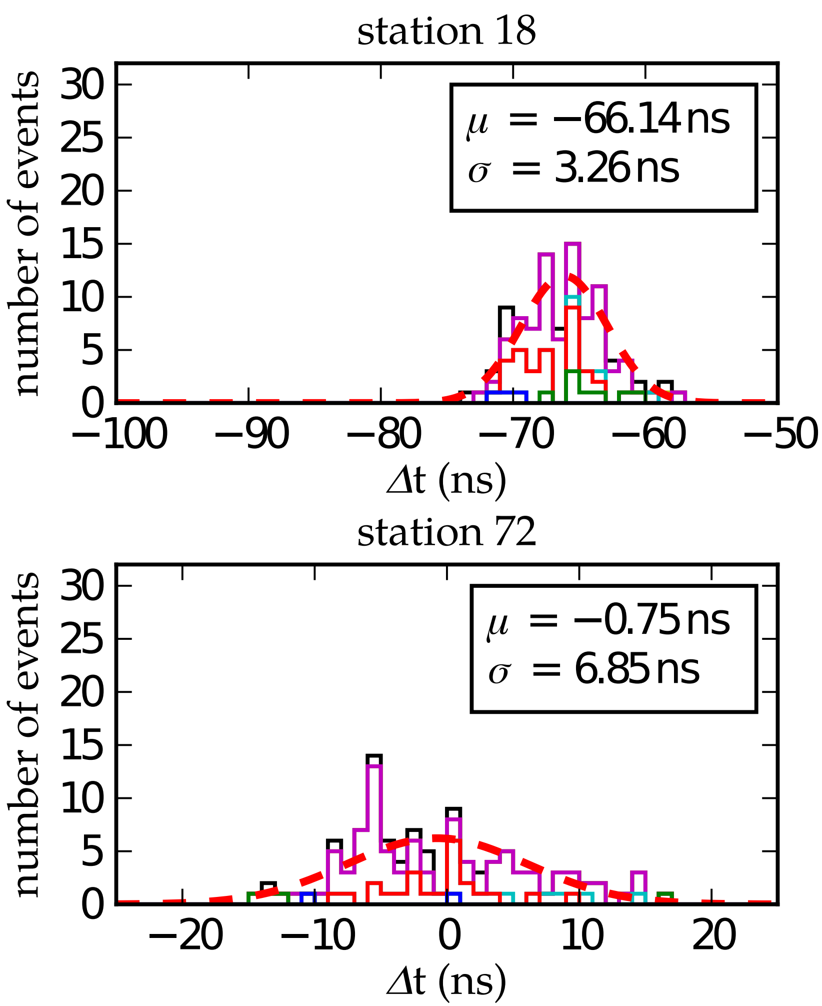
Time delay measured with AERA station



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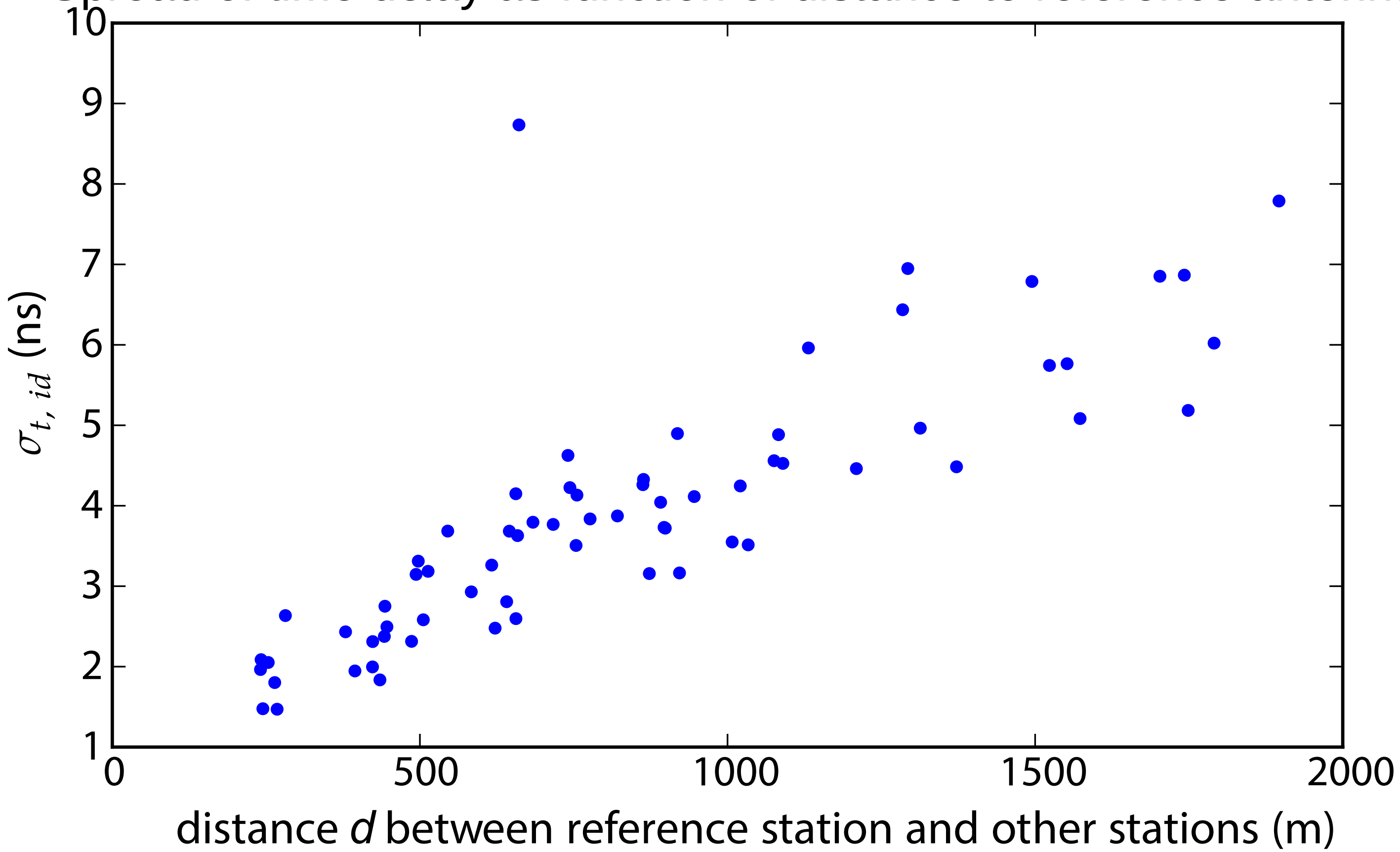
Systematic uncertainties of airplane measurement

Spread of time delay as function of distance to reference antenna



The further from the reference station, the more precisely airplane position should be known

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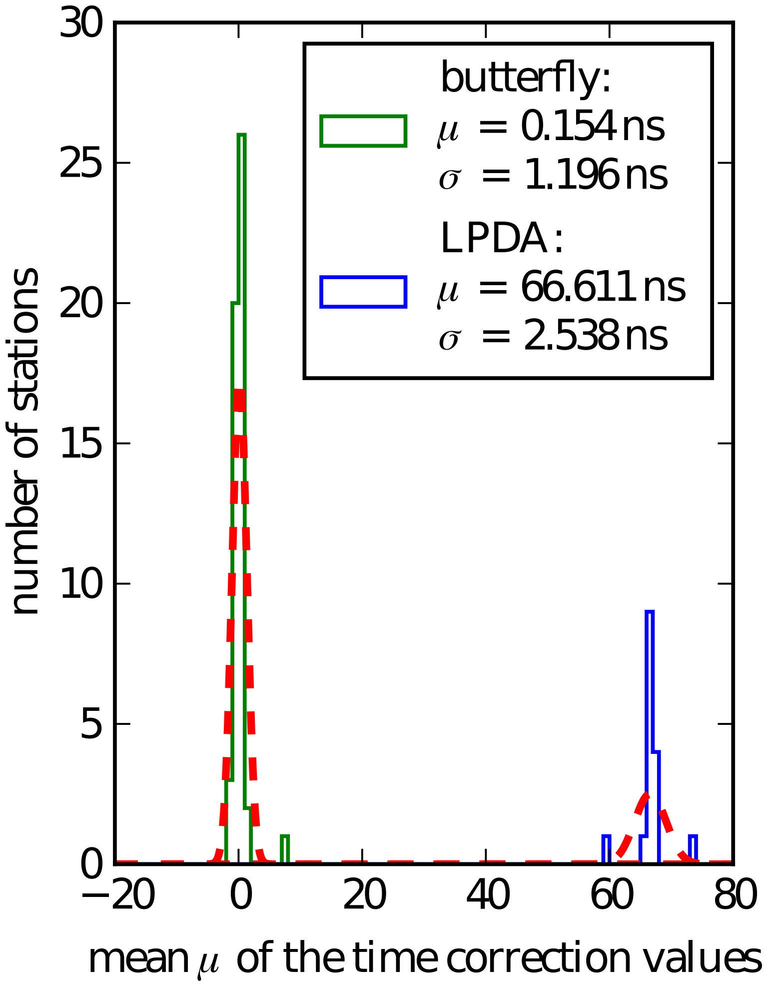
Airplane timing after beacon correction



- quadratic sum of the spread of the mean of time delay: **2 ns**

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