Adding interferometric lightning detection to the Pierre Auger Observatory

AtmoHEAD 2024

Melanie Joan Weitz for the Pierre Auger Collaboration

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University of Wuppertal

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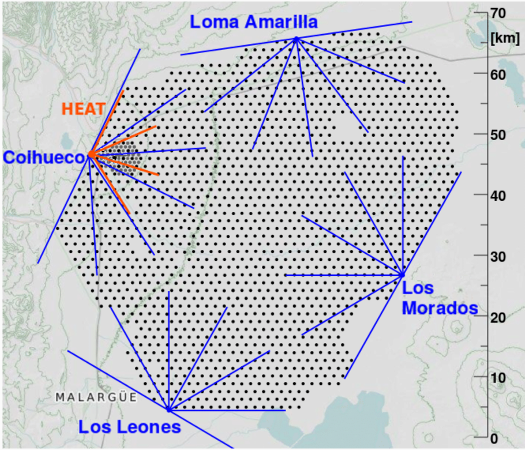
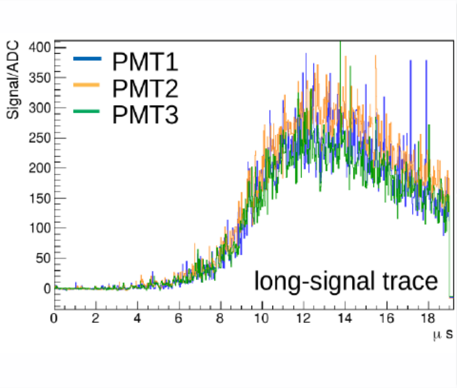
Bundesministerium für Bildung und Forschung

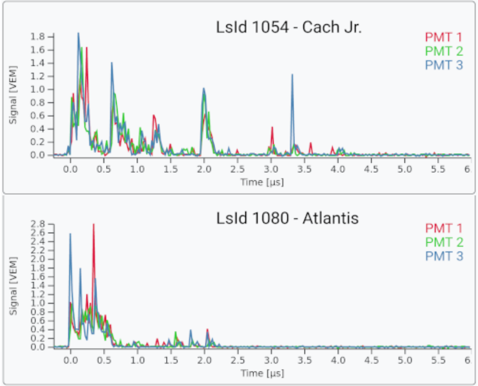
PIERRE AUGER OBSERVATORY

- World's largest observatory for studying ultra-high energy cosmic rays (>10^{17} eV)
- Located in Pampa Amarilla, Argentina
- 3000 km^2 hybrid array:
  - Air fluorescence telescope (FD)
  - Water Cherenkov detector (WCD)
  - Radio detector (RD)
  - Underground Muon detector
  - Scintillator Surface detector
- Offers large opportunities for observation of high-energetic atmospheric phenomena



Detection of peculiar events with WCDs of Pierre Auger Observatory





(Roberta Colalillo, PoS(ICRC2023)439; Auger Open Data, Event: 182318542300)

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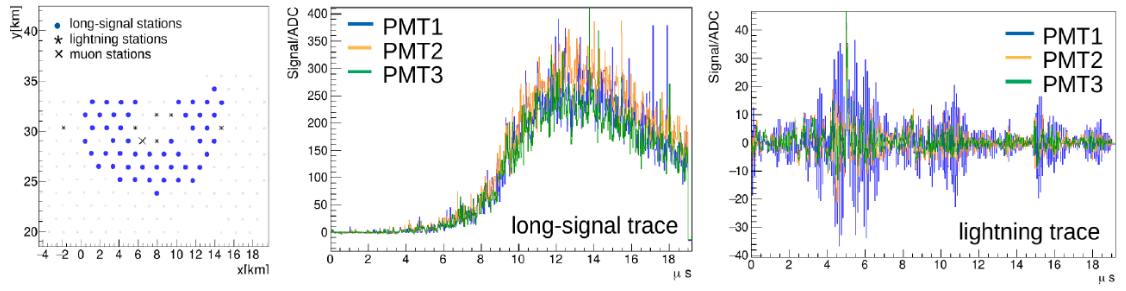
Detection of peculiar events during thunderstorms with WCDs of Pierre Auger Observatory (Auger)
$\rightarrow$ likely related to Terrestrial Gamma-ray Flashes



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- Observations:
  - Larger multiplicity of triggered WCDs
  - Footprint covers $\sim 200\,\text{km}^2$
  - Signal times $> 10\,\mu\text{s}$

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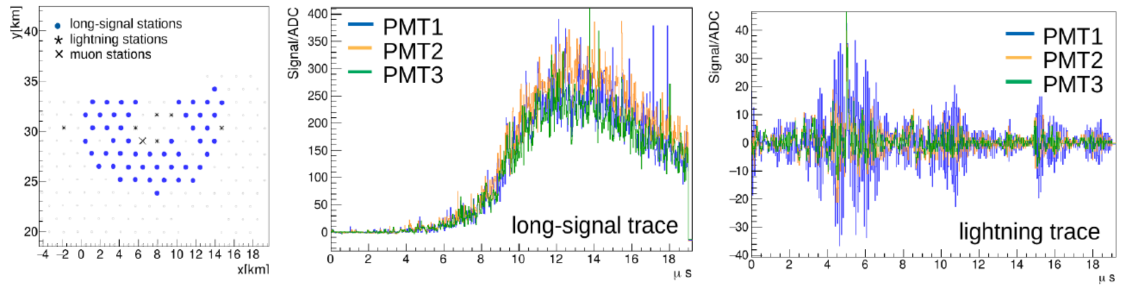

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- Motivation:

What are the properties of thunderstorms triggering Terrestrial Gamma-ray Flashes and at which lightning stage are they produced?

Terrestrial Gamma-ray Flashes (TGFs)

- Gamma-ray bursts originating from Earth's atmosphere during thunderstorms
  - Upward
  - Downward
- Lasting from tens of μs up to ms
- Not clear:
  - Characteristics of boundary conditions
  - Lightning stage involved

Artist interpretation (©NASA/Goddard Space Flight Center)

Thunderstorms influence measurements of Auger hybrid array
⇒ Large disruption source:

- Optical emission → FD
- Electric field → RD
- Radio signal of lightning → RD, WCD

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Thunderstorms influence measurements of Auger hybrid array
⇒ Large disruption source:

- Optical emission → FD
- Electric field → RD
- Radio signal of lightning → RD, WCD
  - Lightning strikes emit radio signal in low frequency band (LF: kHz) and very high frequency band (VHF: MHz)

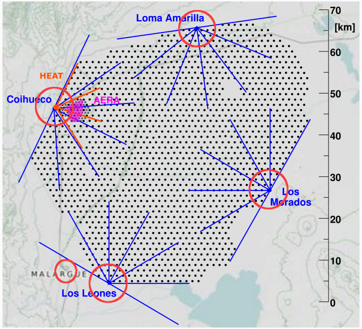
→ Cloud-to-ground lightning detection via Lightning Detection System at Auger for investigation of cosmic ray ↔ lightning connection

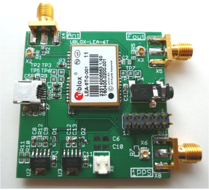
Lightning Detection System at Pierre Auger Observatory

Lightning Detection System consists of
5 Lightning Detection Stations (LDS) installed at FD sites and Malargüe campus

LDS consist of:

- Commercial lightning detector:
  - Boltek StormTracker
  - PCI card with external antenna
  - 2 polarizations: North-South and East-West
  - Sensitivity: $\sim 10 - 90\,\mathrm{kHz}$
- GPS extension:
  - Own-build extension card with ublox LEA-6T chip
  - Delivers GPS time stamp

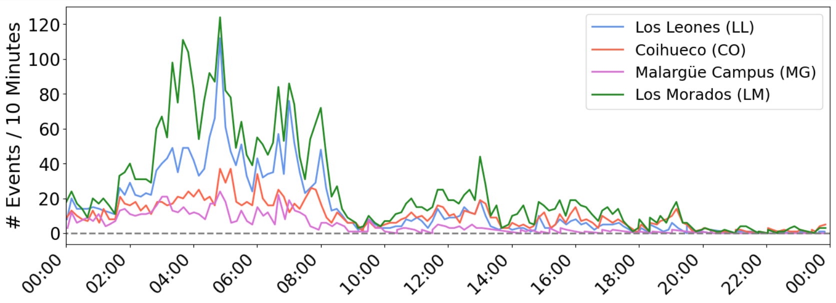




left: Boltek StormTracker, right: ublox LEA-6T (Lukas Niemietz, PhD thesis)

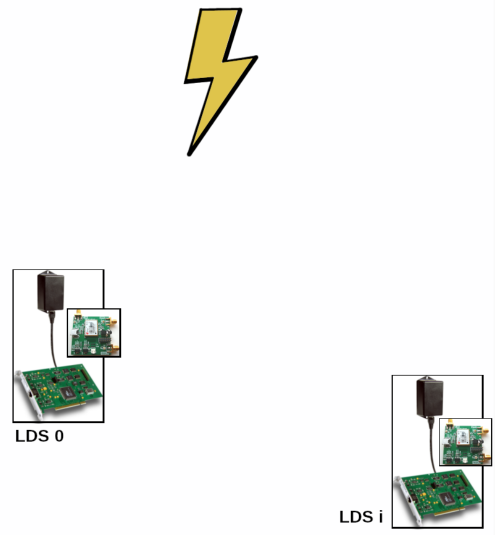
Single LDS Information

- Individual StormTracker data
- Direction and distance based on ratio of polarizations and amplitude
  $\rightarrow$ measurements of October 16, 2014



- Background, e.g. laser firing for atmospheric monitoring

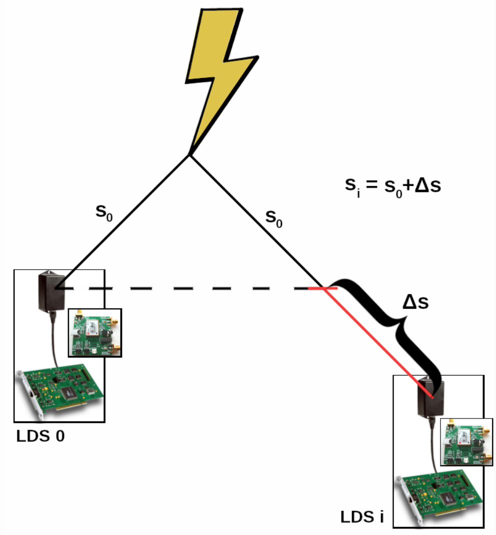
- StormTracker data combined with GPS time



(adapted from Lukas Niemietz, PhD thesis)

Lightning Event Reconstruction: Multiple LDS

- StormTracker data combined with GPS time
- Reconstructed lightning position dependent on
  - Position of stations to each other
  - Time offsets Δt_i from LDS signals to each other



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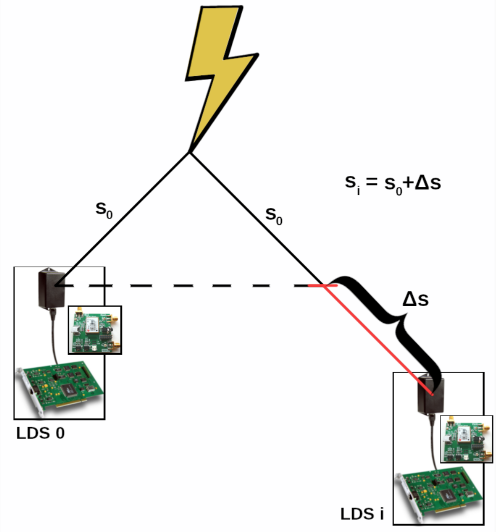
    - → Distance difference:

$$\Delta s = \underbrace{(t_i - t_0)}_{\Delta t_i} \cdot c$$



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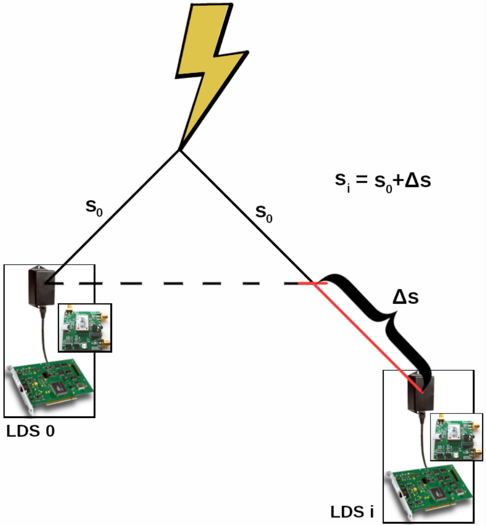

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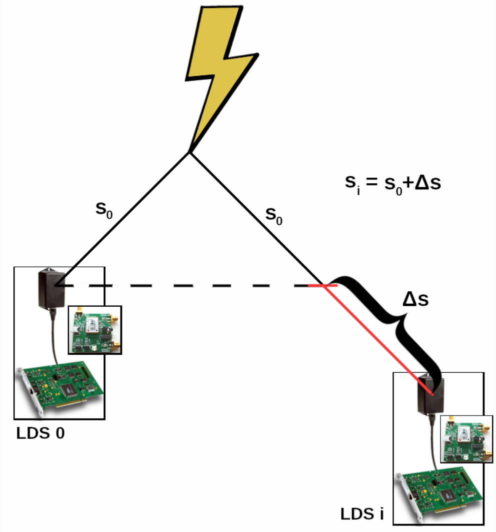
  - $\Rightarrow$ Triangulation for distance to lightning
- More information: J. Rautenberg, PoS(ICRC2015)678



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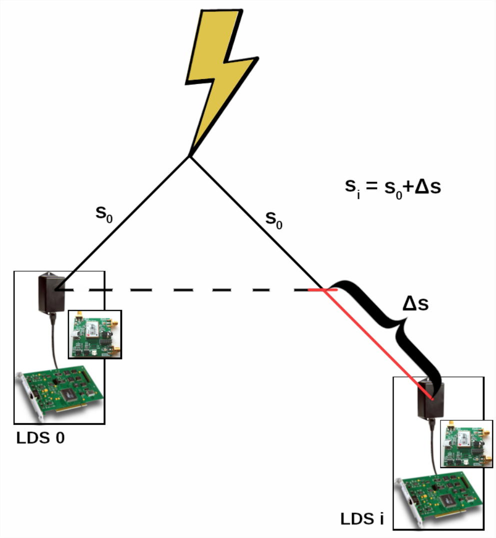

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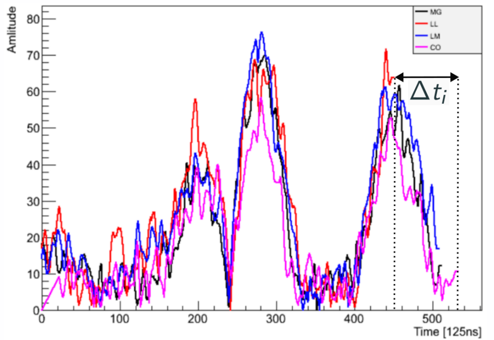
Lightning Event Reconstruction: Cross-correlation

- Optimal Δt_i for lightning position estimation



(Lukas Niemietz, PhD thesis)

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- Optimal Δt_i for lightning position estimation
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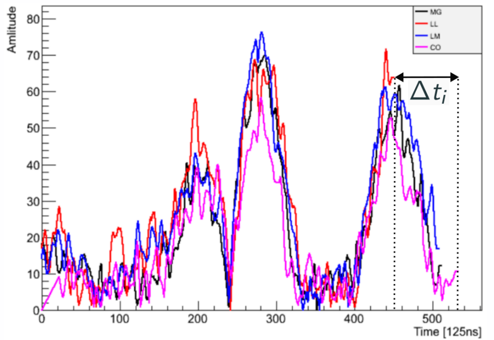

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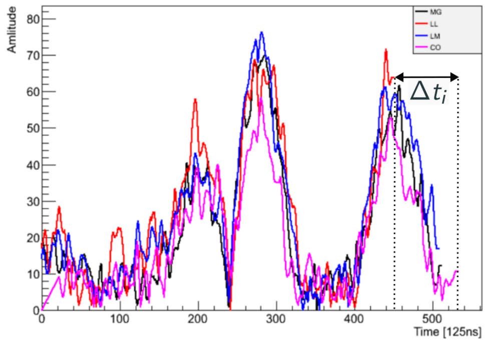
Lightning Event Reconstruction: Cross-correlation

- Optimal Δt_i for lightning position estimation
- Cross-correlation method:
  - Highest signal-product of **full traces**:

$$CC(\text{offset}_i) = \max\left[\sum_j (S_{0,j}\, S_{i,j+\text{offset}_i})\right]$$

$$\text{with } S_{i,j} = \sqrt{S^2_{i,\text{NS},j} + S^2_{i,\text{EW},j}}$$



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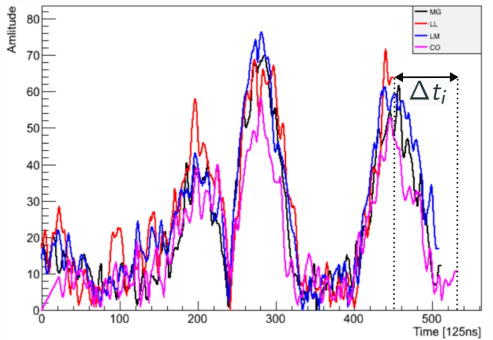
  - Including time binning:

$$\Delta t_i = \mathrm{offset}_i \cdot 125\,\mathrm{ns}$$



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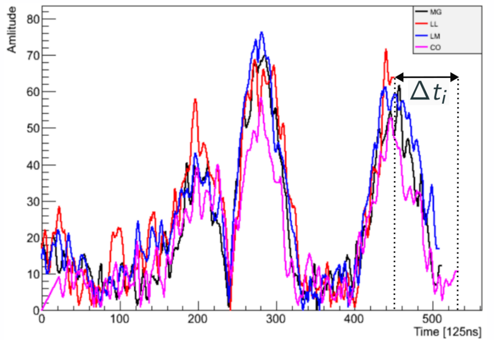
- Resolution of reconstruction: $\sim$ km



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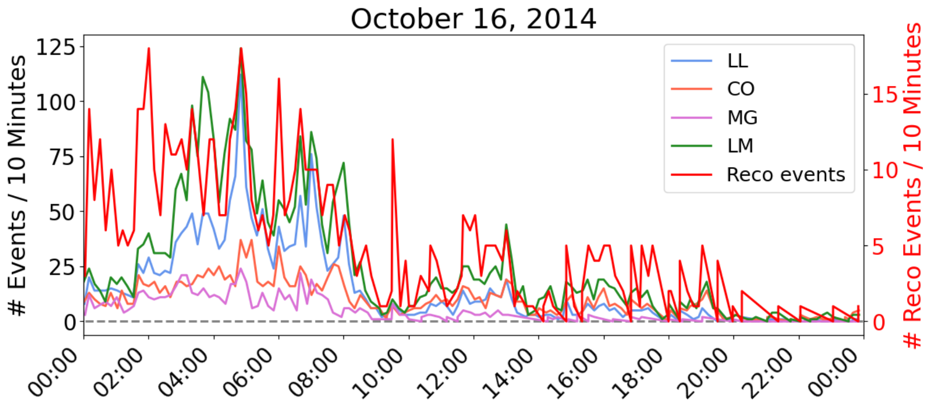

- Multiple station reconstruction suppresses background noise
  $\rightarrow$ important for trigger

Why Interferometric Lightning Detection at Auger?

- Key for connection lightning $\leftrightarrow$ TGFs
  $\rightarrow$ Enhance understanding of thunderstorms and lightning
- One possible enhancement
  $\rightarrow$ Construction of Cloud-to-ground lightning conducting path
- Can lead to
  $\rightarrow$ Properties of thunderstorms triggering TGFs

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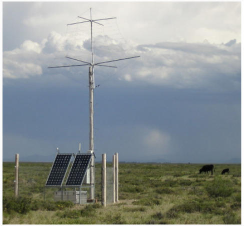
BUT: Lightning Detection System resolution is too small
$\Rightarrow$ Possible solution:

Reuse stations of Auger Engineering Radio Array (AERA)
for interferometric lightning detection

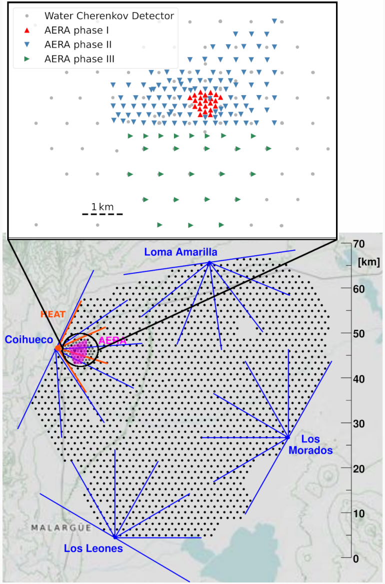
Auger Engineering Radio Array (AERA)

Measurement of short radio pulses emitted by cosmic ray air showers

- Covers $\sim 17\,\text{km}^2$ ($\approx 5\,\%$ of Auger area)
- Radio signal detection: 30 to 80 MHz
  $\Rightarrow$ possibility of VHF lightning measurement with resolution in meter
- 154 radio detector stations with 2 different antenna types




left: Logarithmic Periodic Dipole Antenna, right: Butterfly Antenna



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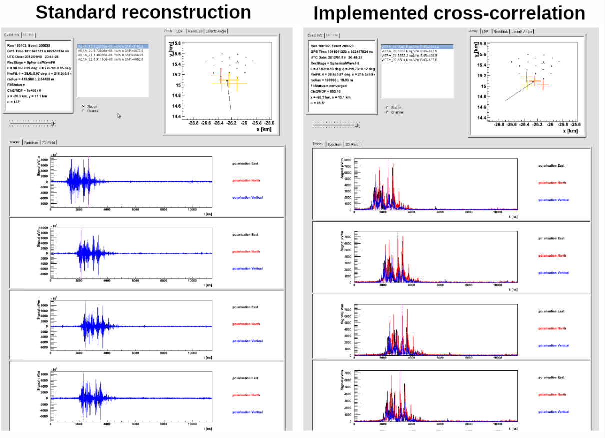
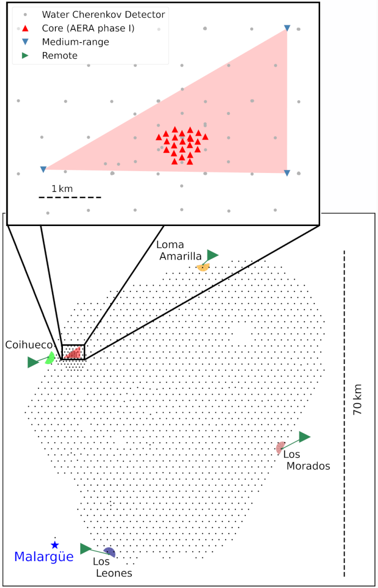
- AERA event at January 19, 2012
  - Early stage of AERA phase I
  - AERA ran with different configurations
- Reconstruction of standard Auger analysis framework
  - Time trace length: $\sim 11\,\mu s$
- Cross-correlation had been implemented
- Self-triggered traces of AERA stations
  - → Visible lightning signal
  - → Proof of principle



(Lukas Niemietz, PhD thesis)

Planned configuration: 3 cluster

- Core
  - 4 stations
  - Baselines: 58 – 127 m
  - → pulse identification density: 137 – 300 ns for sources at zenith angles of 45°
- Medium-range
  - 3 stations
  - Baseline: 1.0 – 2.5 km
- Remote
  - 4 stations
  - Baseline: 3.5 – 66 km



Interferometric Lightning Detection at Auger: Steps to take

- Modification of AERA stations
  - Change trace length from μs up to s
  - Data handling
  - Development of a new filter
- Adjustment of signal dynamical range
  - Investigation of a *characteristic* lightning signal based on self-triggered AERA measurements

⇒ Next Milestone:

First AERA station with long trace read-out in November 2024

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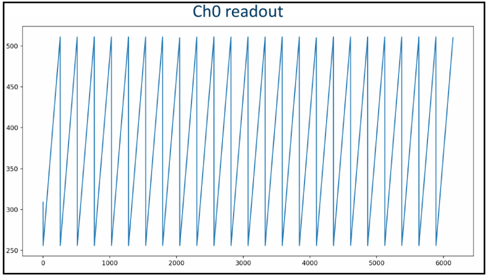
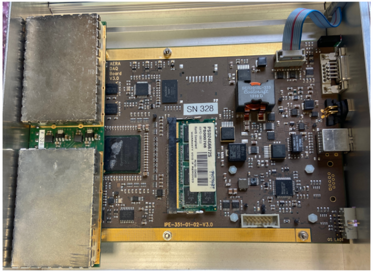
⇒ Next Milestone:

First AERA station with long trace read-out in November 2024

University of Siegen (Q. Dorosti)

- Local test setup including AERA boards
  - Read-out seems to be flawless
- Implementation of long trace read-out
  - Completed
    - 10 ms
    - 100 ms
- Challenges:
  - Slow read-out
  - Long dead time
  - Sampling faster than read-out
    $\rightarrow$ possibly overtakes read-out





AERA Read-out Status: Challenges

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- Data Handling
  - 2 channels with each 2 B per sample
  - Sampling rate: 180 MHz
    $\rightarrow$ 720 MBs^{-1} for both channels
  - $\Rightarrow$ 8 s trace length: 5.76 GB
- Low communication band-width
  - WiFi Bandwidth: 22 MBs^{-1}
  - Read-out time of 8 s trace length $\sim$ 4.4 min
  - Some stations have optical fibers
  - Long dead time

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⇒ First Milestone:

First AERA station with long trace read-out in November 2024

Investigation of Dynamical Range - Outline

- Question: *Adjustment of AERA station signal amplitude?*
- Study with already existing AERA measurements
- AERA measurements + external lightning trigger
  - External lightning trigger:
    - Lightning Detection System reconstructed lightning events
    - Lightning-vetoed WCDs within 5 km distance of AERA
  - Coincidences of GPS timestamps
  - Possible lightning signal

⇒ Adjustment of dynamical range to *characteristic* lightning signal

Investigation of Dynamical Range - Status and Challenge

- External trigger: Lightning Detection System reconstructed lightning events
- Modification of standard Auger analysis framework
  $\rightarrow$ write out self-triggered AERA signal traces
- First analysis with new self-trigger of AERA regarding lightning
- Current challenge:
  - No clear lightning assignment $\rightarrow$ investigation of possible time offset

- Thunderstorms and lightning are important for Auger
  - Impact WCDs and RDs
    → WCDs lightning veto and Lightning Detection System
  - Studies of high-energetic atmospheric phenomena
- First lightning mapping array done with AERA but not optimal (trace length $\sim 11\,\mu s$)
- Interferometric Lightning Detection for correlation lightning stage ↔ TGF

Next steps:

- Solution for long trace readout
- Data handling
- Lightning assignment of (self-)triggered AERA signal traces