Adding interferometric lightning detection to the Pierre Auger Observatory

Astroparticle School 2024

Melanie Joan Weitz

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University of Wuppertal

Thunderstorms and Lightning

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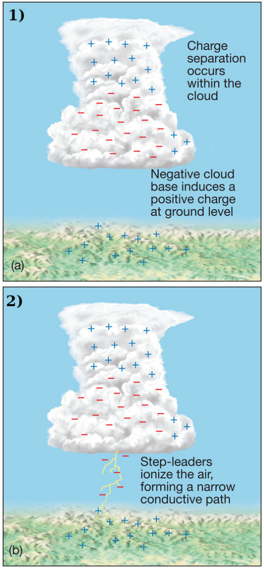
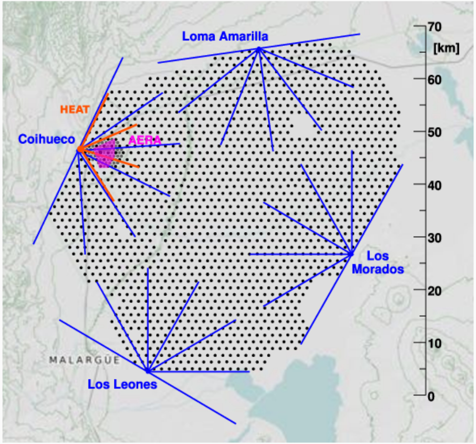
- Thunderstorms (ideal):
  - Anvil shaped cloud
  - Charge separation
    - negative base
    - positive top
- Cloud-to-Ground lightning (CG):
  - CG emit radio signal in low frequency band (LF: kHz) and very high frequency band (VHF: MHz)



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



Thunderstorms and Lightning at the Auger

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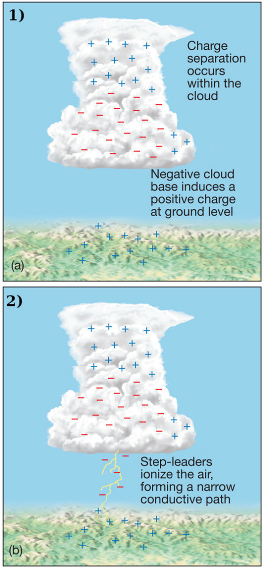
- Radio signal of lightning
  → disrupts RD and WCD stations of Auger



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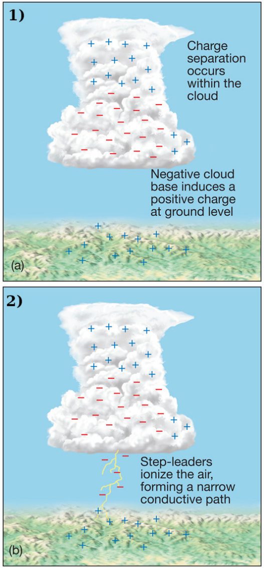
- CG detection via Lightning Detection System at Auger for investigation of cosmic ray ↔ lightning connection



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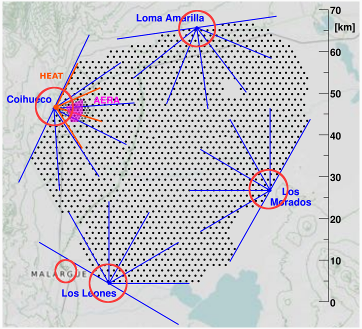
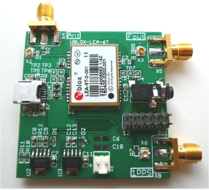
Lightning Detection System consists of
5 Lightning Detection Stations (LDS) installed at FD sites and Malargüe campus

LDS consist of:

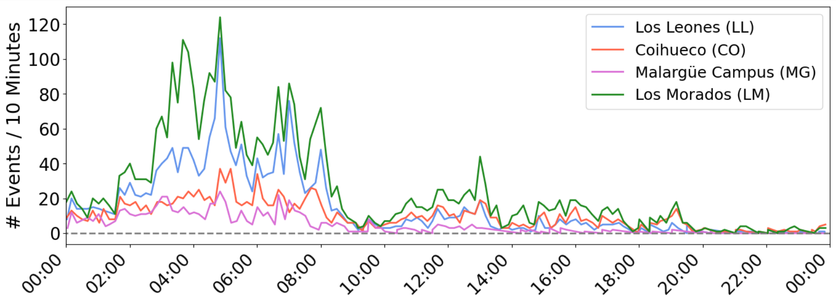
- Commercial lightning detector:
  - Boltek StormTracker
  - PCI card with external antenna
  - 2 polarizations: North-South and East-West
  - Sensitivity: $\sim 10 - 90\,\mathrm{kHz}$
- GPS extension:
  - Own-build extension card with ublox LEA-6T chip
  - Delivers GPS time stamp





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

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

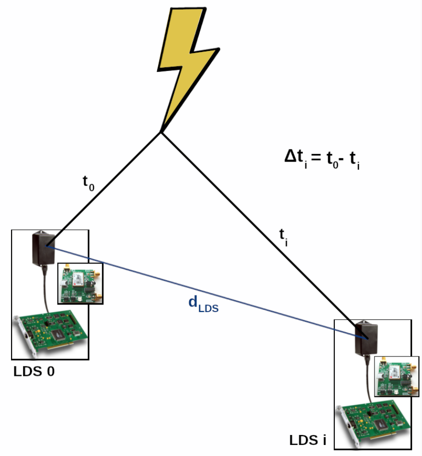


- Background, e.g. laser firing for atmospheric monitoring

Lightning Event Reconstruction: Multiple LDS

- StormTracker data combined with GPS time
- Reconstructed lightning position dependent on
    - Position d_{LDS} of LDS to each other
    - Individual arrival times
    - Time offsets Δt_i from LDS signals to each other
      $\rightarrow$ application of cross-correlation method for optimal Δt_i

  $\Rightarrow$ Triangulation of distance to lightning
- Resolution of reconstruction: $\sim$km



(adapted from L. Niemietz, PhD thesis)

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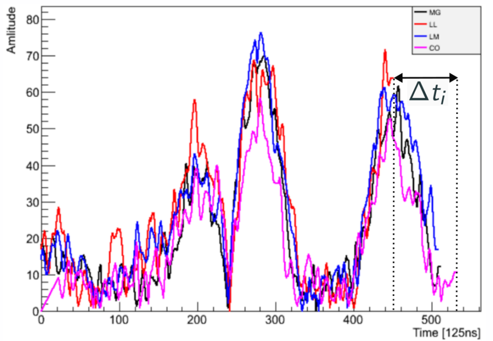

(L. Niemietz, PhD thesis)

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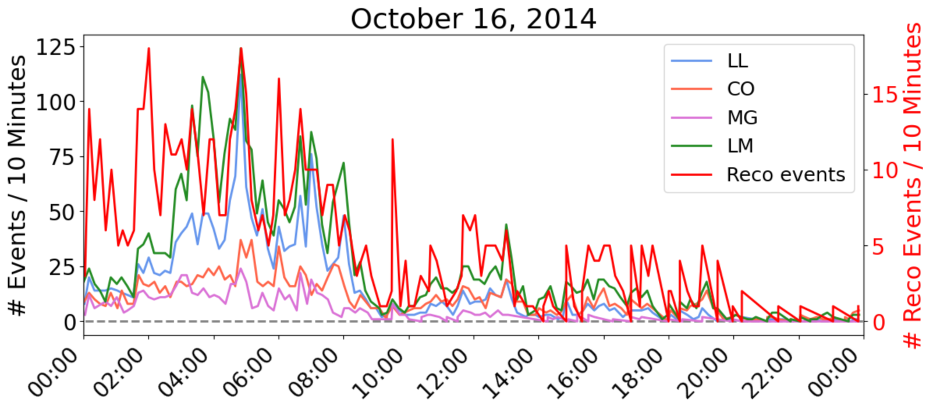
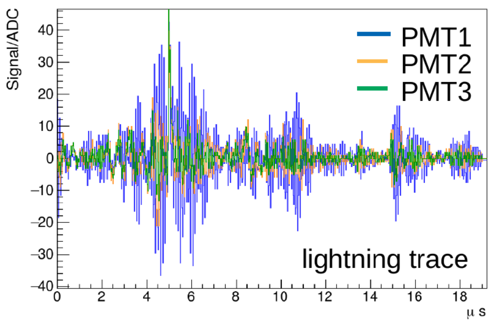


- Multiple station reconstruction suppresses background noise
  $\rightarrow$ important for trigger

Visible lightning signal in WCD stations

- Photomultiplier tube (PMT) cables pick up electric field of thunderstorms and lightning
  $\rightarrow$ act as antennas
- Different PMT signals due to different orientations of cables

$\Rightarrow$ Thunderstorms and lightning are large disruption sources for WCD stations



(R. Colalillo, PoS(ICRC2023)439)

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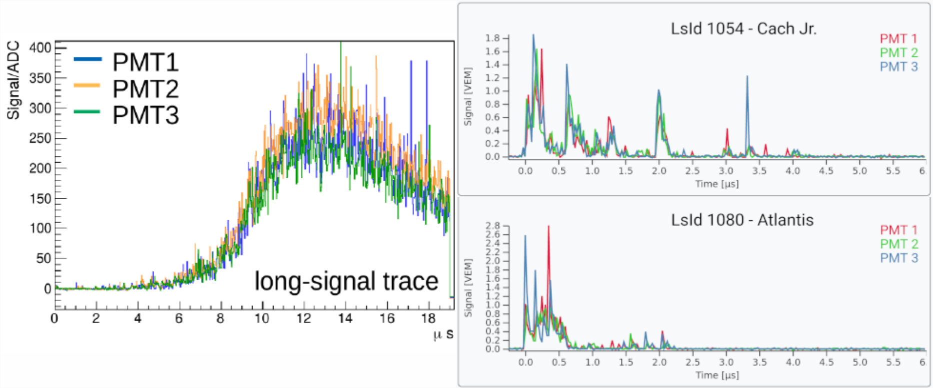
Detection of peculiar events with WCD stations of Auger



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

Terrestrial Gamma-ray Flashes at Auger

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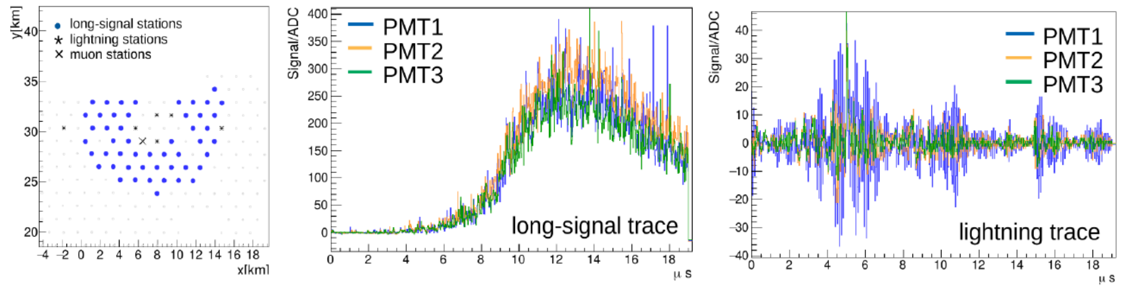
Detection of peculiar events during thunderstorms with WCD stations of Auger
$\rightarrow$ likely related to Terrestrial Gamma-ray Flashes



(R. Colalillo, PoS(ICRC2023)439)

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

Terrestrial Gamma-ray Flashes (TGFs)

- Bursts of gamma-rays originating from Earth's atmosphere produced by lightning
  - Production: Bremsstrahlung of relativistic e^- with $E_{e^-} \sim$ MeV
  - Up- and downward
- Lasting from tens of µs up to ms
- Not clear:
  - Characteristics of meteorological boundary conditions
  - Lightning stage involved

Artist interpretation (©NASA/Goddard Space Flight Center)

Detection of peculiar events during thunderstorms with WCD stations of Auger
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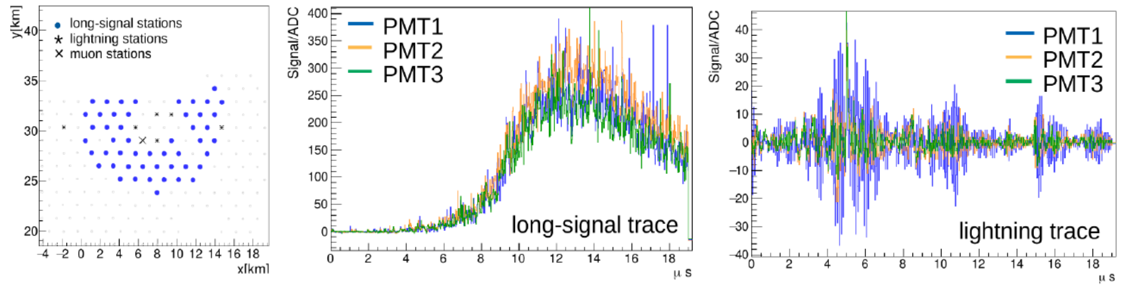

(R. Colalillo, PoS(ICRC2023)439)

- Motivation:

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

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 CG conducting path
- Can lead to
  $\rightarrow$ Properties of thunderstorms triggering TGFs

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BUT: Lightning Detection System resolution is too small

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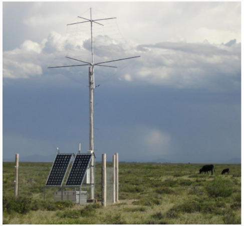
BUT: Lightning Detection System resolution is too small
$\Rightarrow$ Possible solution:

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

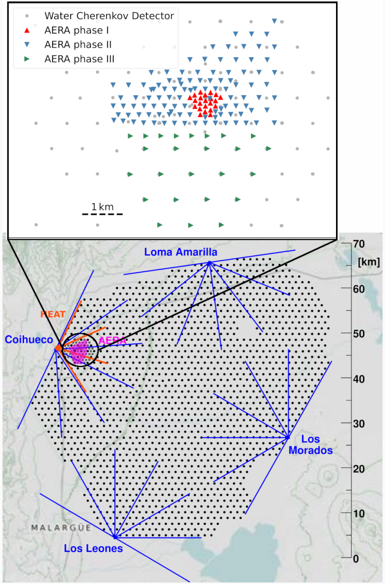
Auger Engineering Radio Array (AERA)

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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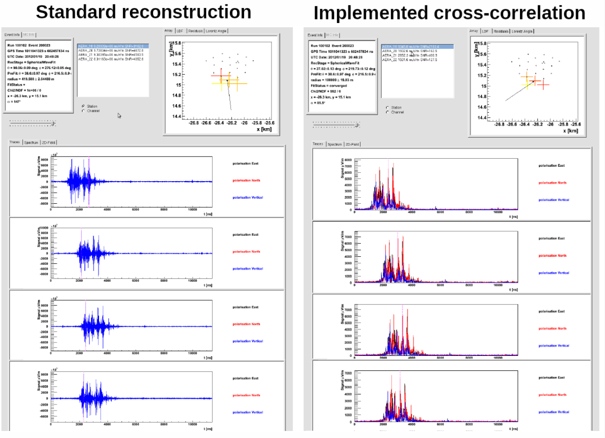
- AERA event at January 19, 2012
- Reconstruction of standard Auger analysis framework
  - Time trace length: $\sim 11\,\mu s$
- Cross-correlation had been implemented



(L. Niemietz, PhD thesis)

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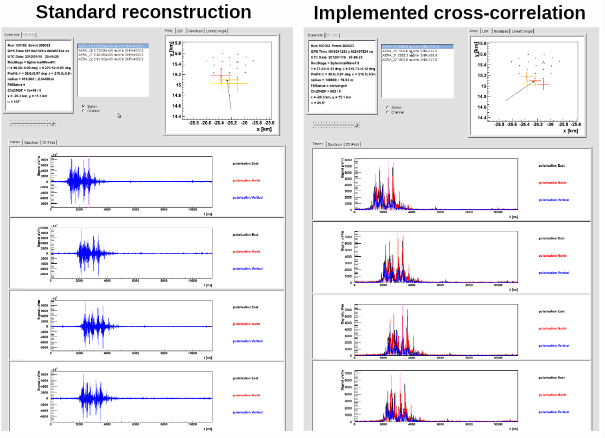
⇒ Self-triggered traces of AERA stations
  - Visible lightning signal
  - Proof of principle



(L. Niemietz, PhD thesis)

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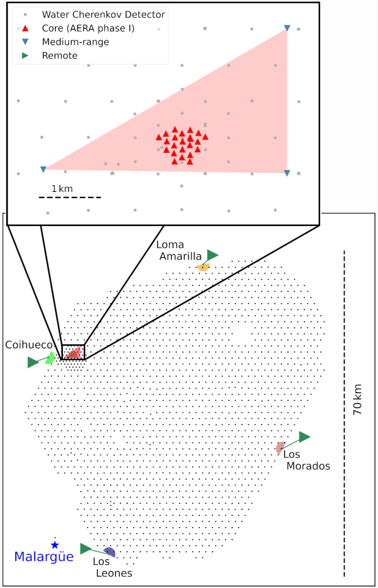
Planned configuration: 3 cluster

- Core
  - 4 stations
  - Baselines: 58 – 127 m
- Medium-range
  - 3 stations
  - Baseline: 1.0 – 2.5 km
- Remote
  - 4 stations
  - Baseline: 3.5 – 66 km



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- 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

$\Rightarrow$ Next Milestone:

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

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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 WCD stations
  - 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 of self-triggered AERA signal traces

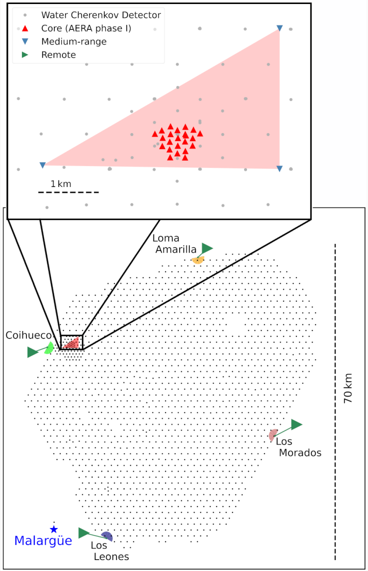
- Current challenge: no clear lightning assignment
  - GPS time coincidences only in seconds
  - Investigation of possible time offset
    - Propagation of radio signal
    - Different lightning sensitivity of frequency ranges

Summary and Outlook

- Thunderstorms and lightning are important for Auger
  - Impact WCD and RD signals
    $\rightarrow$ WCD 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 $\leftrightarrow$ TGF

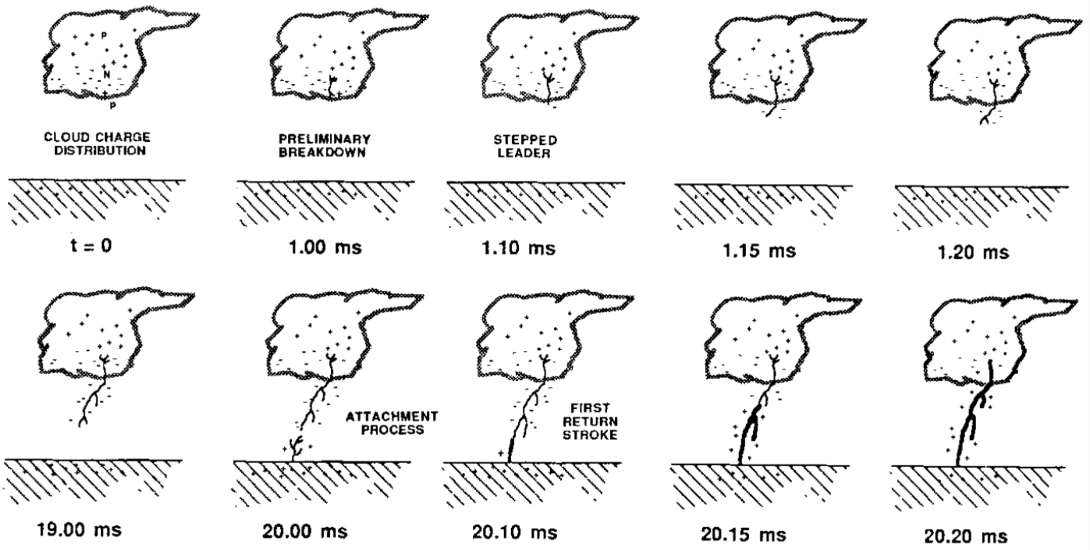
Next steps:

- Data handling
- Lightning assignment of (self-)triggered AERA signal traces



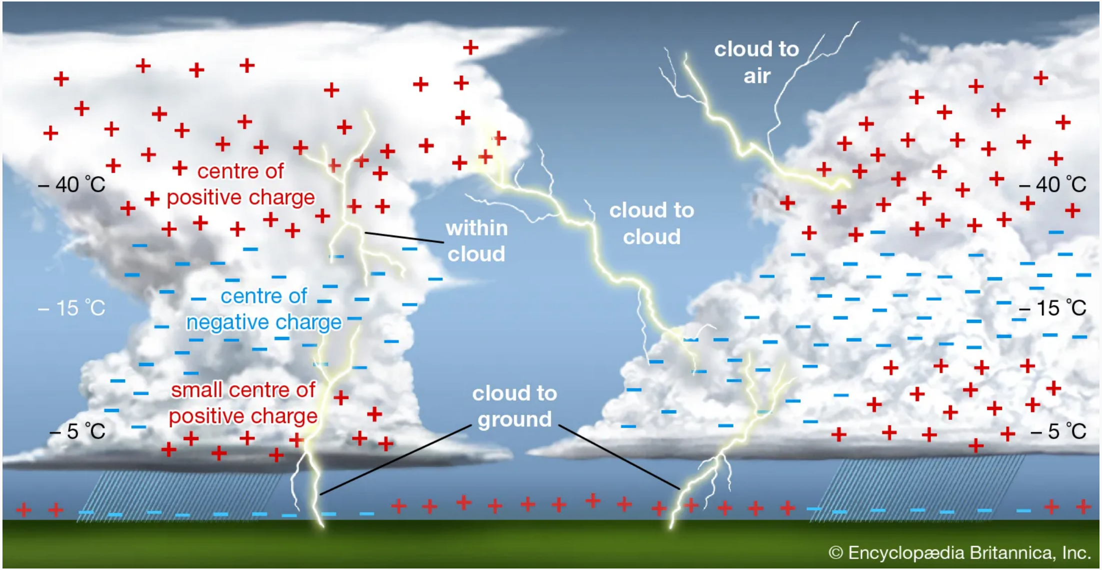
Backup Slides

Lightning stages



(Martin Uman, Science 39(1988)1713-1714)

Lightning types

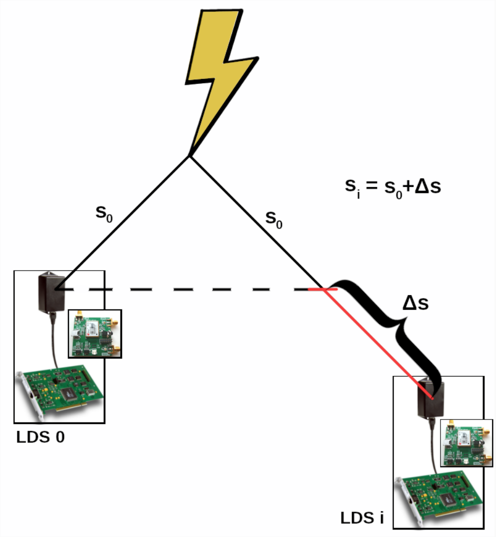


Lightning Event Reconstruction: Multiple LDS

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

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

    - → Application of **cross-correlation method for optimal** Δt_i
  - ⇒ Triangulation for distance to lightning
- More information:
  J. Rautenberg, PoS(ICRC2015)678



(adapted from L. Niemietz, PhD thesis)

Lightning Event Reconstruction: Cross-correlation

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

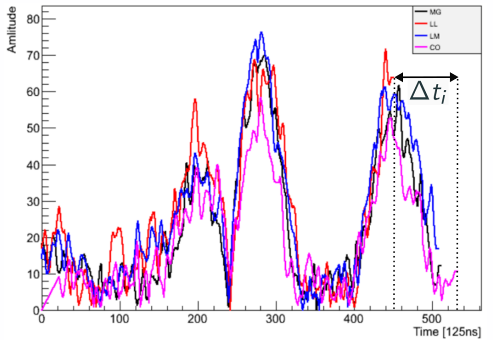
$$\mathrm{CC}(\mathrm{offset}_i) = \max \left[\sum_j (S_{0,j}\; S_{i,j+\mathrm{offset}_i}) \right]$$

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

  - Including time binning:

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

- Resolution of reconstruction: $\sim$ km



(L. Niemietz, PhD thesis)

AERA Read-out: Challenges

- 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

Coinciding Lightning Positions < 100 km