BOLT: Imaging Lightning and Terrestrial Gamma Flashes at the Pierre Auger Observatory

The Broadband Observatory for Lightning and TGFs

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University of Siegen

AtmoHEAD 2026,
Olomouc
29th July

PIERRE AUGER OBSERVATORY

Universität Siegen

HEP Experimental High Energy Physics

CPPS Center for Particle Physics Siegen

Bundesministerium für Forschung, Technologie und Raumfahrt

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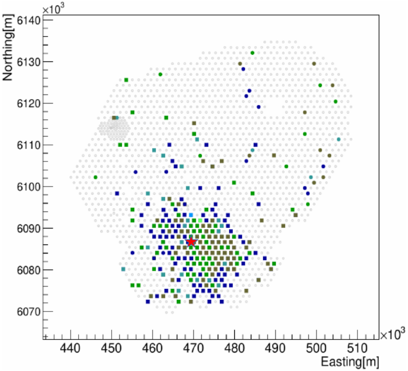
The Pierre Auger Observatory (Auger)

- The world's largest cosmic ray observatory for $E_{CR} > 10^{17}$eV, near Malargüe (Argentina)
- 3000 km^2 array, 1660 Surface Detectors, 4 Fluorescence Detectors



T3 burst December 2021
Source: Colalillo, PoS ICRC 2025

Lightning related phenomena picked up by various systems

- Auger Engineering Radio Array (AERA)
  - $\rightarrow$ Stepped Leaders (but firmware not suitable)
- Water Cherenkov Detectors
  - $\rightarrow$ Downward Terrestrial Gamma Flashes
- Lightning Detection System
  - $\rightarrow$ Return Strokes

Opportunity to study lightning stage where TGFs are produced

$\rightarrow$ requires mapping the development

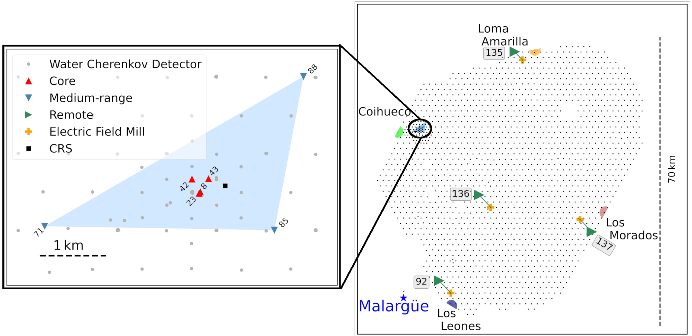
$\rightarrow$ interferometic lightning mapping array

BOLT: Broadband Observatory of Lightning and TGFs

An interferometic lightning mapping array at the Pierre Auger Observatory ...

3 clusters of stations:

- **Core**: 4 stations,
  baselines 58 m to 127 m
  (pulse confusion: backup)
- **Medium-range**: 3 stations,
  baselines 1 km to 2.5 km
- **Remote**: 4 stations,
  baselines 23 km to 59 km



BOLT: Broadband Observatory of Lightning and TGFs

... repurposing Auger Engineering Radio Array (AERA) stations:

Science:

- Sensitivity: 30 MHz to 80 MHz
- Sample Rate: 180 MHz
- 2 Polarisations: North-South, East-West
- High-Gain(20 dB) + Low-Gain channels
- Samples Buffer: 4 GB

$\rightarrow$ 4 s buffer depth 2+2 channel mode
7 s buffer depth 1+1 channel mode

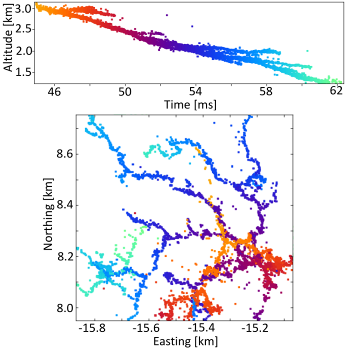
Infrastructure:

- Solar powered ($\mathcal{O}$(12 W) usage)
- Long-range WiFi / optical fiber

BOLT23 with Butterfly antenna

BOLT: Challenges

- Station electronics / firmware
  - Support reading trace lengths $\mathcal{O}(>180\,\text{MSa})$
  - Reading, storing and transmitting large data volumes to DAQ
- DAQ and Trigger development
  - External triggering:
    - Lightning Detection System
    - Surface Detectors (foreseen)
  - Dynamic range $\rightarrow$ Channel saturation?
- Time Synchronisation:
  Nanosecond timing across 60 km: GPS + reference beacons



Example simulation reconstruction

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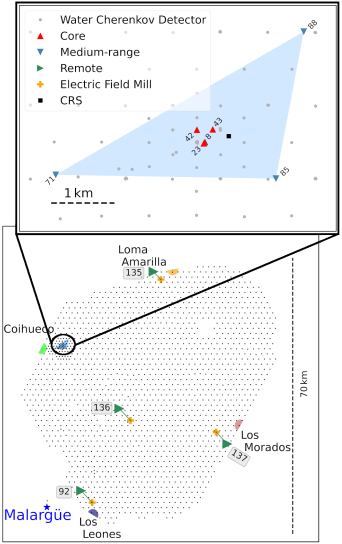
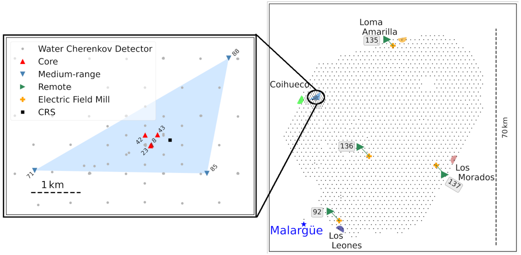
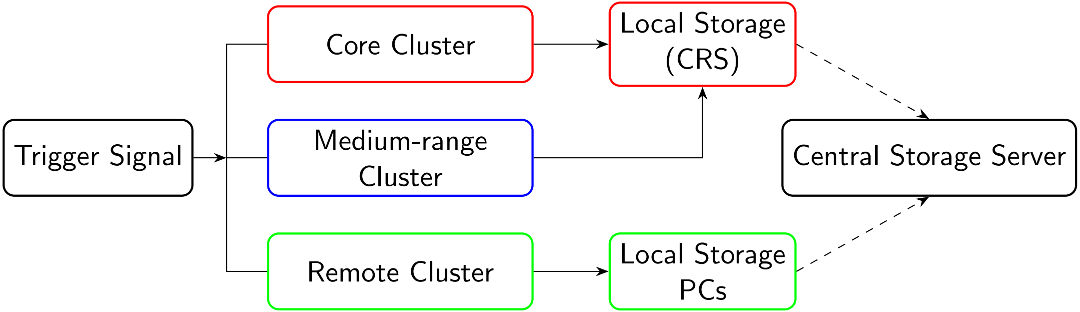


BOLT: DAQ pipeline

Bandwidth limitations:

- Write data to local storage
- Initial processing in CRS
- Slow copy to central storage





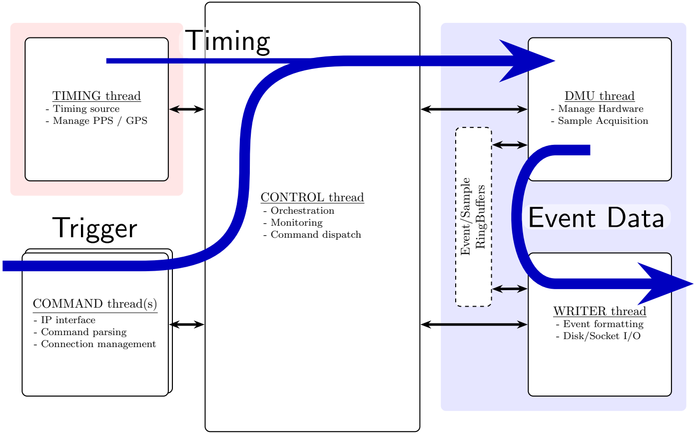
BOLT: Station DAQ

New station DAQ supporting large trace lengths:

1. Accept Trigger
2. “Freeze” samples buffer
3. Stream data
4. (Abort readout)
5. “Unfreeze” samples buffer

Environment:

- GNU C99 (GCC 4.1.2)
- uClibc v0.9.29-nios2



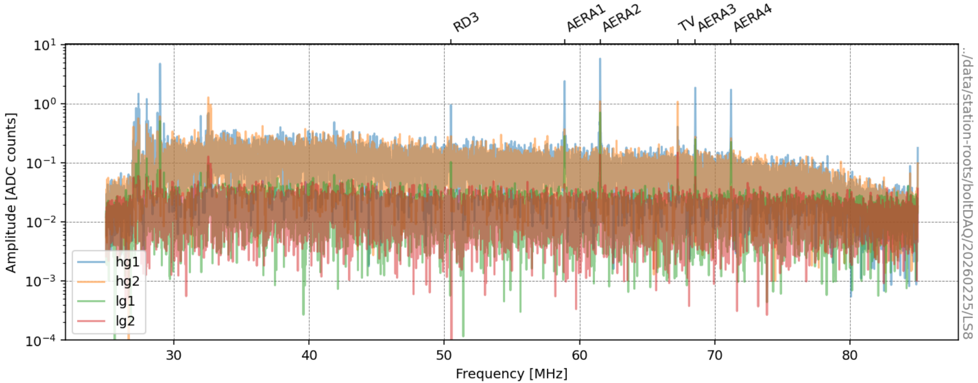
BOLT: Timing Synchronisation

Initial Synchronisation: GNSS (<100 ns)

- Common absolute time reference
- Requires known antenna position (<30 m for <100 ns)

Extended Synchronisation: Reference Beacon

- Synchronisation embedded in data (known phase relationships)
- Relative timing improved to <2 ns



Manual readout of a 1 ms trace on BOLT08

BOLT: Status / Field Data

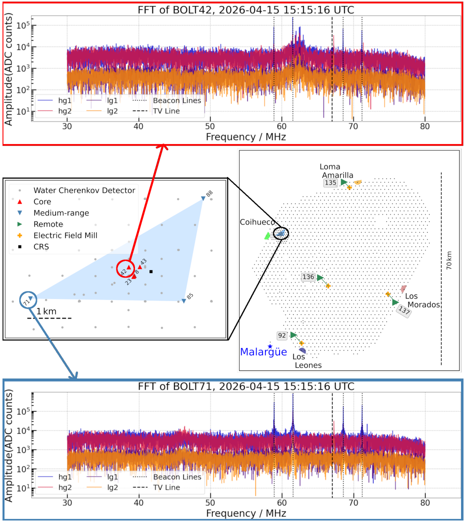
Remote cluster:

- Deployed Spring 2026, now in commissioning

Core and Medium-range cluster:

- Deployed Autumn 2025
- Coincident data readouts + large data volumes transmitting

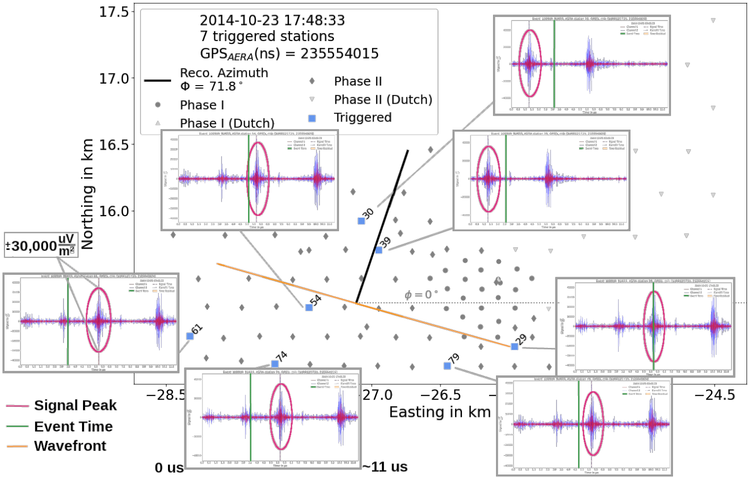
Lightning season starts November 2026



Lightning Candidate Event

- Event Info: *Oct 23, 2014, 17:48:33 UTC*
  - $\mathrm{d}_{\text{Core, Reco}} = 89.5\,\text{km}$
  - $\Delta\mathrm{T} = 641\,\text{ms}$
- Radio emission affects stations in whole array
- Same radio signal pulse time shifted
- Trace lengths $\sim 11\,\mu\text{s}$

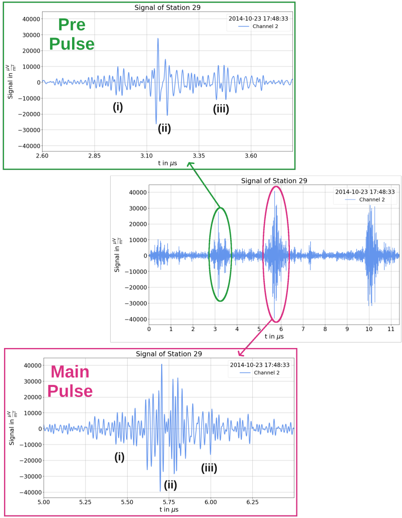
$\Rightarrow$ Proof of principle!



Lightning Candidate Event - Structure

- Closer look into two pulses:
  - Main Pulse
  - Pre Pulse
- Pulse durations: $\sim 1\,\mu s$
- Three visible sub-structures
  - (i) Small initial
  - (ii) Larger central
  - (iii) Small final

$\Rightarrow$ Pre Pulse:
Clearer separation of sub-structures



Example Signal Trace: Main and Pre Pulse

Insights from previous AERA measurements: Algorithm

Lightning Candidate Event - Interferometry

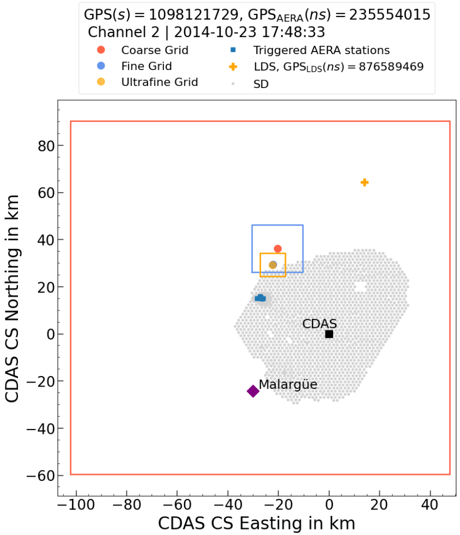
- Cross-Correlation Beamforming Grid Search
- Maximum values of grids:

Grid	x (km)	y (km)	z (km)
Coarse	-20.36	36.05	5.92
Fine	-22.19	29.26	4.96
Ultrafine	-22.23	29.15	4.94

- Result in agreement with direction from Lightning Detection System (LDS):

$$\begin{pmatrix} x \\ y \end{pmatrix}^{\text{LDS}} = \begin{pmatrix} 14.01 \\ 64.21 \end{pmatrix}, \quad \Delta T_{\text{AERA, LDS}} = 641\,\text{ms}, \; d_{\text{Ultrafine, LDS}} = 50.42\,\text{km}$$

$\Rightarrow$ Could be the same thunderstorm

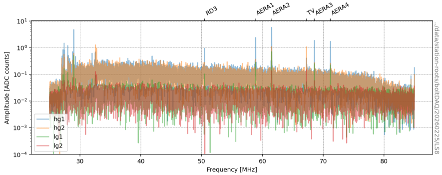


Summary and Outlook

- Opportunity at the Pierre Auger Observatory to study lightning and TGFs
- **B**roadband **O**bservatory of **L**ightning and **T**GFs:
  imaging lightning propagation in high spatial and time resolution
- Deployment of BOLT hardware complete
- First commissioning data from Core and Medium-range clusters

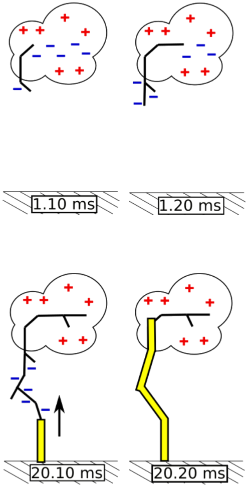
Outlook:

- Observation of first BOLT lightning event
- Include Remote cluster into BOLT data stream
- Development of lightning analysis chain



Supplemental Material

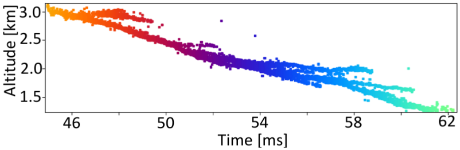
Dynamics of Lightning Discharges

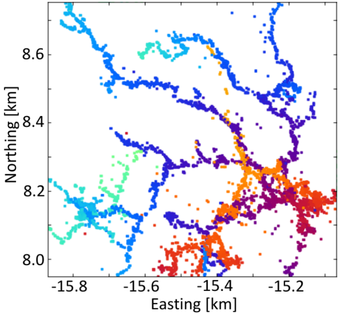


B. Hare & LOFAR Lightning Collaboration

Stepped Leaders:
multiple discrete pulses
in VHF (MHz)
(radio interferometry)

Return Stroke:
single intense pulse
in LF (kHz)
(used as trigger)

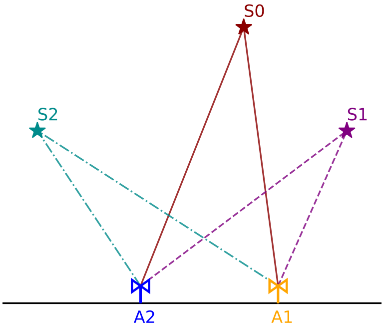


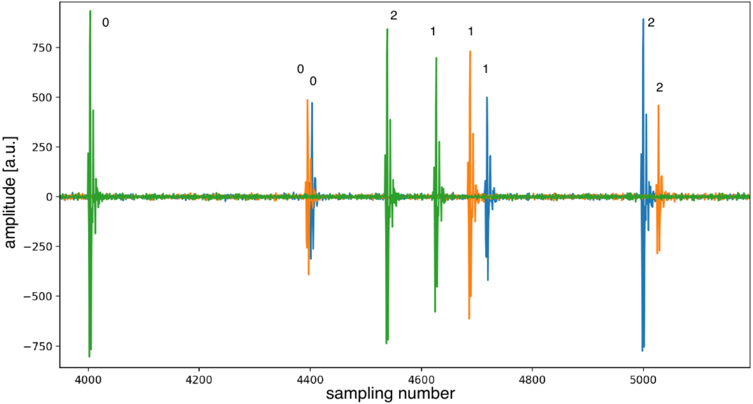


Example simulation reconstruction

Pulse Confusion

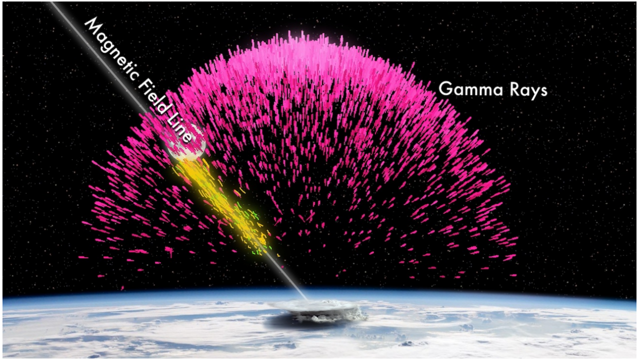
High Source Density + Times of Arrival → Pulse Confusion





Green: Medium-range, Blue and Orange: Core

Terrestrial Gamma-Ray Flashes & Lightning



NASA/Goddard Space Flight Center/J. Dwyer/Florida Inst. of Technology

- First detected by BATSE[a] instrument on the CGRO[b] satellite (1994)
- Burst of gamma radiation from lightning
- Energies up to 40 MeV
- Up- and down-going

[a] Burst and Transient Source Experiments
[b] Compton Gamma Ray Observatory

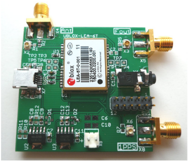
It is unclear at what lightning stage the emission is generated.
Spaceborne experiments are sensitive but lack resolution.

Lightning Detection System

Detect lightning strikes around Auger, installed at FD sites and Malargüe campus

- Commercial lightning detector:
  - Boltek StormTracker
  - PCI card with external antenna
  - Sensitivity: 10 kHz to 90 kHz
- GPS extension for timing:
  - uBlox LEA-6T on custom extension board
  - Delivers GPS timestamp for trigger mechanism

Boltek StormTracker



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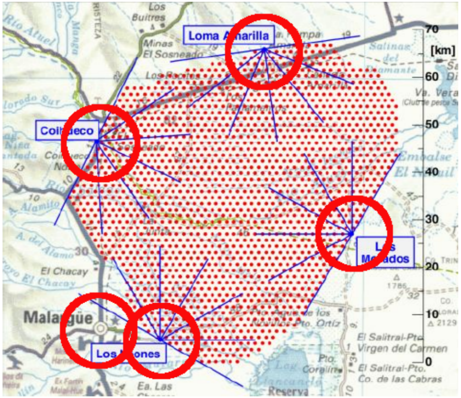


Source: L. Niemietz's PhD thesis

Radio detection for Lightning versus Air Showers

Rule of Thumb for Radio Interferometry:

'Timing accuracy must be better than 1/4 (1/12) of the period.'

.. but we are doing (digital) broadband interferometry.

Air Showers

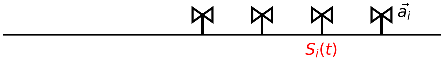
- relativistic emitter
- single pulse
  ($\lesssim 10\,\mathrm{ns}$)
- localised footprint
  (projected around shower axis)

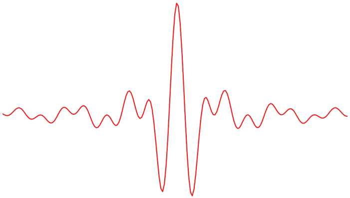
Lightning

- extended emitter
- multiple pulses / substructure
  ($10\,\mathrm{ns}$ to $10\,\mu\mathrm{s}$, $\Delta \sim 10\,\mathrm{ms}$)
- large footprint

Interferometry: Amplitude + Timing information of the signal

- Measure signal $S_i(t)$ at antenna $\vec{a}_i$





Radio Interferometry

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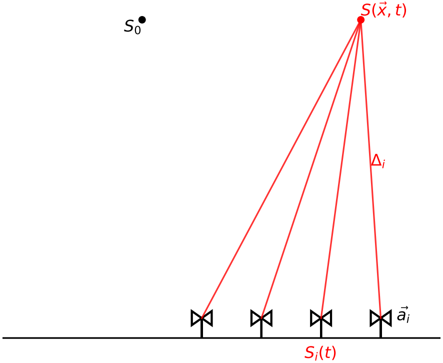
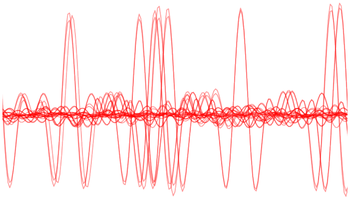


- Measure signal $S_i(t)$ at antenna $\vec{a}_i$
- Calculate light travel time

$$\Delta_i(\vec{x}) = \frac{|\vec{x} - \vec{a}_i|}{c} n_{eff}$$

- Sum/Multiply waveforms accounting for time delay

$$S(\vec{x}, t) = \sum S_i(t + \Delta_i(\vec{x}))$$



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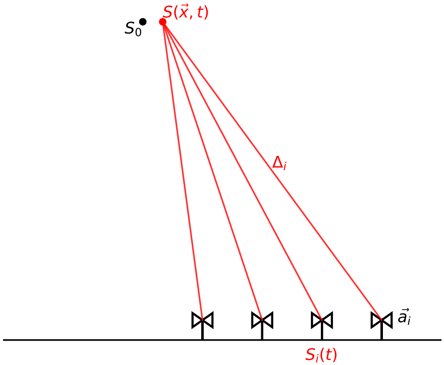

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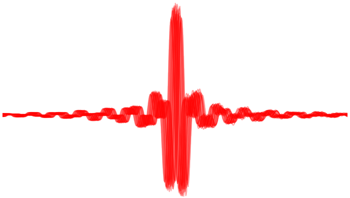

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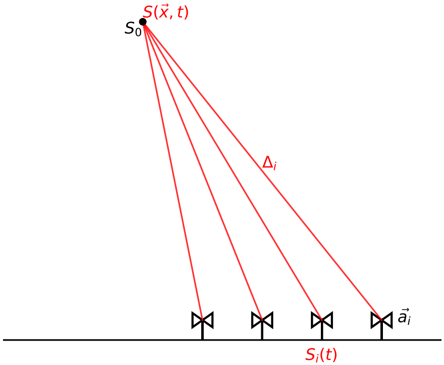

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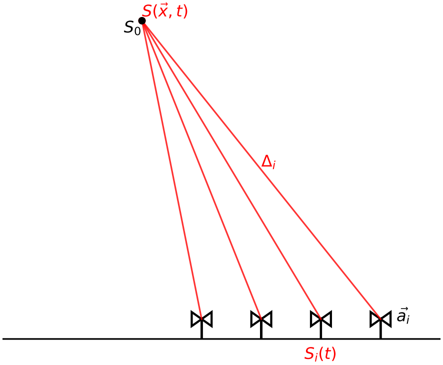

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- Sum/Multiply waveforms accounting for time delay

  $$S(\vec{x}, t) = \sum S_i(t + \Delta_i(\vec{x}))$$

/ Cross-Correlation Beam Forming:

$$CC_{\text{beam}}(\vec{x}, t) =$$

$$\pm \sqrt{\frac{1}{(N-1)\frac{N}{2}} \sum_{i=1}^{N-1} \sum_{j>i} S_i(t + \Delta_i(\vec{x})) \cdot S_j(t + \Delta_j(\vec{x}))}$$