Detecting Radio Pulses from Air Showers

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Cosmic Rays

- high energy particles
- dominated by hadrons (atomic nuclei)
- similar in composition to solar system
- broad range in flux and energy
- different energy regimes:
  - $< 10^{10}$ eV: modulated by solar wind
  - $< 5 \times 10^{14}$ eV: direct detection possible
  - $> 5 \times 10^{14}$ eV: indirect detection (air showers)
Sources of Cosmic Rays

Scientific American, (c) 1998

1 PARTICLE
PER SQUARE
METER PER SECOND

1 PARTICLE
PER SQUARE
METER PER YEAR

KNEE

1 PARTICLE
PER SQUARE
KILOMETER
PER YEAR

LHÇ →

Particle Energy (in eV)

Radboud University Nijmegen
Sources of Cosmic Rays

![Graph showing particle flux as a function of particle energy.](image)

**LHCB**
Sources of Cosmic Rays

Correlated with nearby Galaxies
Air Showers

- high energetic cosmic rays interact with nuclei in the atmosphere
- in a cascade lots of secondary particles emerge
- a “pancake” of particles
  - a few meters thick (with trailers)
  - up to a few kilometers wide
  - travelling with about light speed in the direction of the primary particle
Detection of Air Showers

- Air-Cherenkov
  - detection of (visible) Cherenkov light with telescopes
  - allows discrimination of gamma induced air showers

- Air-Fluorescence
  - detection of fluorescence light from nitrogen molecules
  - used at highest energies
  - allows determination of primary particle mass & energy

- Ground based Particle Detectors
  - high duty cycle; measuring around the clock
  - determination of primary mass & energy by measuring different components e.g. muons and electrons
Radio Emission from Air Showers: History

- first detection of radio pulses from air showers 1965 by Jelley et al.
- intensive research in the following years
- measurements ceased after the 1970s mostly due to difficult interpretation, success of other methods, and radio interference

Jelley et al. (1965)
Radio Emission from Air Showers: Facts

- Air showers emit a radio pulse with less than 20 ns width.
- Radiation due to geomagnetic emission process e.g. geosynchrotron.
- Coherent emission at low frequencies.
- Measuring the radio emission from air showers could give several benefits:
  - Higher duty cycle than fluorescence telescopes.
  - Effective RFI suppression allows measuring in polluted (populated) areas.
  - Data integrated over the shower evolution, can be complementary to particle detectors.
  - High angular resolution possible.
- This can be achieved by new digital radio telescopes.
Analog vs. Digital Receiver

In the 1970ties:
- analog detection/demodulation of signals
- display on oscilloscopes

Now:
- fast ADCs sample the whole waveform
- processing and display on computers
Analog vs. Digital Receiver

Antenna → Filter and Amplifier → Analog Detector → Oscilloscope

Field Strength

Time

Voltage

Antenna → Filter and Amplifier → Analog to Digital Converter

>80 MSPS >10 bit

A/D

HD & PC

+ beamforming
Analog vs. Digital Receiver

Antenna → Filter and Amplifier → Analog Detector → Oscilloscope

Field Strength

Time

0 20 40

0 0.5 1

0 0.5 1

Antenna → Filter and Amplifier → Analog to Digital Converter

>80 MSPS  >10 bit

A  D

HD & PC

+ beamforming

Voltage

Time

0 20 40

0 0.05 0.1

0 0.5 1

0 0.5 1

Radboud University Nijmegen
LOFAR
A new kind of Radio Telescope

- digital radio interferometer for the frequency range of 10 - 270 MHz
- array of 36+ Dutch and 8+ international stations of 48 to 96 simple antennas
- fully digital: received waves are digitized and sent to a central computer cluster
  - digital radio interference suppression
  - ability to store the complete radio data for a short amount of time
  - this allows to form beams after a transient event has been detected, combining the advantages of low gain and high gain antennas
KASCADE-Grande

example of an air shower experiment with ground based particle detectors
LOPES
(LOFAR Prototype Station)

- set up at and working together with KASCADE-Grande
- frequency range of 40 – 80 MHz
- Triggered by KASCADE or Grande large event trigger
  - 10 antennas in the first phase
  - 30 antennas in second phase
  - reconfigured for dual-polarization
- plus LOPES$^{\text{STAR}}$ antennas

Goals:
- develop techniques to measure the radio emission from air showers
- determine the radiation mechanism of air showers
- measure the properties of the radio emission from air showers
- calibrate the radio data with theoretical and experimental values from an existing air shower array
Hardware of LOPES

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Active Antenna
- Coax cable: 100 m or 180 m

Master Clock Module
- Clock generation & distribution
- Sync signal distribution
- Clock: 80 MHz, 40 MHz
- Sync signal: 2 m, 100 m, or 150 m

Slave Clock Module
- Clock distribution
- Sync signal distribution
- Clock: 80 MHz, 40 MHz
- Sync signal

RML (Receiver Module LOPES)
- RF: 40-80 MHz
- Amp + filter
- A/D: 80 MSPS, 1 Gbit/s
- Optical transmit

Veto
time-stamp Clock Card
- Trigger input: 1 Hz Input, 5 MHz Input from KASCADE

Optical Receiver
- Dig. data: 2 x 1 Gbit/s

Memory Buffer (TIM-Module)
- RAM module: 2 GByte

Frontend PC
- Ethernet

DAQ PC
- Ethernet
> 100 GB
Hardware of LOPES

LOPES-Antenna

- short dipole with “inverted vee shape”
- beamwidth 85°-130° (parallel/perpendicular to dipole)
Hardware of LOPES

Receiver Module

- direct sampling of the radio signal with minimal analog parts: amplifier, filter, AD-converter
- sampling in the 2nd Nyquist domain of the AD-converter
Memory Buffer
aka. TIM-Module
(Twin Input Module)

- uses PC133-type memory
- memory for up to 6.1 seconds per channel
- pre- and post-trigger capability
Hardware of LOPES

Clock & Trigger distribution board

- 1 master & 3 slave boards
- Master board generates clock and accepts trigger
- Slave boards distribute clocks and trigger
Data Processing

- steps of the data processing:
  1. instrumental delay correction from TV-phases
  2. filtering of narrow band interference
  3. frequency dependent gain correction
  4. flagging of antennas
  5. correction of trigger delay
  6. beam forming in the direction of the air shower
  7. 3D direction fitting
  8. quantification of peak parameters
  9. event discrimination
Delay correction

- TV-transmitter with picture- and two sound carriers
- relative phases between antennas lets us correct for delay errors

![Graph showing time and delays](image)

- Delay corrections
- Residual delays
Digital Filtering

raw data:

filtered data:

blocksize: 128 samples

blocksize: 64k samples

power spectrum:
Digital Filtering

raw data:

filtered data:

power spectrum:
Gain Calibration

- Antenna gain from simulations
- Electronic Gain from measurements with reference source
  - Also mitigates errors of the antenna simulations

\[ \varepsilon = \sqrt{\frac{4\pi \nu \mu_0}{G(\theta, \phi, \nu) c A_{ele}(\nu) R_{ADC}}} \cdot V_{ADC} \]
Beamforming
Step 1

- shift data in time to compensate for arrival delay
Beam Forming
Step 2

- filtered and time shifted data from single antennas
- beamformed data after correlation of all antennas
  - air shower pulse at -1.8μs
  - particle detector noise from -1.75μs to -1.3μs
  - Phasing ↔ Correlation
3d-Position Fitting

- find maximum pulse height in 3d space (azimuth, elevation, radius):
  1. starting point from KASCADE
  2. maximum on a small grid
  3. uphill-simplex algorithm
Example Event

- single antenna traces
- animated skymap
  - time resolution: 12.5 ns
  - no cleaning → side lobes

after beam-forming
Radio Pulse Height Parametrisation

comparison with KASCADE data leads to parameterization formula:

\[ \varepsilon_{EW} = A \cdot (B - \cos(\alpha)) \cdot \cos(\theta) \cdot \exp\left(\frac{R}{R_0}\right) \cdot \left(\frac{E}{10^{17} \text{eV}}\right)^\gamma \] [\mu \text{V/m MHz}]

With:

- \( A = 11 \pm 1 \)
- \( B = 1.16 \pm 0.025 \)
- \( R_0 = 236 \pm 81 \)
- \( \gamma = 0.95 \pm 0.04 \)

Horneffer et al. (LOPES coll.) ICRC(2007) Merida
Preparing the Future

- **LOFAR:**
  - high sensitivity
  - excellent calibration
  - multi level radio trigger

- **Radio@Auger**
  - autonomous antennas
  - self triggering

- **Simulations!!!**
cosmic ray air showers emit short radio pulses
- have been measured in the 1960s and 1970s

with fast ADCs and fast computers one can store and process the whole waveform information
- digital RFI suppression, e.g., by flagging in Fourier space
- beam forming suppresses incoherent noise and noise from other directions

LOPES was the first experiment to detect air shower radio pulses with this technology
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