Recent results from cosmic-ray measurements with LOFAR

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Radio emission from air showers

- Shower disc is ~ (2-3)m thick
- e- & e+ produce (mostly) synchrotron radiation in geo-magnetic field
- This corresponds to a wavelength of ~ 100 MHz radiation
- Coherence effect expected at frequencies below ~100 MHz

Two main contributions to signal:

\[ j' = (Q \cdot v)' = Q' \cdot v + Q \cdot v' \]

- Total charge variation (~20%)
- Synchrotron radiation (~80%)

Actual emission seems far more complicated:
- Time varying currents
- Cherenkov effects
- Transition radiation, ........
Air shower radio measurements: Recent experiments

CODALEMA, France
24 antennas (0.5 km$^2$)

LOPES, Germany
30 antennas (0.5 km$^2$)

LOFAR, Netherlands+
2000+ antennas (core)
~5 km$^2$

ARGENTINA
Tunka-Rex, Siberia
20 km$^2$
~160 antennas

20 antennas (1 km$^2$)
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An ideal instrument to probe complex radio properties of air showers

Argentina
~160 antennas
20 km²
LOFAR: The LOw Frequency ARray

- An astronomical radio telescope in the Netherlands and its neighboring countries
- 33 Dutch + 8 International stations
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- An astronomical radio telescope in the Netherlands and its neighboring countries
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- Replaced big dishes by many cheap dipole antennas
- 24 stations in a dense core of ~5 km² in the Netherlands
- Each station consists of 96 low band + 48 high band antennas
- Low band: (10-80) MHz and High band: (100-240) MHz
- For air shower measurements: Only core stations ~ 2000+ low band antennas

Superterp: center of LOFAR
LOFAR: Phased Array Detectors

- It can point to different directions in the sky at one time
- Also, useful for cosmic-ray measurements
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LORA: LOFAR Radboud air shower Array

- Purpose is to provide:
  - CR trigger to LOFAR
  - Air shower parameters
- 20 scintillation detectors
- Detector spacings ~ 50-100 m
- Energy range > $10^{16}$ eV
- Energy resolution ~30%
- Core position accuracy <5m
- Arrival direction accuracy <1°
**Cosmic-ray observation**

**LORA**
- Online processing
- Determine shower parameters
- Overall processing time ~ \((100+30)\) ms
- For bright events \( (>10^{16} \text{ eV}) \):
  - Send trigger to LOFAR
- Trigger rate ~ 1/hr

**LOFAR**
- (Data stored in a memory ring buffer for 1.3 s)
- Dump radio data

*LOFAR started taking data in June 2011*
*Regular observation started early 2012*
*Collected \(~400\) good quality events*
A measured cosmic-ray event

P. Schellart
A measured cosmic-ray event

Signal at one station

Beamformed signal

Lateral distribution
More events

P. Schellart, A. Nelles
Measured distribution of events

- All events triggered by LORA
- 367 events fully reconstructed
- North-South asymmetry: (vxB) effect

Arrival direction distribution

Energy distribution

4x10^{16} \text{ eV}

P. Schellart, A. Nelles
On-going works
$X_{\text{max}}$ measurements

* Radio lateral distribution is sensitive to $X_{\text{max}}$
* Mainly due to geometrical effect
* Protons penetrate deeper into the atmosphere
* Deeper $X_{\text{max}}$ => Steeper distribution
$X_{\text{max}}$ measurements

- Lateral distribution
- Fit Quality
- Reduced Chi$^2$
- Signal profile in the shower plane

S.Buitink, in preparation
Ability of LOFAR to measure shape of shower front

LOFAR can resolve 2 ns (no additional phase calibration)

Simulated spherical shower front for measured air shower signals

Differences in time with respect to plane wave are resolvable

Residuals with respect to plane wave

Simulated wavefront curvature, R = 4 km
Understanding the emission components

*Unfolding the antenna pattern to get xyz polarization of the signal*
In-situ gain & timing measurements

Octocopter

Gain measurements

Timing measurement

M. Krause, A. Corstanje
Summary

- LOFAR, with its high density antennas, is an ideal instrument to measure complex radio properties of air showers.
- Since June 2011, LOFAR has measured ~370 good quality cosmic-ray events.
- Current studies mainly focus on:
  - Detailed comparison with simulations
  - $X_{\text{max}}$ estimation
  - Understanding emission mechanisms
  - Shape of the shower front
- In near future, LOFAR will give us a detailed understanding of radio emission from air showers.

Thank you for your attention.