Multi-scale and multi-frequency studies of cosmic ray air shower radio signals at the CODALEMA site

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Motivations
To explore new or neglected ways of exploitation of the radio signal emitted by EAS

**Successes**

| Simulation codes: very good understanding of the emission mechanisms |
| Properties of EAS: arrival direction, energy, mass-sensitive observables |
| At least 10 ground experiments of radio detection of UHECR currently operated in the world + neutrino search + SWORD... |

**Lacks**

| Determination of $X_{\text{max}}$: seems needing high antenna density (contradictory with high energies) |
| Covering large areas: standalone detectors, but either reject parasitic transients (self-triggering) or use scintillators (slave mode) |
| Detection range in classical [30-80] MHz band too short (sensitivity too low) |
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**Solutions?**
- Look at high frequencies?
- Look at low frequencies?
- Very selective, composite radio trigger with several antennas (increased sensitivity)?
- 3-polarization detection?
Since 2011

CODALEMA-3

CODALEMA standalone radio detection station 57 over 1 km²

13 particle detectors (scintillators)

Butterfly antenna and LONAMOS LNA (exported on AERA)
Event reconstruction

Polarization studies
Charge excess contribution

EVA simulations predict consistent dispersion with the charge excess effect.

Dispersion of the polarization signals (II)
Amplitudes and polarization oscillation in the experimental distribution = charge excess effect
Locality around the shower core ↔ polarization dispersion
The shower can be localized from the polarization values. More precise than lateral distribution of the electric field?

Shower core determined here by a standard 1D LDF minimization. Must improve using simulation-based minimization.

R = 0 → only transverse current
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Amplitudes and polarization oscillation in the experimental distribution $\equiv$ charge excess effect.

Locating around the shower core $\leftrightarrow$ polarization dispersion!

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$R = 0 \rightarrow$ only transverse current

Frequency band: 25-200 MHz

Deconvolved

L. Martin, ARENA 2014

R. Dallier - ICRC2015
SELFAS simulation

• Search for best core position
• Search for best 2D-LDF match
• Recover EAS parameters

Xmax minimization

\[ X_{\text{Max}} = 673 \pm 26 \text{ g/cm}^2 \]
\[ X_{\text{core}} = 80.2 \pm 9 \text{ m} \]
\[ Y_{\text{core}} = -10.5 \pm 8 \text{ m} \]
\[ E = (2 \pm 0.7) \times 10^{17} \text{ eV} \]
Reconstruction of the parameters of cosmic ray induced extensive air showers

• The CODALEMA experiment (see R. Dallier et al., found the injected X simulated radio footprint and the one sampled by the CODALEMA array of antennas. The method is explained here through one of nature through the reconstruction of X which the number of particles is maximum, is strongly correlated to the nature of the primary cosmic ray which has generated it. The agreement between the simulated core positions from which the X of the experimental event of the LDF. The method minimizes the

Reconstruction method

An event detected at CODALEMA

Motivations for a pure radio reconstruction method

Set of 150 simulated events

Influence of the frequency band

SELFAS simulation

• Search for best core position
• Search for best 2D-LDF match
• Recover EAS parameters

Xmax minimization

LOFAR HBA observation of Cherenkov ring at 100 m from axis > 110 MHz

The instantaneous [25-200] MHz band covers both the LBA and HBA bands of LOFAR (not usable at the same time): filtering band can be selected depending on antenna location vs. axis. Could compensate a lower antenna density over a larger area (in progress)
The Compact Array

Mid-2013

10 antennas + LONAMOS LNA, dual linear horizontal polarisation, over a square of 150m x 150m (24 to 146m spacing), working as an interferometer (sensitivity $\times \sqrt{10}$)
Aim: testing a composite trigger, able to detect and select online the EAS events by testing in real time all sky directions at once.

Two observing modes:

- **SD triggered** (20 channels, 6 μs snapshot), [10-200] MHz
- **Self detecting mode** (in progress), [30-80] MHz
  - continuous sampling of (up to) 8 channels, in circular polarisation @100 MHz
  - real-time software (using GPU 5 Tflops)
  - for each successive time-window corresponding to the array time aperture (500 ns): generate ~2000 beams in sky (~2° apart) via beamforming, and search for beam(s) containing signal above some intensity threshold
EXTASIS: search for the low-frequency components [2-5] MHz

Butterfly type + modified LONAMOS LNA; the pole acts as a part of the antenna; the height of 7 m is optimized
EXTASIS: the low-frequency components

The “classical” signal (here vertical polarization, full band)

SELFAS simulation

CODALEMA, LOPES, LOFAR, AERA...
EXTASIS: the low-frequency components

And the expected “new one” (still vertical polarization, full band)

Low frequency (< 10 MHz), “sudden death” signal
- Absolute timing
- Shower core position
- Larger detection range
A newly designed 3-Polarization antenna

Aim: testing the “far-field” hypothesis (no longitudinal E-field component)
NenuFAR: twice the LOFAR core sensitivity @ Nançay

Completion 2017

Astronomical radio interferometer

SKA pathfinder, LOFAR Super Station (LSS)

96 arrays of 19 antennas (Compact Array type) in dual polarization [10-80] MHz

96 out of the 1824 antennas (1/array) devoted to UHECR detection (ext. trigger)
Another possible use in dedicated observation mode (not 100% of time): phasing each mini array in different directions, the whole covering all the sky, externally triggered (“Compact Array” mode)

Effective area: 19 x single LBA
Nançay facilities: a swiss-knife for UHECR radio detection

• Unique wide frequency band (2 - 200 MHz)
• Multi-scale antenna densities
• Test bench for future projects (SKA, see T. Huege’s talk on saturday)
• Anyone interested is welcome!