Main features of cosmic ray induced air showers measured by the CODALEMA experiment

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Motivations of CODALEMA

- **Goals:**
  - Study the properties of the radio electric field produced in extensive air showers
  - Promote the radio detection technique as an competitive alternative to SD and FD techniques
  - Contribute to cosmic ray physics within the CODALEMA energy range

- **Context:**
  - Installed since 2002 at the Nançay radio astronomy observatory
  - Several generations of antennas, LNA, triggers, daq and arrays developed...

Radio electric transients produced by the geomagnetic and charge excess mechanisms
The CODALEMA instruments

- 57 autonomous stations (B.Revenu et al. [CRI109])
- 13 scintillators
- 10+5 cabled antennas (A.Lecacheux et al. [CRI103])
- 1 tripole antenna (R.Dallier et al. [CRI104])
- 7 LF antennas (A.Escudie et al. [CRI102], D.García-Fernández et al. [CRI118])

Surface: ~ 1 km²
The autonomous station

EW and NS horizontal polarizations
Wide band – [20 – 200] MHz
LONAMOS LNA
1 Gs/s – 2.5 μs
Self triggering – On board processing
GPS timing
Event reconstruction in the arrays

- Typical rates (in a month):
  - SC: 40,000 evts
  - SA: 1,200,000 evts (loose trigger)
  - Coincidences: 60 evts!

- Arbitrary small sample of events for this preliminary analysis:
  - Reflect roughly the observed variety in multiplicities, signal amplitudes, shower axis and locations
  - Not representative of the array acceptances
  - SA and SC arrival directions agree
Convolution of the antenna response

- Systematic comparisons with model predictions: SELFAS*
- Convolution: (Model predictions → ADC values) vs Data
- Calculated/measured global transfer function of the detection chain (including the antenna response)

Is the sensitivity preserved?

Model: SELFAS

ADC: SELFAS convol.

Spectrum and amplitude variations are preserved!
Extracting cosmic ray features

- SELFAS+CONEX simulation with a virtual antenna array using $E=10^{17}$ eV and $(\theta, \phi)_{\text{exp}}$
- Interpolate amplitudes $F(x,y)$
- Convolution with the antenna response $H(f, \theta, \phi)$
- Process a set of SELFAS simulations (typ. 50 p, 10 Fe) per event to sample the $X_{\text{max}}$ range
- Calculate $\chi^2$ from amplitude differences
  \[ \chi^2 = \sum_{\text{ant}} \left( \frac{A_{\text{ant}} - \alpha F(x_{\text{ant}} - X_{\text{core}}, y_{\text{ant}} - Y_{\text{core}})}{\sigma_{\text{ant}}^2} \right)^2 \]
- Loop over a range of core location $(X_{\text{core}}, Y_{\text{core}})$ and scaling energy factor $\alpha$
- The lowest $\chi^2$ determines the overall most probable $(X_{\text{core}}, Y_{\text{core}})$, $E=\alpha \times 10^{17}$ eV and $X_{\text{max}}$

Inspired by the method used on AERA data by F.Gaté et al., ARENA 2016, Groningen, June 7-10, 2016.

- Combination of $(X_{\text{core}}, Y_{\text{core}})$ and $\alpha$ with the lowest $\chi^2$ ($= \chi^2_{\text{min}}$) is the most probable set of values.

\[ \chi^2_{\text{min}} \text{ vs } X_{\text{max}} \]
Some examples

- Amplitude footprint
- $\chi^2$ vs core location
- $\chi^2$ vs $X_{\text{max}}$

Lateral distribution function
- Data + SELFAS

Few antennas give access to the CR properties!
Polarization patterns solve ambiguities

Data SELFAS

Local minimum in the $\chi^2_{\text{min}}$ values versus $X_{\text{max}}$ distribution. Polarization patterns support only one solution. Both EW and NS amplitudes must be matched separately!
Comparison with the scintillators

Shower core often outside of the SC array: $E_{\text{particle}}$ underestimated!
Better agreement using $(X_c,Y_c)_{\text{radio}}$ for the $E_{\text{particle}}$ estimation

No error bars on $E_{\text{radio}}$ yet, no real atmosphere for $X_{\text{max}}$

Preliminary analysis seems on the right direction but still lots of (careful) work to do!

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Conclusions and Outlook

- CODALEMA is routinely observing high-energy cosmic rays in the $10^{16} - 10^{18}$ eV range.

- CODALEMA data compare well with SELFAS simulations: shower core locations, $X_{\text{max}}$ and energies can be estimated using the radio signals.

- Further improvements:
  - Careful estimations of systematics, error bars and resolutions
  - Analysis extended to the full CODALEMA set of data (especially at lower E)
  - Analysis method (comparison with simulations) extended to the two polarizations and the full spectrum
  - Sensitivity and resolution estimation for a sparser array

- Analysis in progress in parallel with other R&D developments:
  - 3-polarization antenna, standalone and phased triggers, LF antennas...
Spares
Trigger and Acquisition systems

Analog T1 trigger: no permanent digitization of the signals and a controlled energy budget (~20W per station).

SA - multi-level triggering strategy:
- **T1** on trigger board: filter, threshold discrimination, combination of channels, coarse timing...
- **T2** on local PC: timing, pulse shape discrimination, polarization, spectral content...
- **T3** on central acq. syst.: relative timing between stations, direction of arrival, occurrence frequency...

SC – particle trigger selection:
- Individual threshold (15 mV)
- Multiplicity selection (5 or more over 13 SC)
- Trigger GPS timing
- Trigger broadcast over the network
Convolution of the antenna response

- Electric field pattern is not simple, dependence to the \((v, B)\) angle \(\rightarrow\) compare to realistic simulations!
- **Direction?**
  - **Deconvolution:** data \(\rightarrow\) \(E_{\text{field}}\) vs Model
  - **Convolution:** Model \(\rightarrow\) ADC vs Data

- **Global transfer function:**
  - \(H(f, \theta, \phi) = H_{\text{ant.}}(f, \theta, \phi) H_{\text{ana.}}(f) H_{\text{digit.}}(f)\)
  - Calculated or/and measured transfer functions

\[ F^{-1}(H \cdot F(E(t, \theta, \phi))) = ADC(t) \]

Extracting cosmic ray features (II)