Investigating the extensive air shower properties using the polarization and frequency features of the radio signals measured by the CODALEMA autonomous station array.

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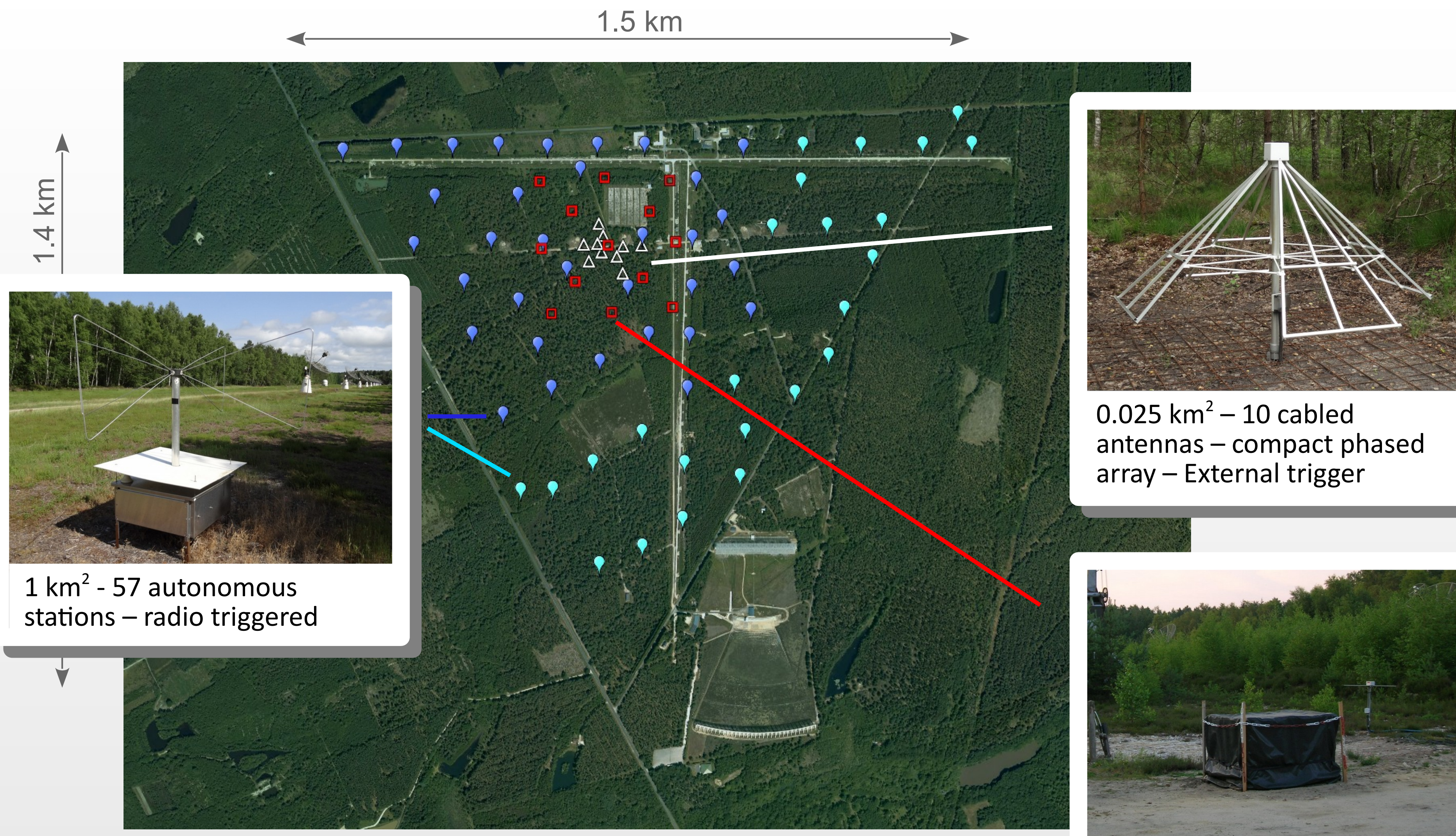
CODALEMA
LESIA, Paris-Meudon
Station de radio astronomie, Nançay
SUBATECH, Nantes

Radio detection of cosmic rays at Nançay

- **Aims of the CODALEMA experiment**
  - R&D effort on the radio detection of CR
  - Promote the technique as a comprehensive and competitive method
  - Understand the details of the relationship between the electric field and the air shower development
  - **Not an CR observatory**
- **Advantages of the Nançay location**
  - Existing and modern infrastructure
  - Nearby and open to new developments
  - Long experience of radio astronomy
  - Clean site and clean vicinities
- **Understanding the radio signal production : theoretical developments**
  - Boosted Coulomb field boosted model : A.LeCacheux et al.
  - SELFAS microscopic model : V.Marin et al. **(See B.Revenu's talk)**
- **Experimental developments**
  - 2004 : a new LNA chip (codalamp)
  - 2006 : a new fat dipole array
  - 2007 : a new scintillator array
  - 2008 : a new butterfly antenna **(See D.Charrier's talk)**
  - 2010 : a new autonomous station
  - 2012 : a new LNA chip (lonamos)
  - **2013 : new radio arrays (See A.LeCacheux's talk)**

CODALEMA 3 : An ensemble of instruments



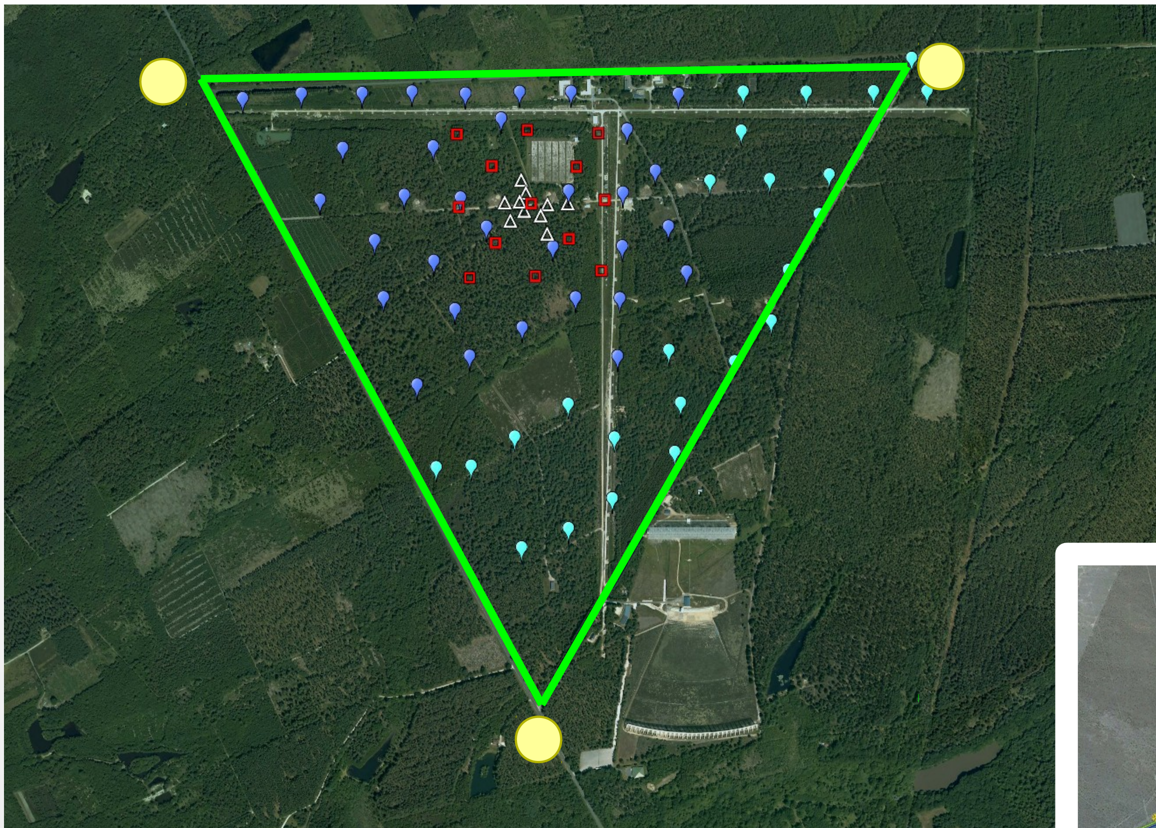
1 km² - 57 autonomous stations – radio triggered

0.025 km² – 10 cabled antennas – compact phased array – External trigger

0.1 km² – 13 scintillators – Trigger and off-line CR ident.

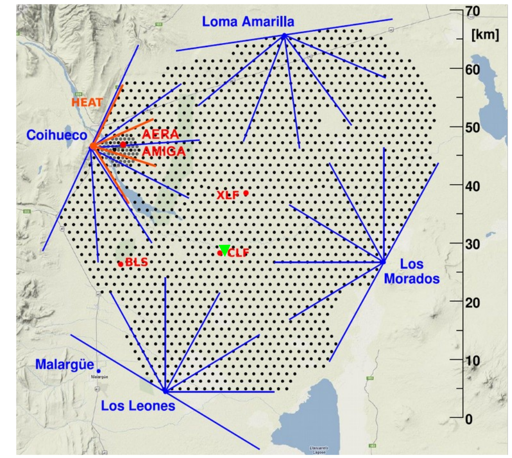
Scintillators : 2007
Autonomous Stations : 2011 et 2013
Compact array : 2013 **(See A.LeCacheux's talk)**

Comparing CODALEMA to AUGER

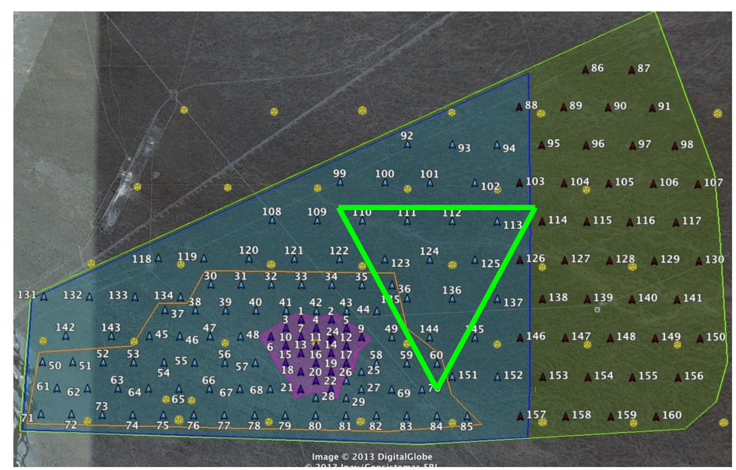


CODALEMA is equivalent to an elementary cell of the AUGER surface detector !
CODALEMA is about 10 times smaller than AERA.

CODALEMA is not a large scale (i.e. high energy) cosmic ray observatory.

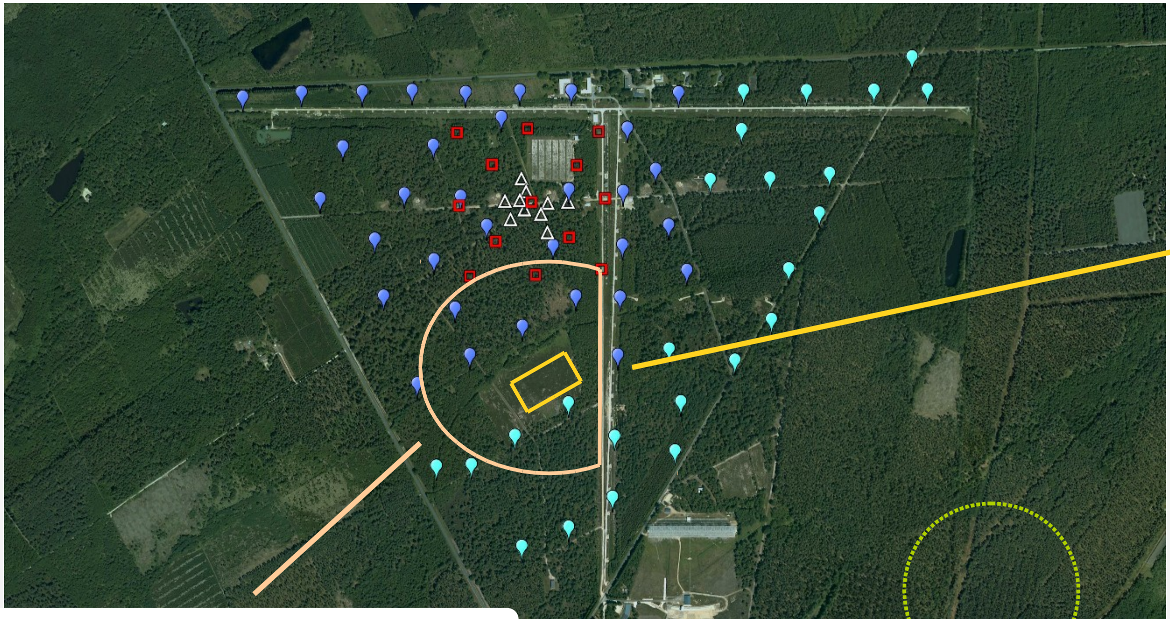


AUGER surface detector – 1600 tanks – 3000 km^2



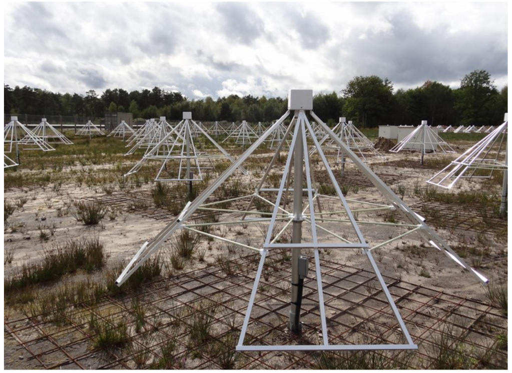
AUGER radio array prototype : AERA – 160 radio stations – 13 km^2 – hybrid detection

Comparing CODALEMA to LOFAR



The LOFAR international station at Nançay – 192 antennas

LOFAR superterp (Netherlands) – 21x96 antennas – Ø = 350 m



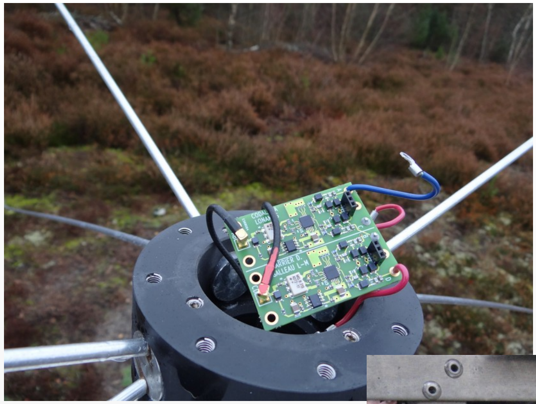
The NenuFAR project (Nançay) – 19x96 antennas – Ø = 400 m

CODALEMA covers a surface bigger than the LOFAR superterp in the Netherlands.

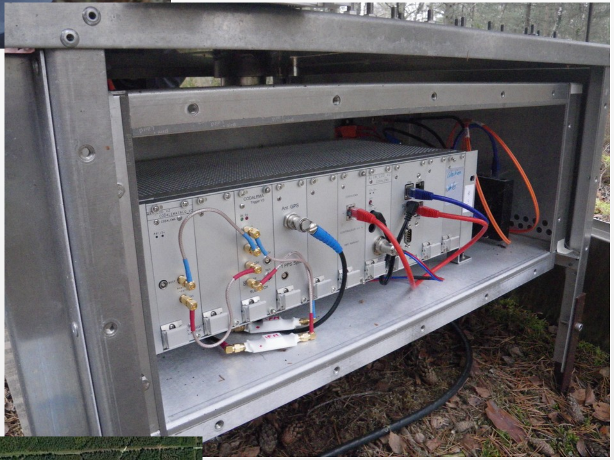
CODALEMA = LOFAR LBA+HBA antennas combined
CODALEMA surrounds the LOFAR and NenuFAR array

Some key items of the autonomous station array

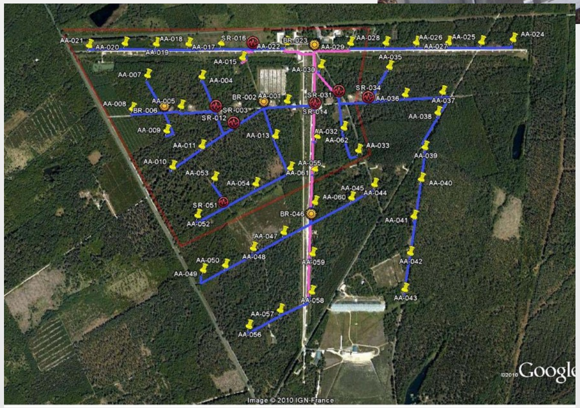
- A robust, linear wide-band antenna : a dedicated LNA and successful design (exported in AERA and NenuFAR). **See D.Charrier's talk**
- Modular (one board=one function) , on-board and upgradeable electronics : Power, GPS, Trigger, Comm., ADC, PC...
- Radio self pollution limited : electromagnetic compatibility of the crate and the mechanical box tested in an anechoic chamber and on site.
- A power network and a computing network (10 km of buried power cables and optical fibers) : no solar panels nor radio comm. network to deal with (problem common to all scattered arrays)
- Analog L1 trigger (orthogonal choice compared to AERA). No permanent digitization of the signals : a controlled energy budget (~20W per station). L2 trigger on the station. L3 trigger on the array.



The dual channel low noise amplifier integrated into the antenna head



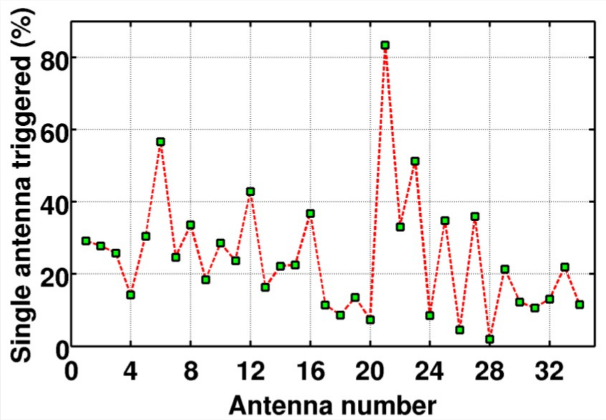
A double EMC barrier: crate and box with metallic seals



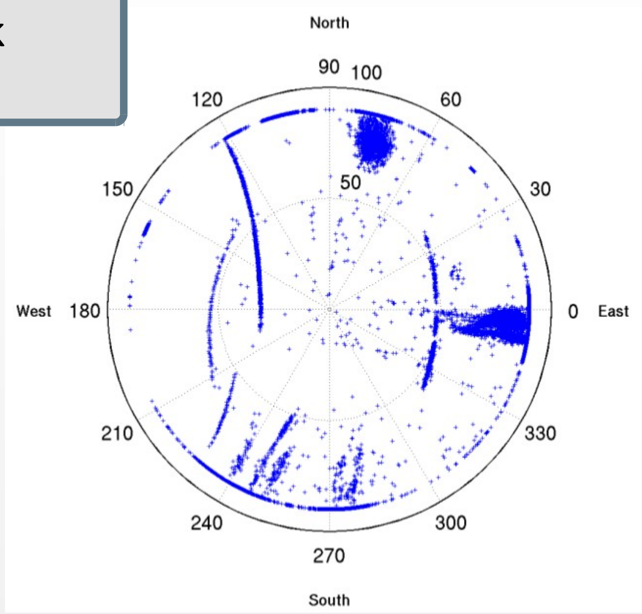
10 km of cuttings and gutters along the forest tracks and the roads.

The transient sky : a brand new world

A large fraction of the events concerns only one or few stations : very local noise sources

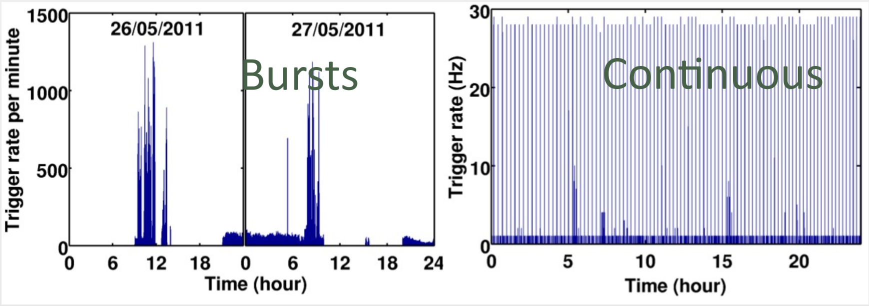


A typical day at Nançay :
mobile vs static
intense vs weak
spot vs diffuse



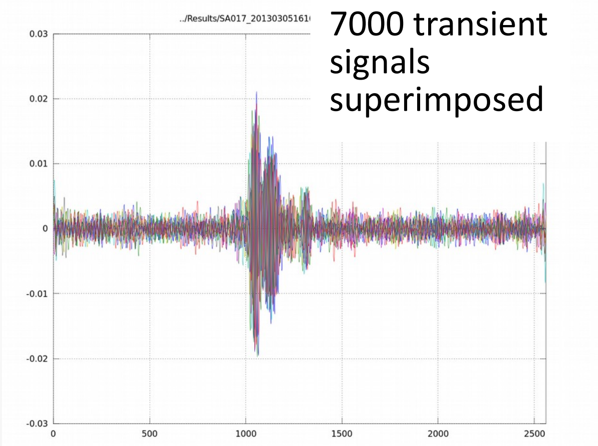
Despite a very severe regulation in term of RFI, the radio-astronomy station of Nançay is surrounded by various parasitic transient sources : planes, power lines, power transformers, fences.

Permanent signals or periodic bursts : identity of the sources



A large fraction of the transient sources has been identified, characterized and localized
Selected strategy : Do not turn them off. Try to become immune to their emission !
Human activities are (almost) everywhere...

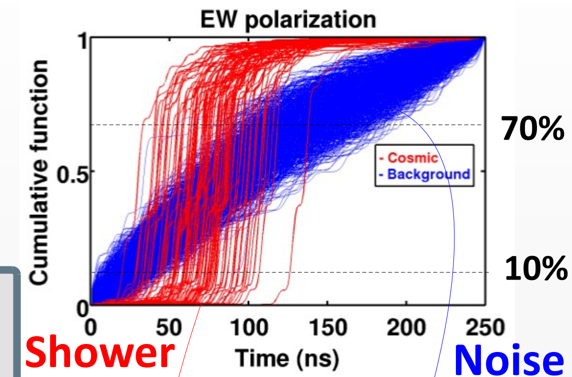
Transient noise rejection methods



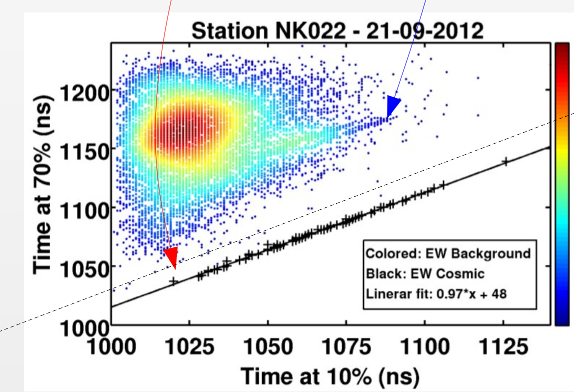
7000 transient signals superimposed

Shower/noise signals are short/long.
Noise signals are similar, with secondary pulses and often periodic.
Wave form, energy or occurrence selection

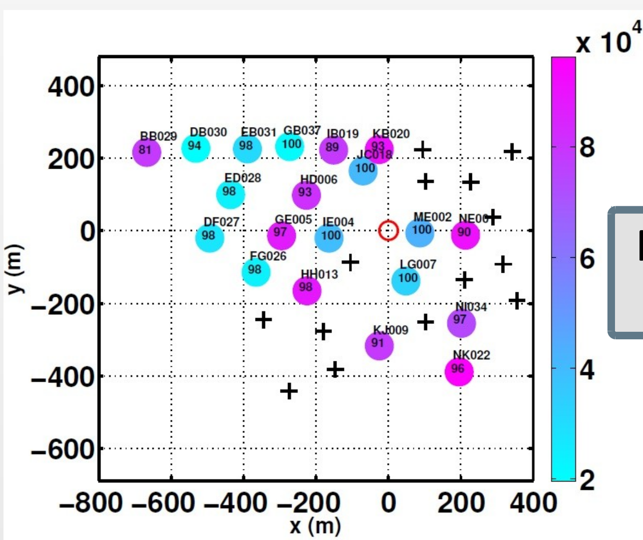
Normalized cumulative V^2



Wave form selection



Rejection above the shower signal accumulation line



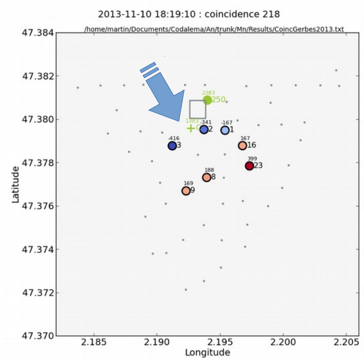
Parasitic signal rejection

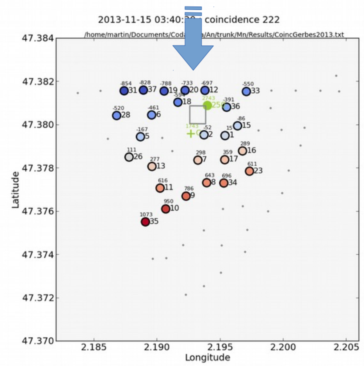
Rejection yield : 94.2 % (T2)
To be implemented in the T1 level
Optimization at the T2 et T3 levels

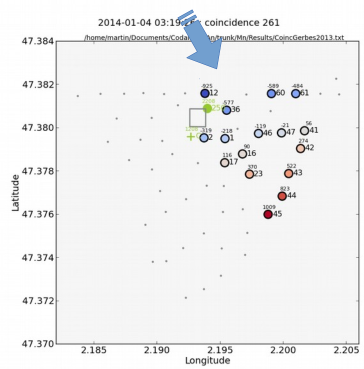
Rejection methods are working but results in self trigger is not satisfactory yet : purity, efficiency and duty cycle must be improved.

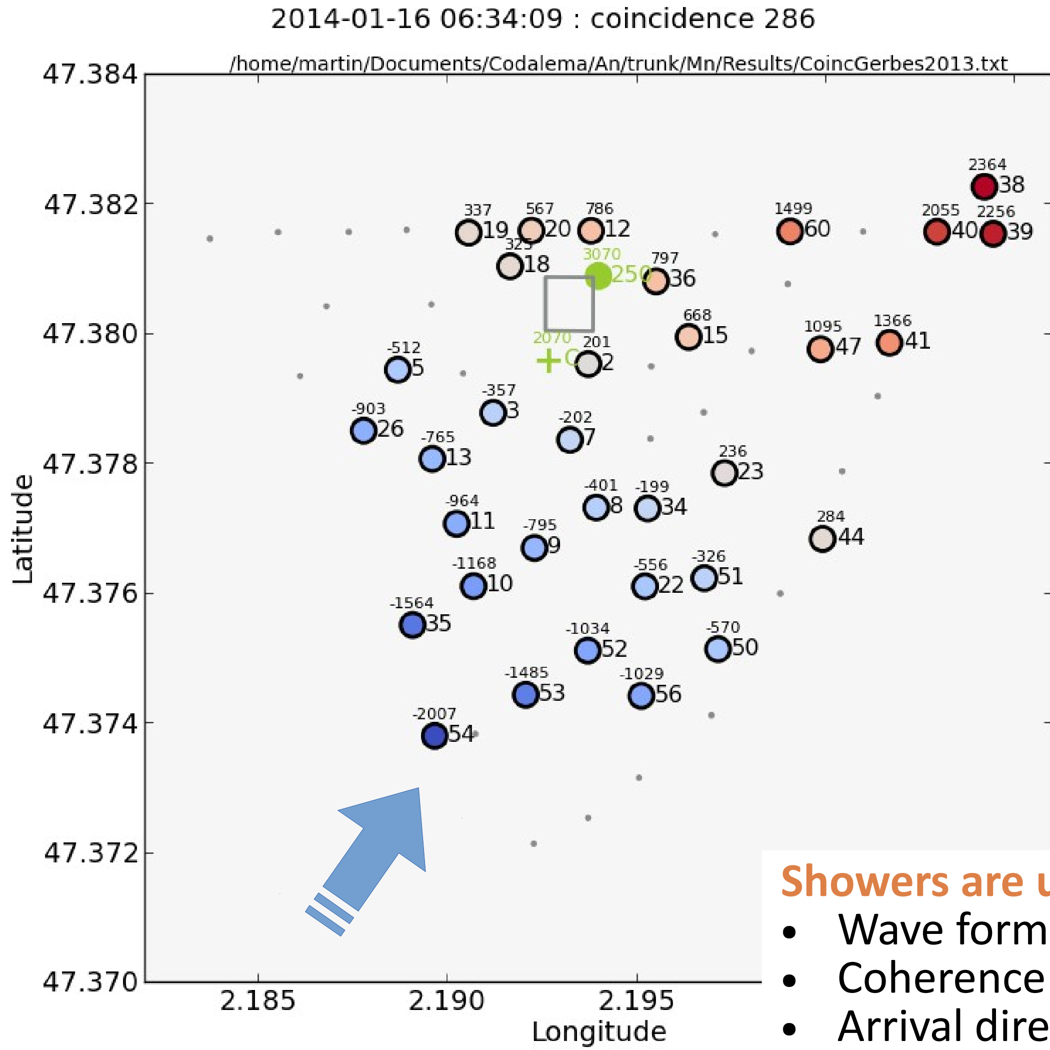
Work on L1 to improve duty cycle. Comb. of selections on L2.
Adding local particle trigger will work but that is not the goal
Still EAS events are observed and recorded ...

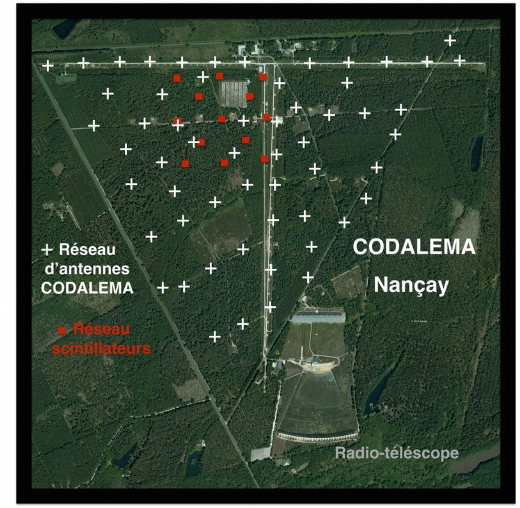
Observing and analyzing cosmic ray events









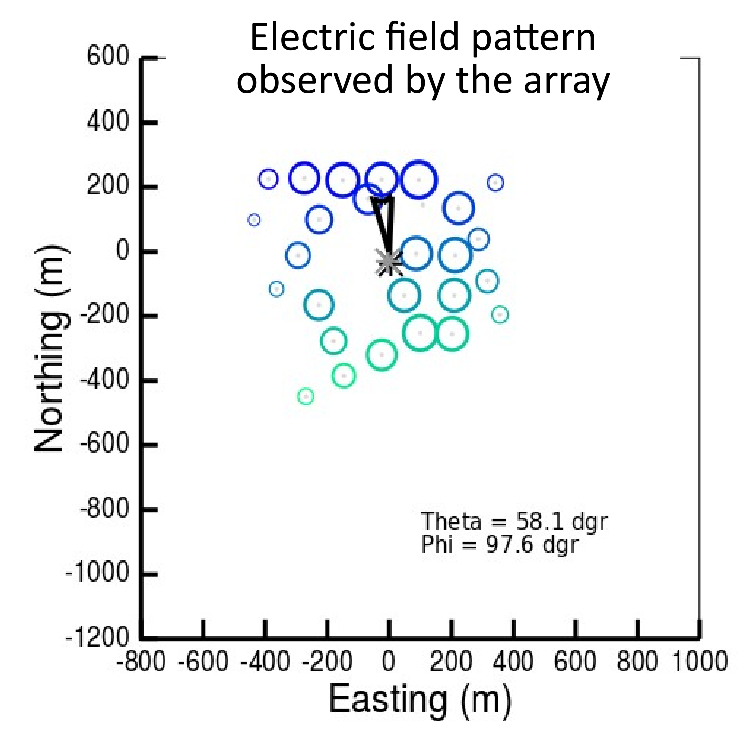


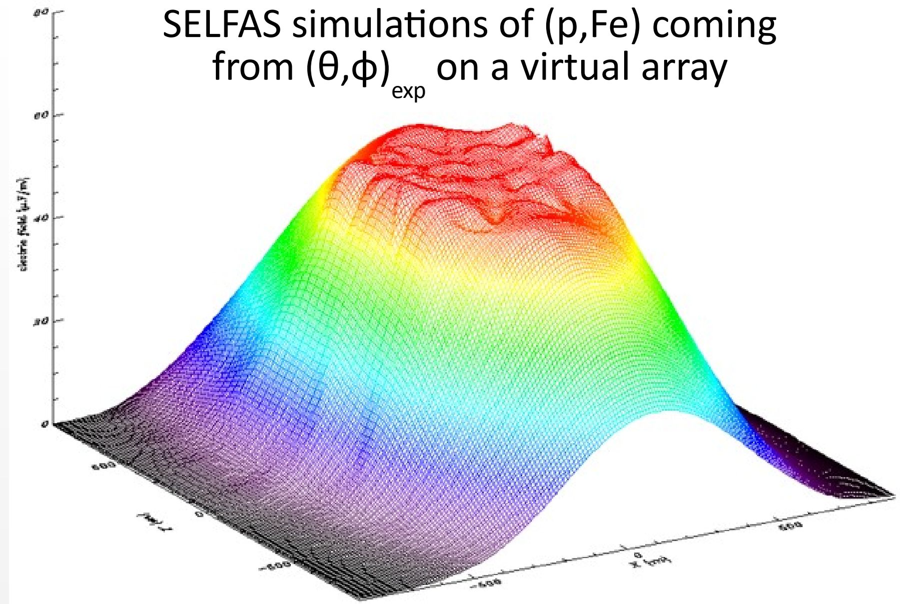
The EAS has been seen by 33 stations. Missing stations were busy (triggering on noise). Almost 1.5 km between the furthest stations.

Showers are unambiguously identified :

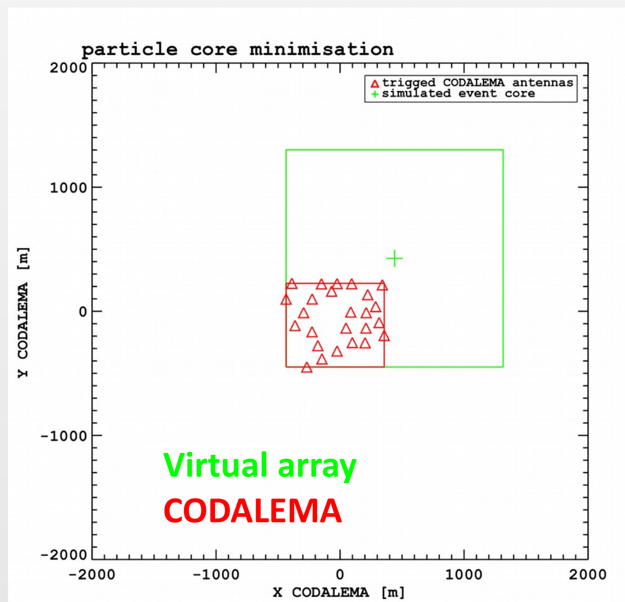
- Wave form and spectral signature
- Coherence of the GPS times
- Arrival direction above the horizon
- Angular and temporal coincidence with the scintillator array

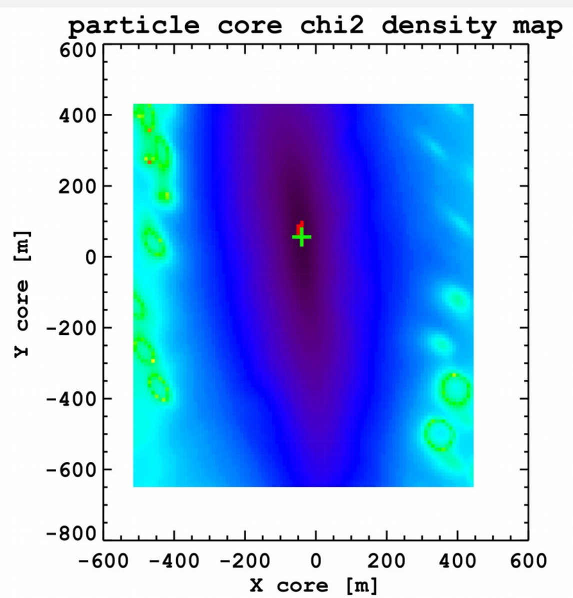
Shower core location using simulations (I)



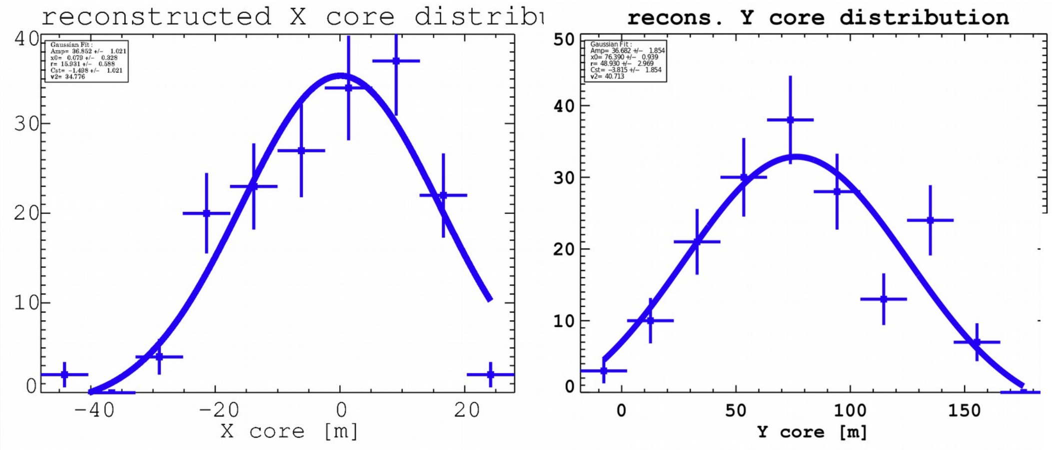


For each simulation, the virtual array is displaced relative to CODALEMA. The electric field values are compared and a core location is determined by selecting the smallest χ^2

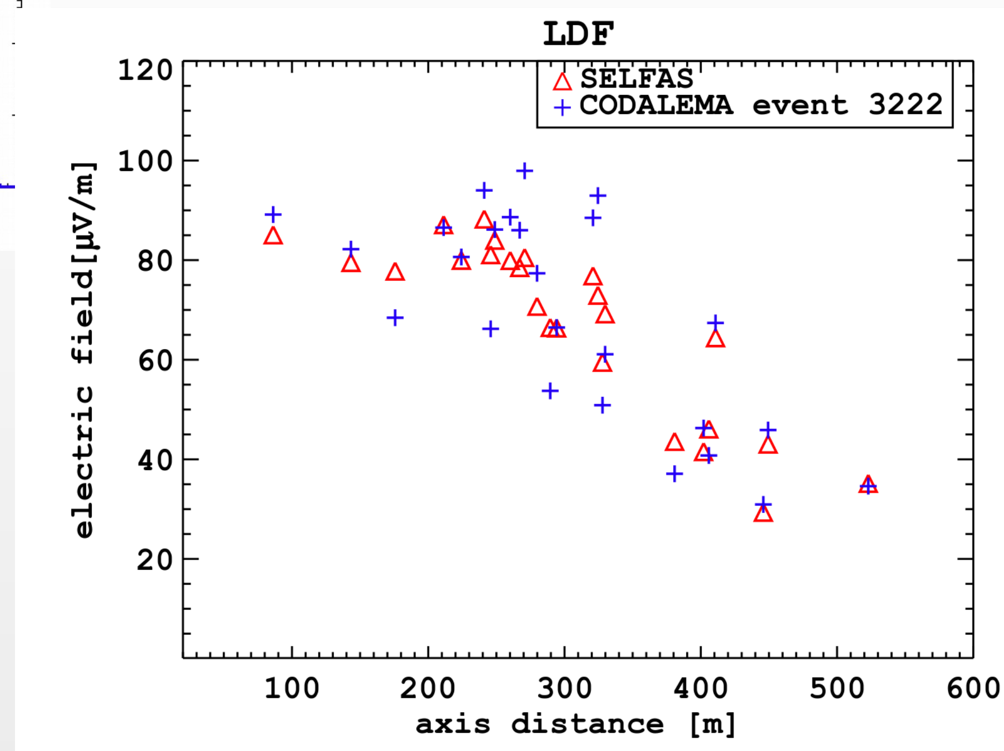


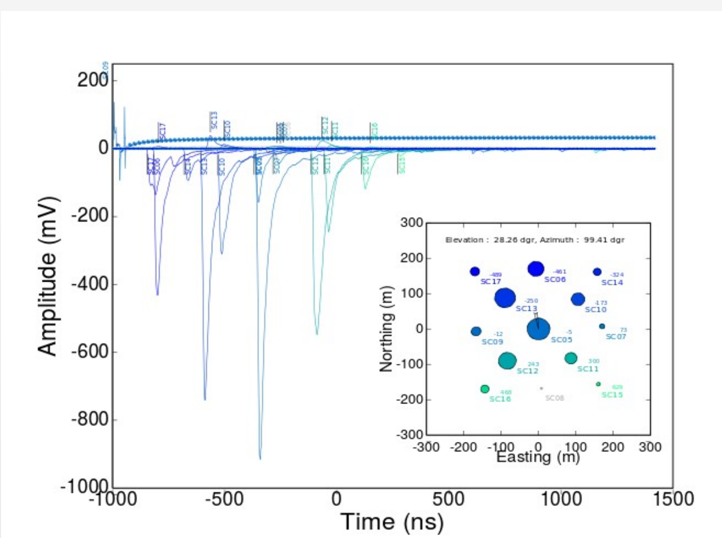


Shower core location using simulations (II)



The most probable core location is deduced from the X and Y distributions

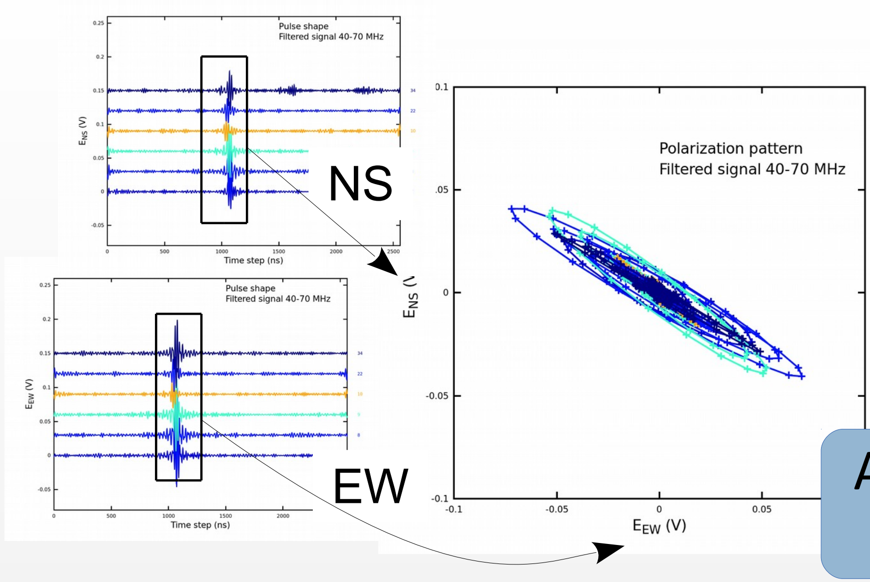




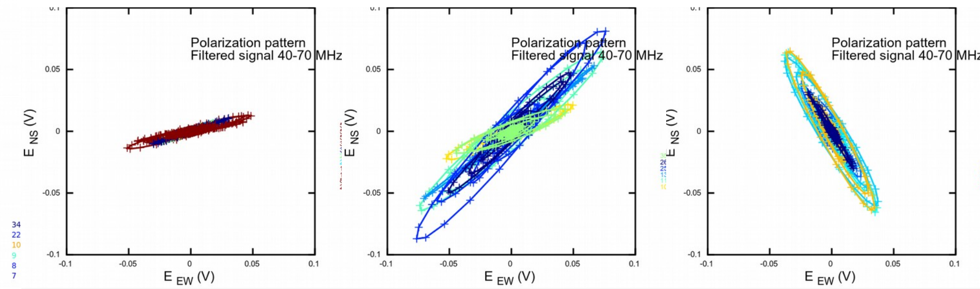
The scintillator array data confirm the core location deduced from the simulations but now can be ignored !

Systematic comparisons with simulations can be used to extract core locations, energy and Xmax values.
Both polarizations can be used
Frequency ranges can be explored
Noisy antenna can be identified

Beyond basic properties : signal polarization



Radio signals are strongly polarized !



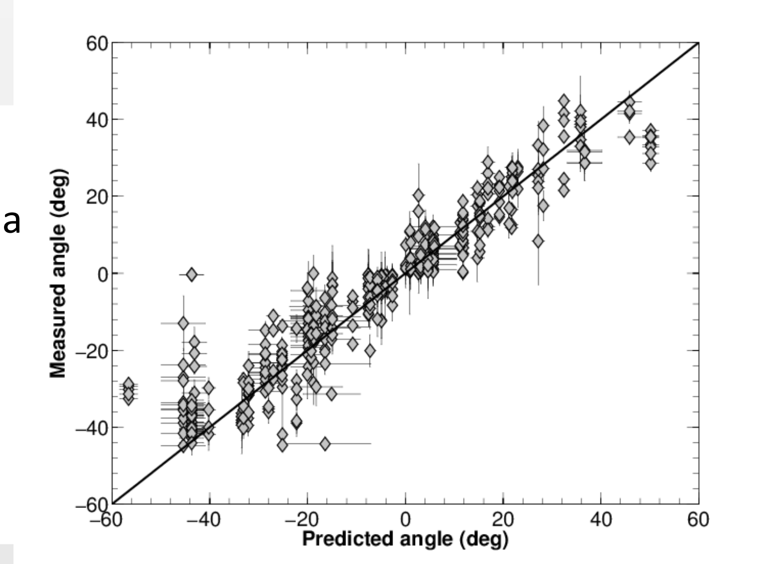
Amplitudes and polarization

Stokes parameter analysis : for each event and and antenna

$$Q=\frac{1}{n}\sum_{i=1}^{n}(E_{EW,i}^2-E_{NS,i}^2)$$

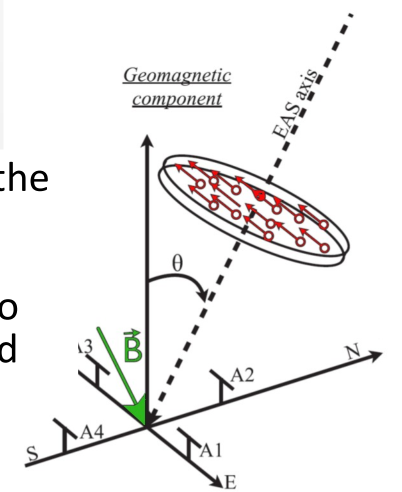
$$U=\frac{2}{n}\sum_{i=1}^{n}(E_{EW,i}E_{NS,i})$$

$$\psi_{meas.}=\frac{1}{2}\tan^{-1}(\frac{U}{Q})$$



Transverse current : the signal polarization is given by the shower orientation relative to the geomagnetic field

$$\psi_{Pred.}=\tan^{-1}(\frac{(\vec{v}\times\vec{B})_{NS}}{(\vec{v}\times\vec{B})_{EW}})$$

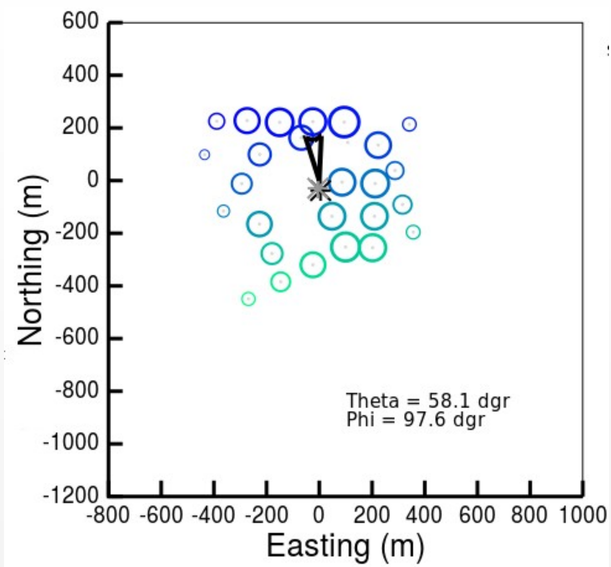


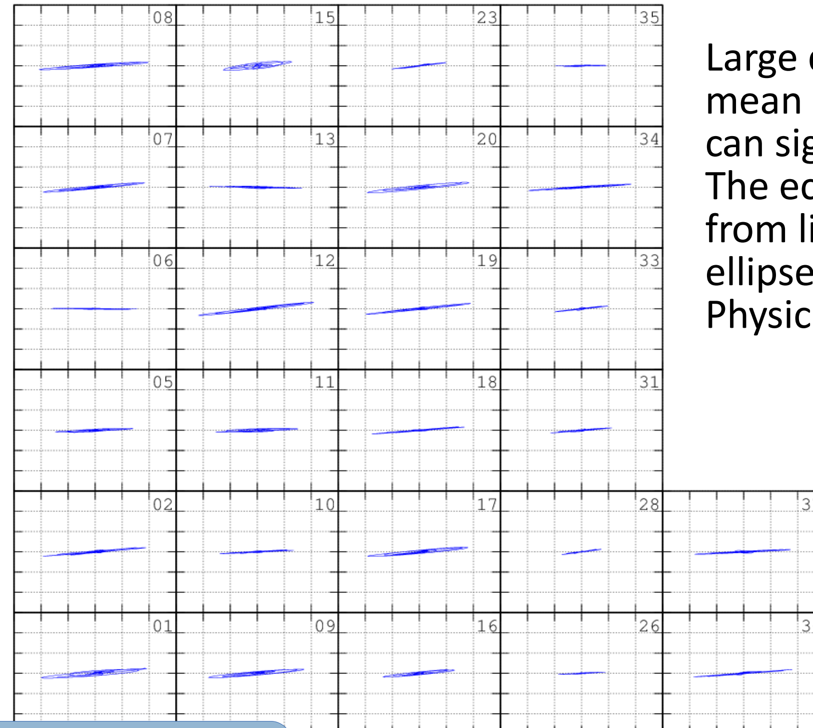
Strong correlation with the predicted angle

Arrival direction ↔ Polarization !

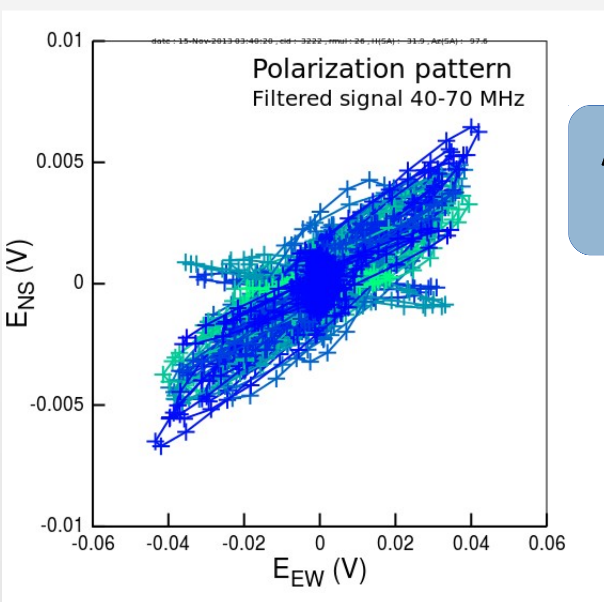
Shower – Noise discrimination !

Dispersion of the polarization signals (I)

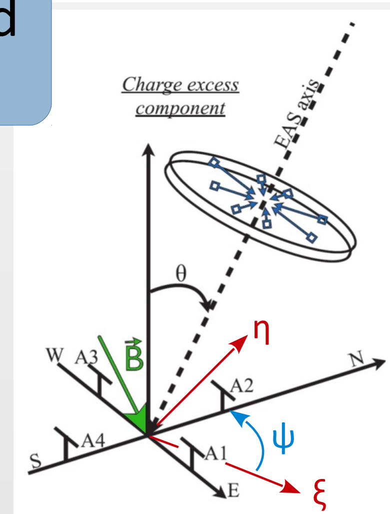




Large dispersion from a mean polarization angle can sign bad antenna.
The eccentricity (departure from linear polar.) of the ellipse is clearly variating : Physics ? Instrument ?



Amplitudes and polarization



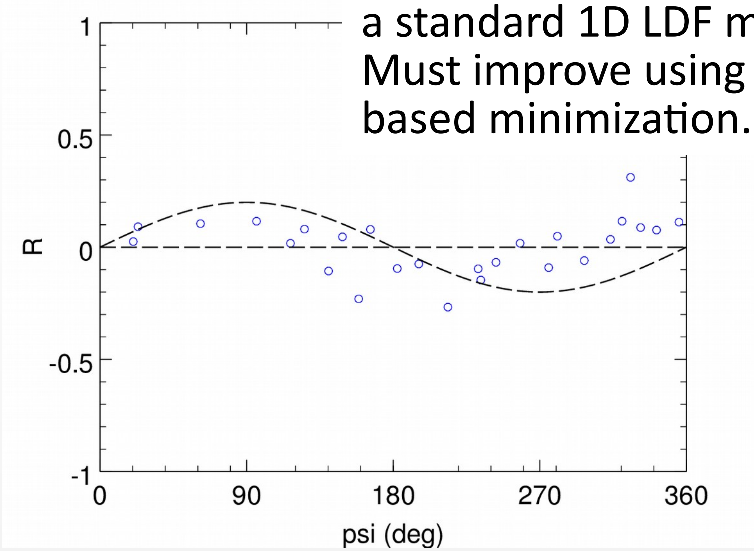
The polarization is computed in a (ξ,η) frame specific to each shower (where the transverse current contribution cancels out) :

$$R(\psi)=\frac{2\sum_{i=1}^{n}\left(E_{\xi,i}E_{\eta,i}\right)}{\sum_{i=1}^{n}\left(E_{\xi,i}^{2}+E_{\eta,i}^{2}\right)}$$

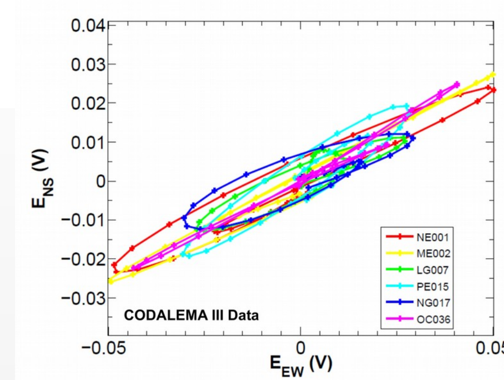
A radial contribution appears as a sinusoid !

Dispersion of the polarization signals (II)

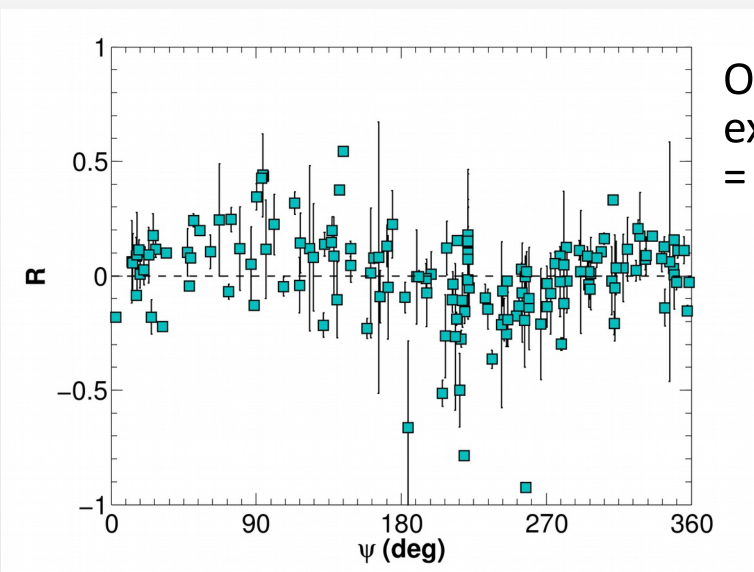
Shower core determined here by a standard 1D LDF minimization. Must improve using simulation based minimization.



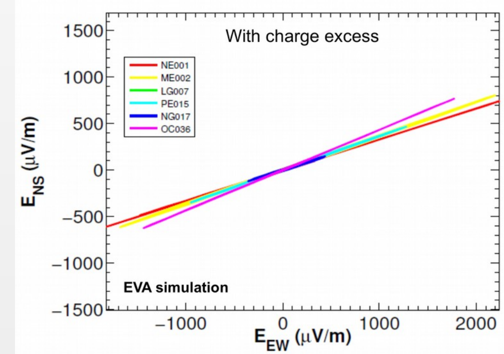
EVA simulations predict consistent dispersion with the charge excess effect



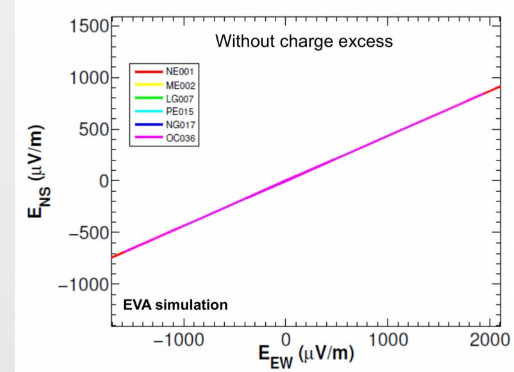
Amplitudes and polarization



Oscillation in the experimental distribution = charge excess effect

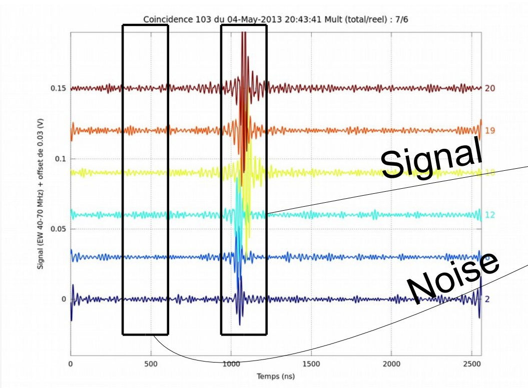


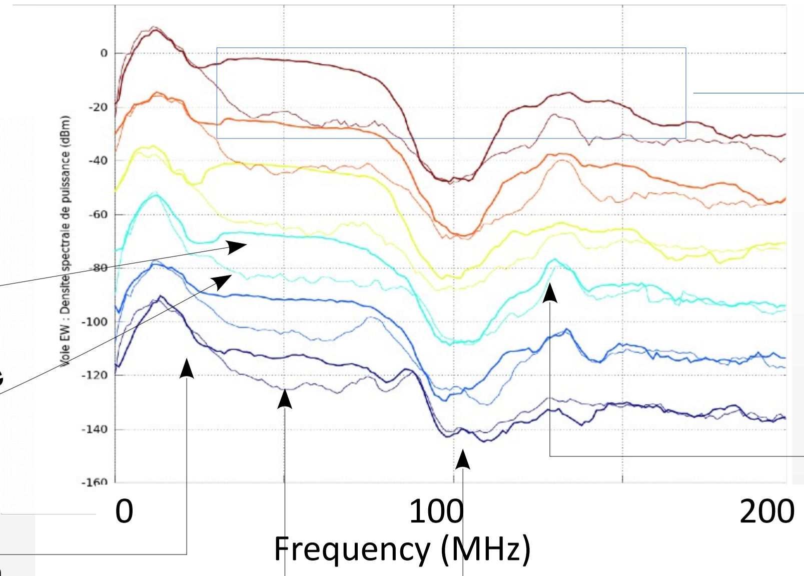
Location around the shower core ↔ polarization dispersion !
The shower can be localized from the polarization values.
More precise than lateral distribution of the electric field ?



Beyond basic properties : frequency spectrum

The antenna+LNA ensemble is a sensitive and wide-band sensor





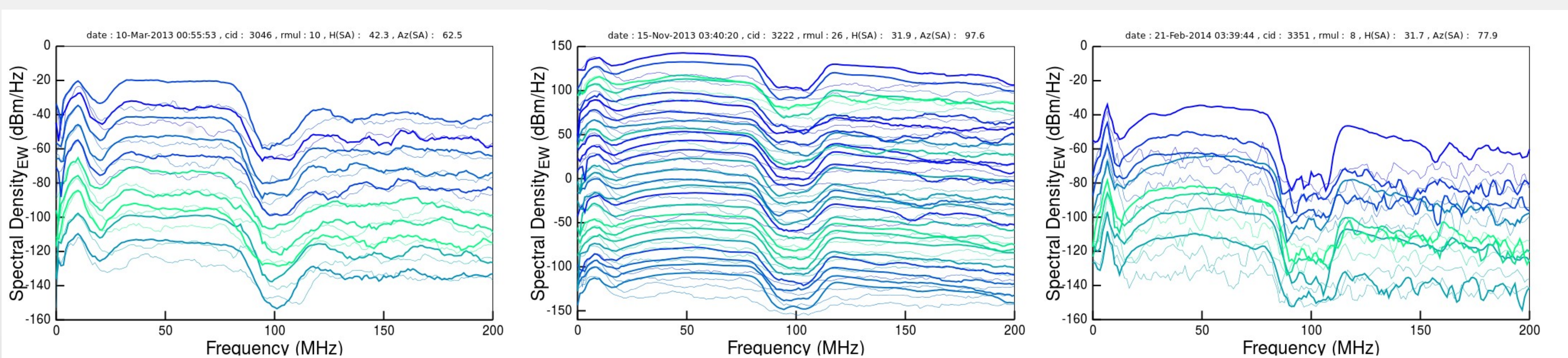
The spectral density exhibits content clearly associated to the CR radio transients

Some temporary lines may appear but are identified in the noise spectrum

The AM lines are attenuated and enlarge by the frequency resolution

The FM lines are suppressed by the antenna stop-band filters

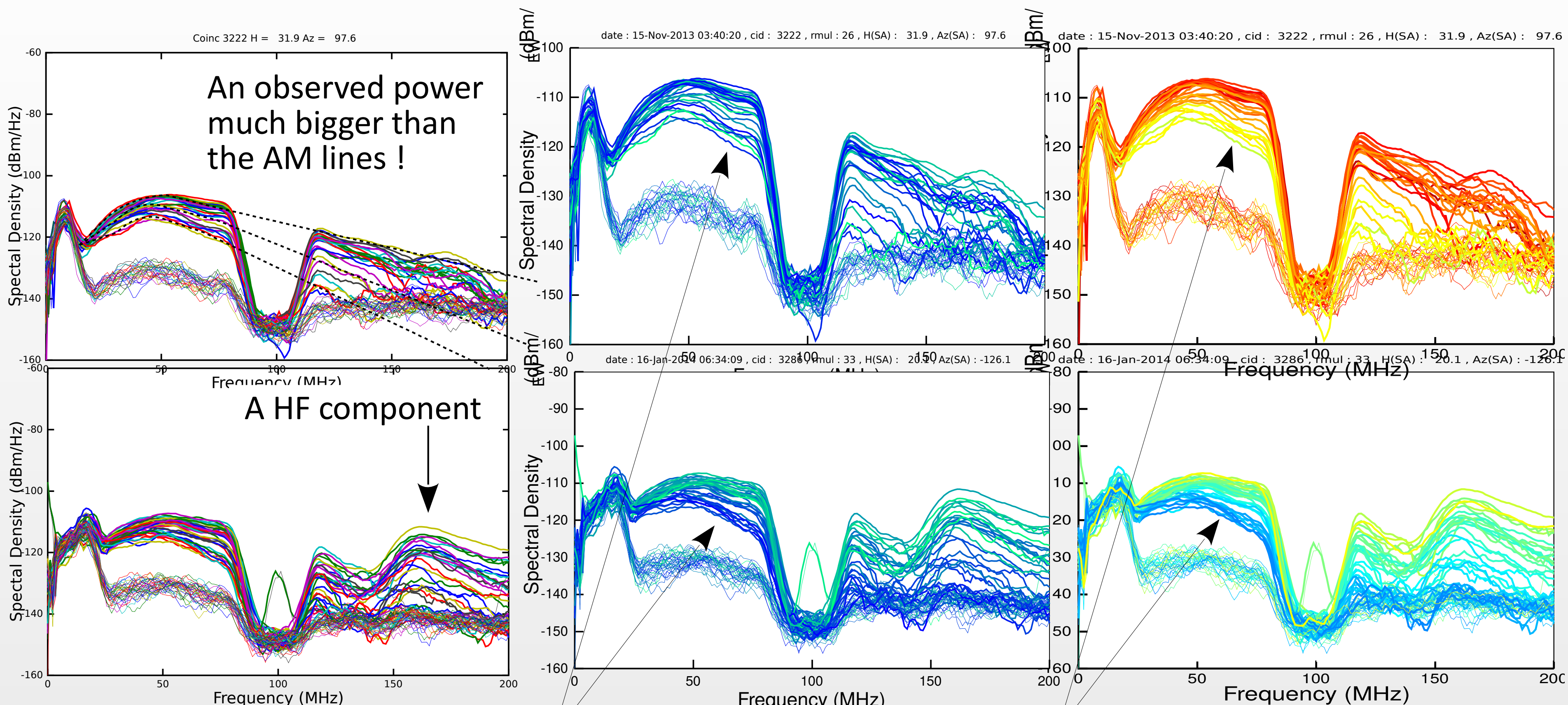
The noise spectrum is a good reference since it shows galactic variations



Various shapes, various frequency extents and antenna to antenna variations

Beyond basic properties : variating spectra

Superimposing the spectra reveals strong variations between events and within the events



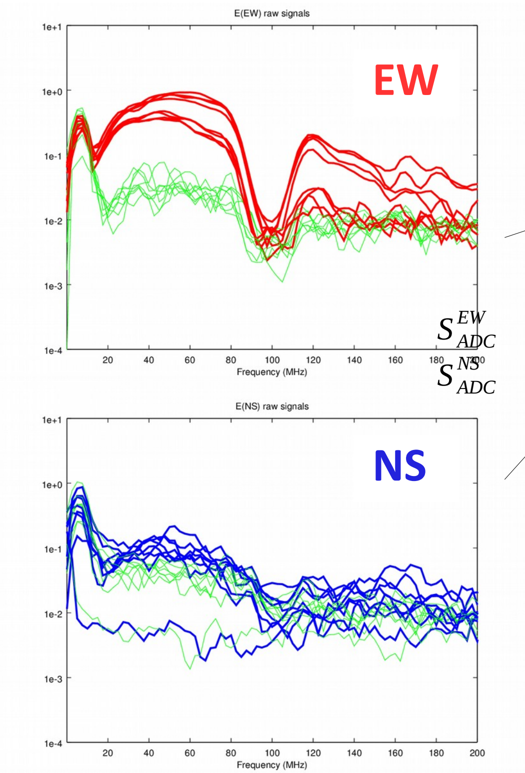
Some coherent correlations with the arrival times in the antenna (blue:early, green : late)

A clear correlation with the distance to the shower axis (red:close, blue : far)

Deconvolution of the full acquisition chain is needed to understand the spectrum variations and the spectrum structures

Unfolding the acquisition chain response

Raw signals



$$E_{\theta}(f,\theta,\phi)=\frac{H_{\phi}^{EW}\,FFT(S_{ADC}^{EW})-H_{\phi}^{NS}\,FFT(S_{ADC}^{NS})}{H_{\phi}^{NS}H_{\theta}^{EW}-H_{\phi}^{EW}H_{\theta}^{NS}}$$

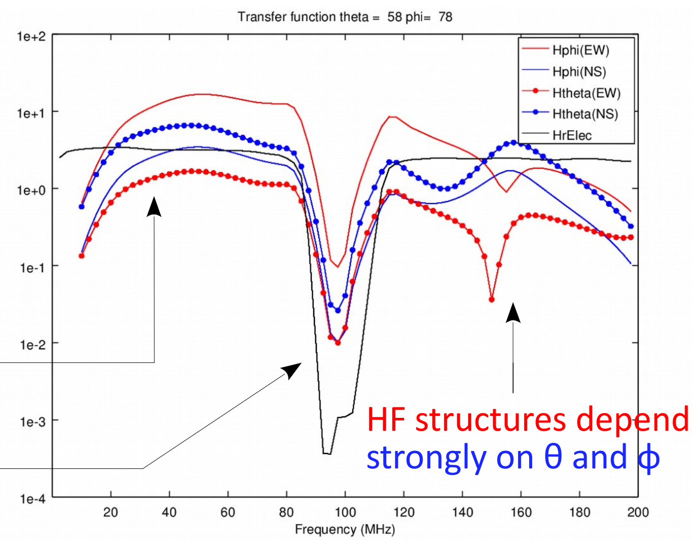
$$E_{\phi}(f,\theta,\phi)=\frac{H_{\theta}^{EW}\,FFT(S_{ADC}^{EW})-H_{\theta}^{NS}\,FFT(S_{ADC}^{NS})}{H_{\phi}^{NS}H_{\theta}^{EW}-H_{\phi}^{EW}H_{\theta}^{NS}}$$

$$E^{EW}(f,\theta,\phi)=\cos(\theta)\cos(\phi)E_{\theta}-\sin(\phi)E_{\phi}$$

$$E^{NS}(f,\theta,\phi)=\cos(\theta)\sin(\phi)E_{\theta}+\cos(\phi)E_{\phi}$$

$$[H]=\begin{pmatrix}H_{\theta}^{EW} & H_{\phi}^{EW}\\ H_{\theta}^{NS} & H_{\phi}^{NS}\end{pmatrix}$$

Transfer functions

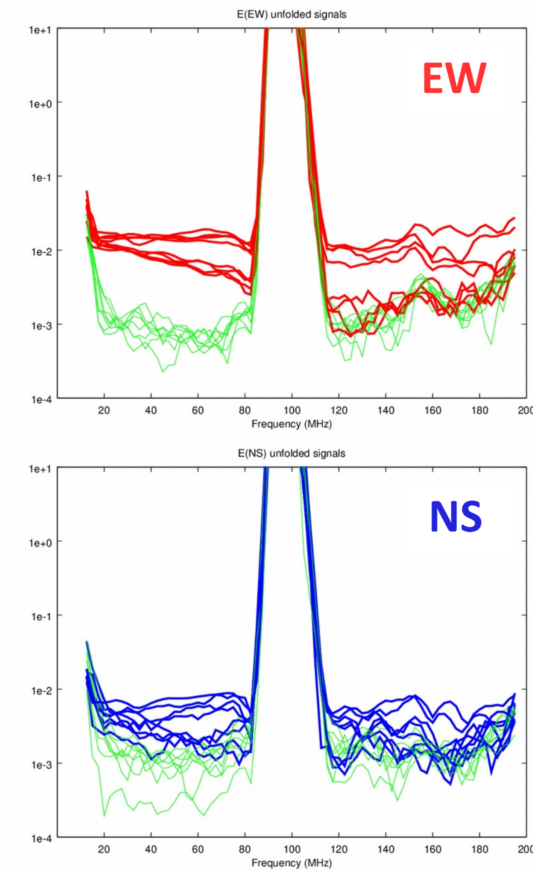


Antenna+LNA responses : AM line suppression and soft FM stop band

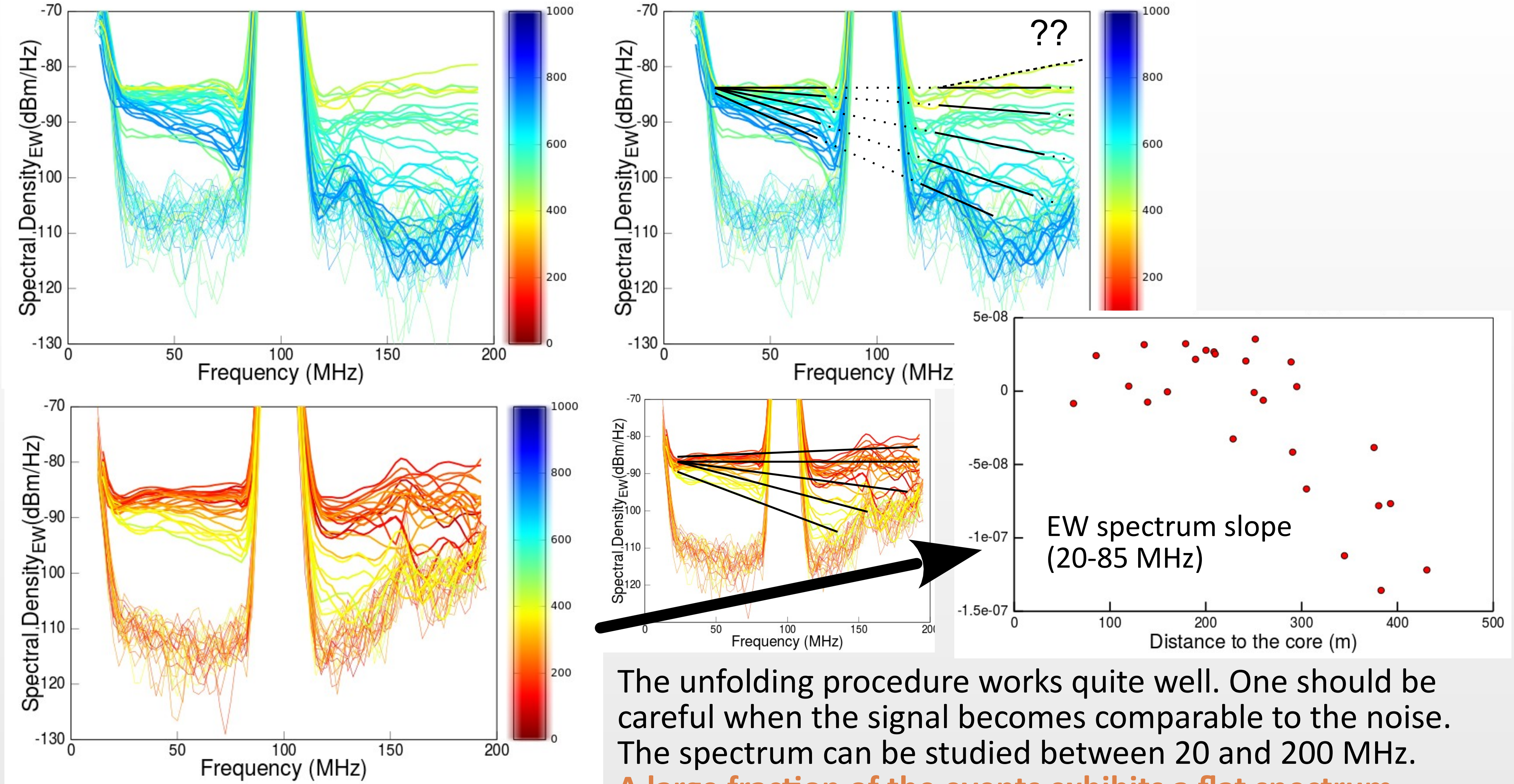
ADC board + trigger board + hard FM stop band response

HF structures depend strongly on θ and φ

Unfolded signals



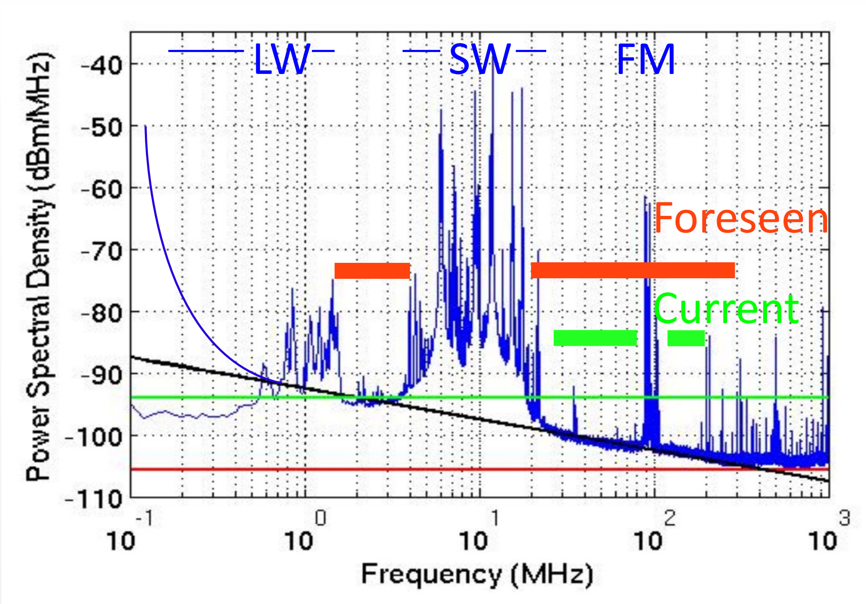
Beyond basic properties : frequency studies



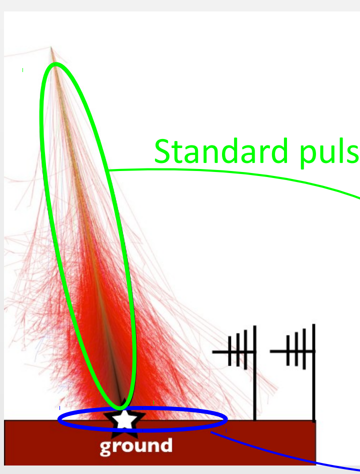
The unfolding procedure works quite well. One should be careful when the signal becomes comparable to the noise. The spectrum can be studied between 20 and 200 MHz.

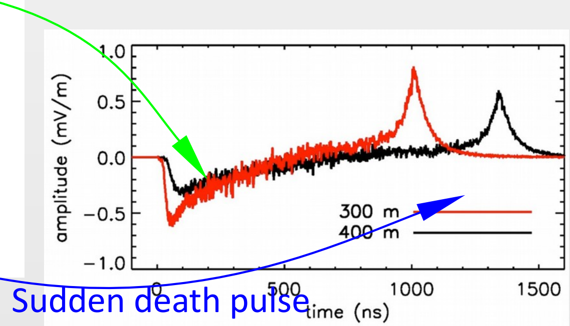
A large fraction of the events exhibits a flat spectrum. Within events, the spectral index varies significantly and consistently with distance to the shower axis. Careful use of the unfolding process. On going work !

Conclusions and outlook



Investigating the sudden death pulse





Fast and coherent deceleration of particles

Conclusions :

- The CODALEMA experiment is running steadily.
- Extensive Air shower events are continuously registered
- Comparisons with SELFAS simulations allow core location.
- Polarization analysis has shown features interesting both in terms of shower information and event selectivity.
- Raw spectra are clearly dominated by the antenna response (selectivity) but reveal sensitivity to distance to the shower axis after a meticulous processing.
- The compact array is also accumulating data and giving valuable information.

Near future :

- Systematic analyses of polarization, frequency content and simulations of the collected sample of data.
- New optimization step of the radio self trigger.
- Development of an on line composite trigger (compact array).
- Development of a tripole antenna.
- Extension of the frequency range (10-300 MHz). New frequency range at few MHz.
- Looking for the signal associated to the showers hitting the ground.
- **The EXTASIS project at Nancay.**