Some possible interpretations from data of the CODALEMA experiment

P. Lautridou for CODALEMA - SUBATECH Nantes

Study the of the radio-detection method in the energy range of 10^{16}-10^{18} eV @Nançay

Purpose of these analyzes:

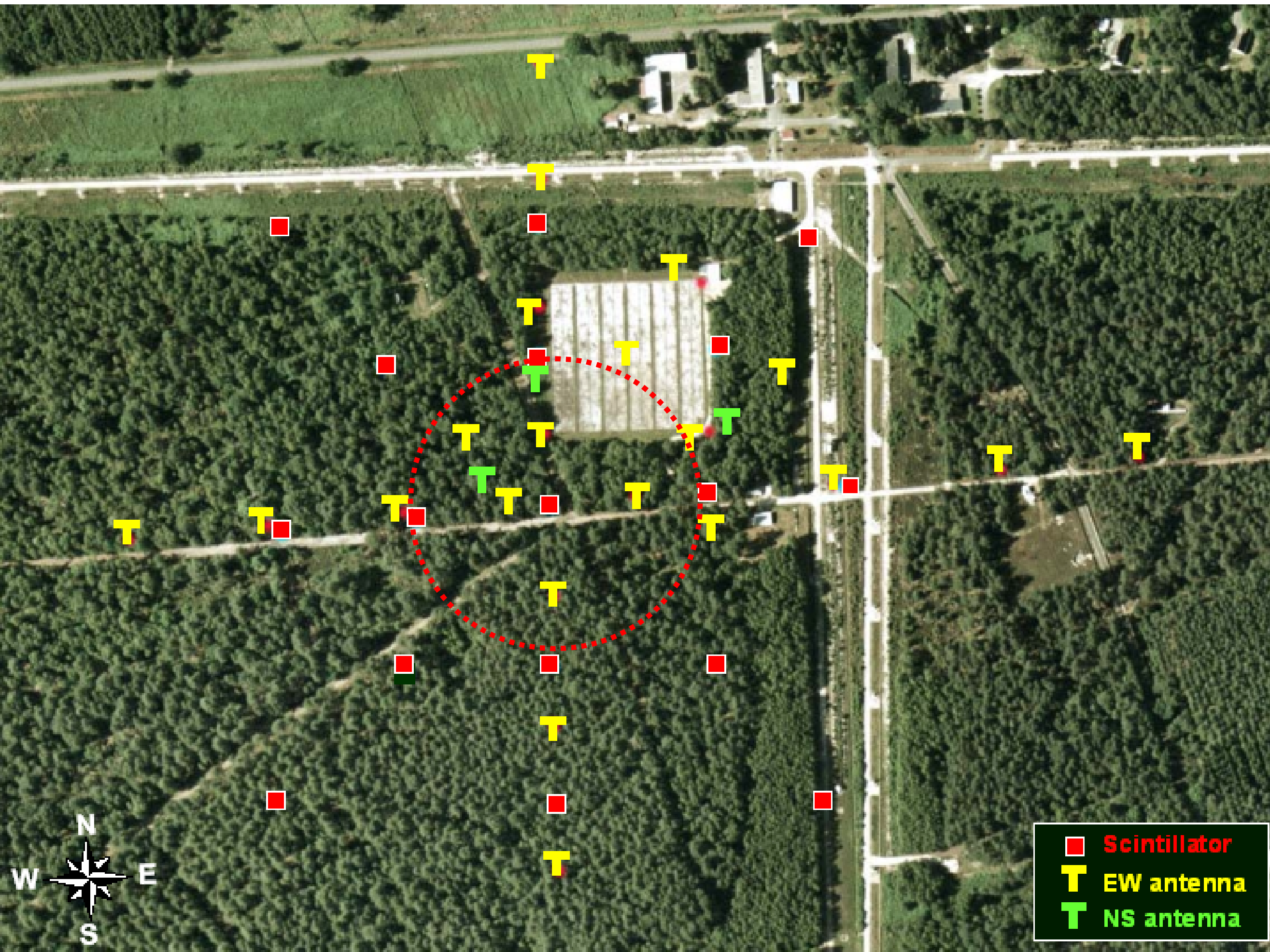
Try to go further on some previous studies (potential of some observables)

- **Study of an energy estimator** => internal correlations (with the original setup)

- **Study of the wave fronts** (first step in retrieving information about the incoming wave) => source identification (made necessary with the autonomous stations)

CODALEMA 2006-11 @ Nançay (0.25 km²)

Antenna array in slave mode of the scintillator array



Radio array

-24 dipole antennas

cross: 600 m x 500 m

21 ant. in E-W polarization

3 ant. in N-S polarization

Analyzes in 24-82 MHz

-Decametric Array

Cables + central acquisition

12 bits ADC

@ 1 Gsample/s, 2.5 μs

Particle array

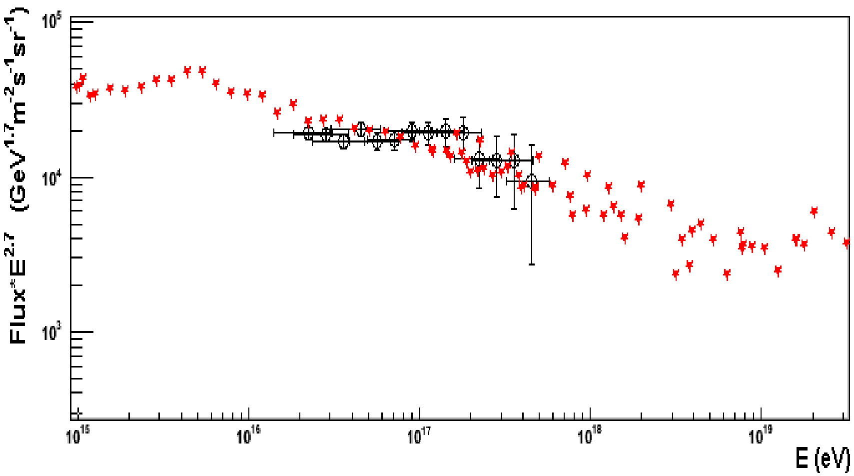
17 scintillator stations : square 350 m x 350 m

Trigger : the 5 central particle stations

Internal Showers : higher signal in central stations

Core Position + Direction + Energy (via CIC method)

Study of an energy estimator



Event overall features

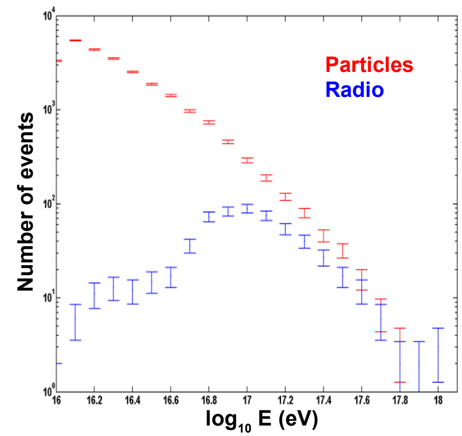
Energy calibration of particle detector array

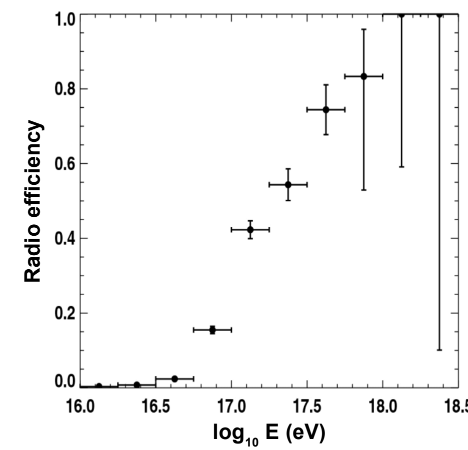
(for internal events)

=> NKG distribution

=> CIC method

=> $\sigma(E_p)/E_p = 30\%$



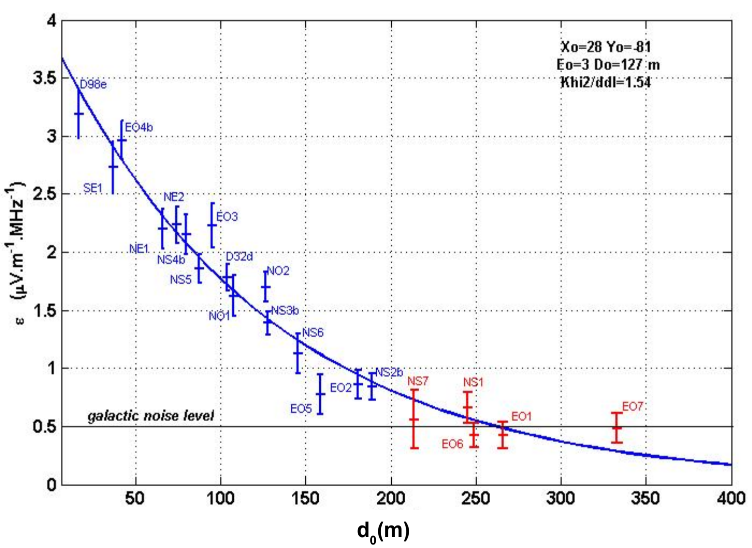


Coincidences in E-W polarization with internals

Criteria on: angle, time, core position

+ antennas > 4 + $\log_{10}(E_p) > 16.6$

= 315 events retained

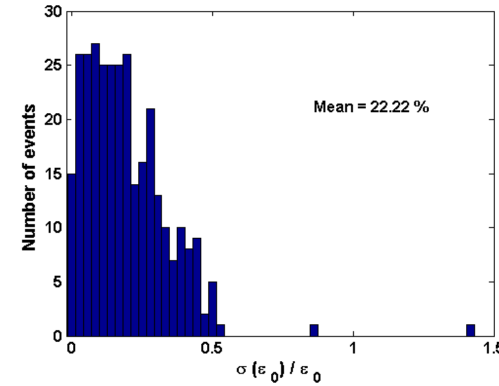


Radio Lateral Distribution Function

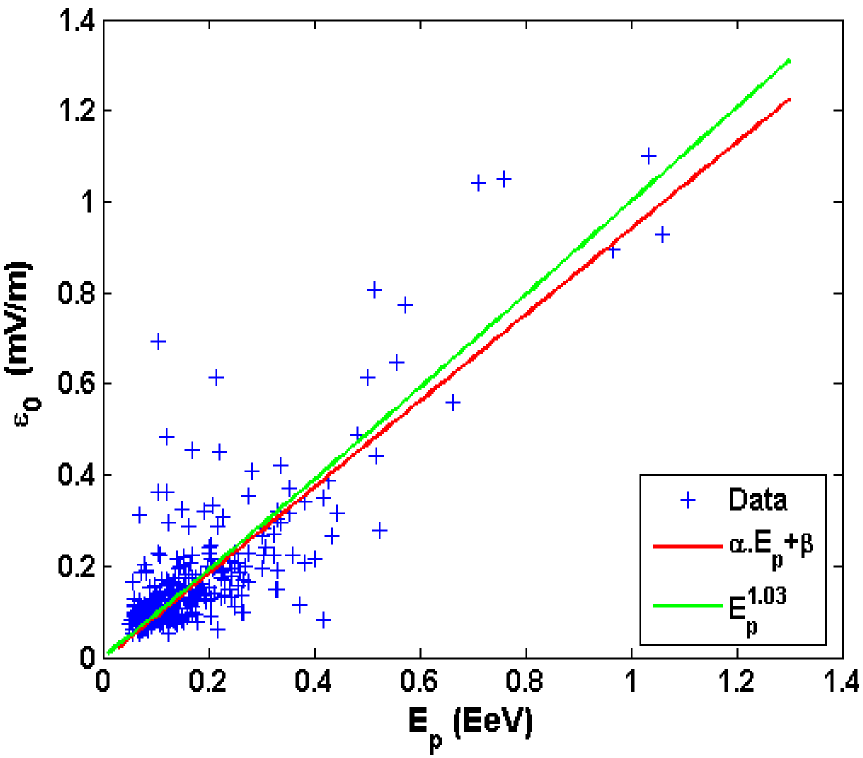
$\varepsilon = \varepsilon_0 \, e^{-d/d0}$

=> Extract the electric field at the shower core ε_0

Error estimation on ε_0 by Monte-Carlo => $\sigma(\varepsilon_0)/\varepsilon_0 = 22\%$



Relationship between ε_0 and E_p



Compatible with linear dependence

Adjustment with $\varepsilon_0 = \alpha . E_p + \beta$

=> Minimization of

$$\chi^2 = \Sigma_i [\varepsilon_0 - (\alpha . E_p + \beta)]^2 / [\sigma^2(\varepsilon_0) + \alpha^2 . \sigma^2(E_p)]$$

With $\sigma(\varepsilon_0)/\varepsilon_0 = 22\%$, $\sigma(E_p)/E_p = 30\%$

Inversion => Energy radio: $E_0 = 1/\alpha . \varepsilon_0 - \beta/\alpha$

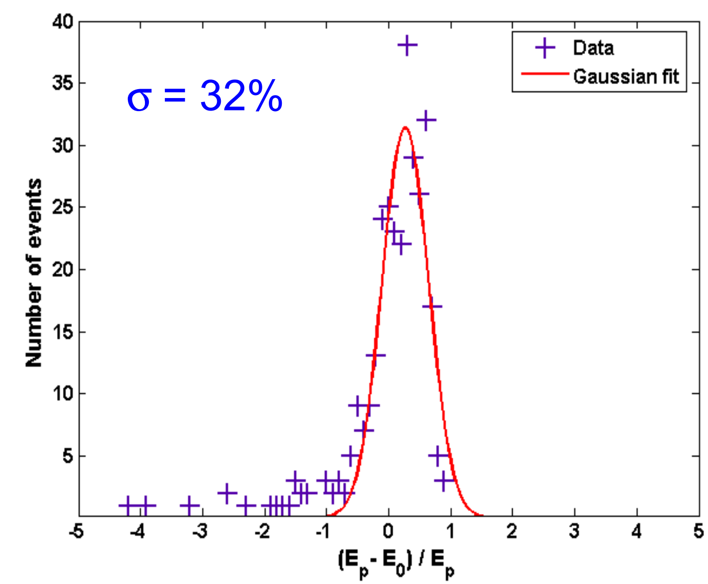
Characterization of the distribution (E_p,E_0)

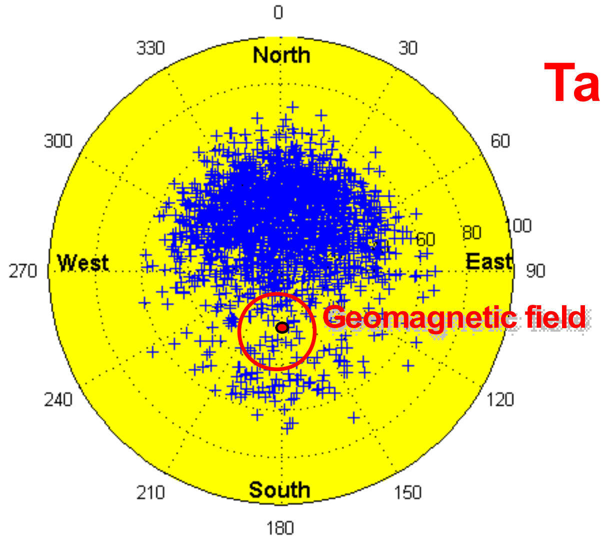
=> Distribution of the relative differences $(E_p-E_0)/E_p$

=> Analysis of $\sigma(E_p-E_0)/E_p$

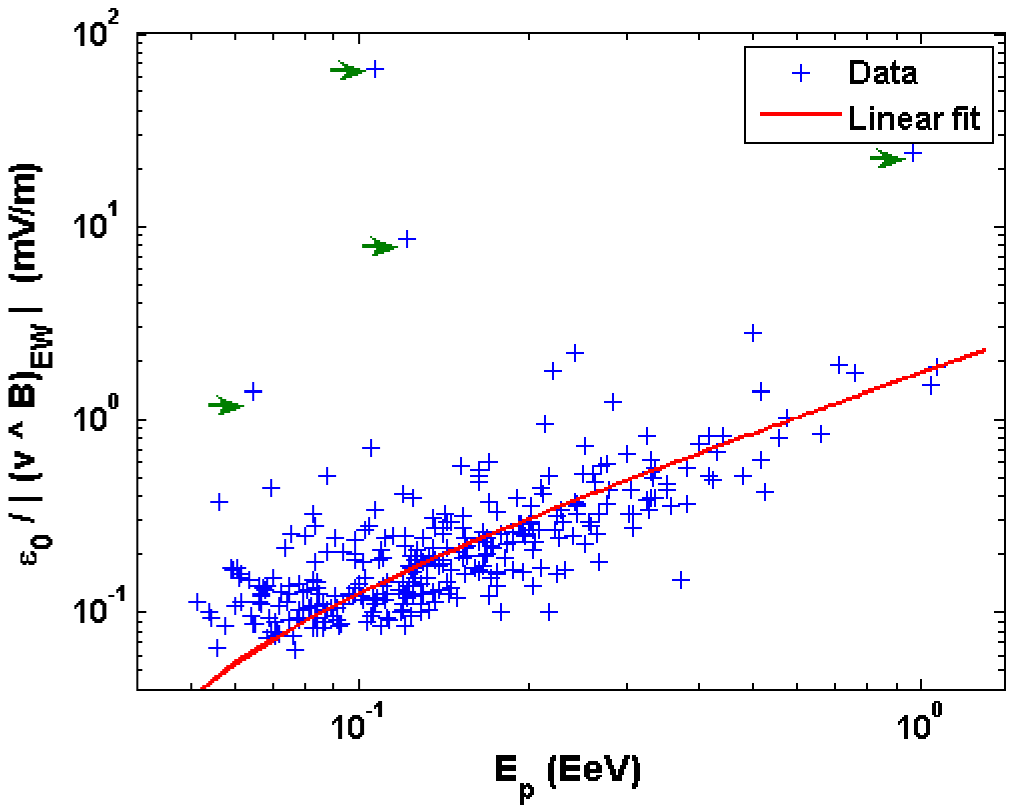
(due to the tail, standard deviation used instead of Gaussian adjustment)

Error on $(\sigma(E_p-E_0)/E_p) = \sqrt{2}.\sigma^2/(N-1)^{1/2} \sim 0.1\% - 1\%$





Taking into account the the geomagnetic effect



=> Correction by the geomagnetic effect

$$\varepsilon_0 \sim E\,.\,|(\mathbf{v}\wedge\mathbf{B})_{EW}|$$

$$\varepsilon_0' \sim E\,.\,|(\mathbf{v'}\wedge\mathbf{B})_{EW}|$$

=> $\varepsilon_0 \rightarrow \varepsilon_0 / |(\mathbf{v}\wedge\mathbf{B})_{EW}|$

=>Overestimation of the energy for events near the geomagnetic field

- Relevant of ε_0 with the geomagnetic correction ?

=> Arguments of counting:

- Events are detected
- Uniform detection expected for higher energies (near the geomagnetic field)

=> an additional contribution to the correction

Simplest assumption:

Additional contribution proportional to the total charge produced in the shower

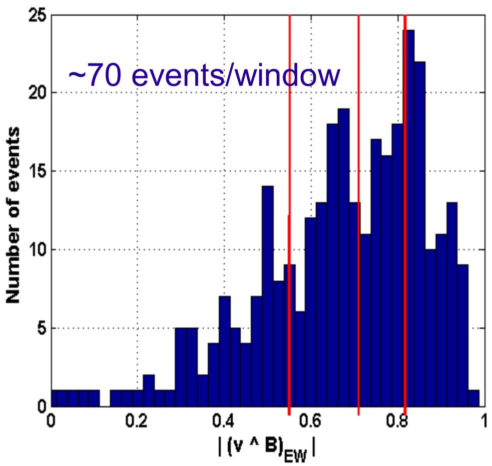
$\varepsilon_0 \sim E.|(\mathbf{v}\wedge\mathbf{B})_{EW}| + E.c$

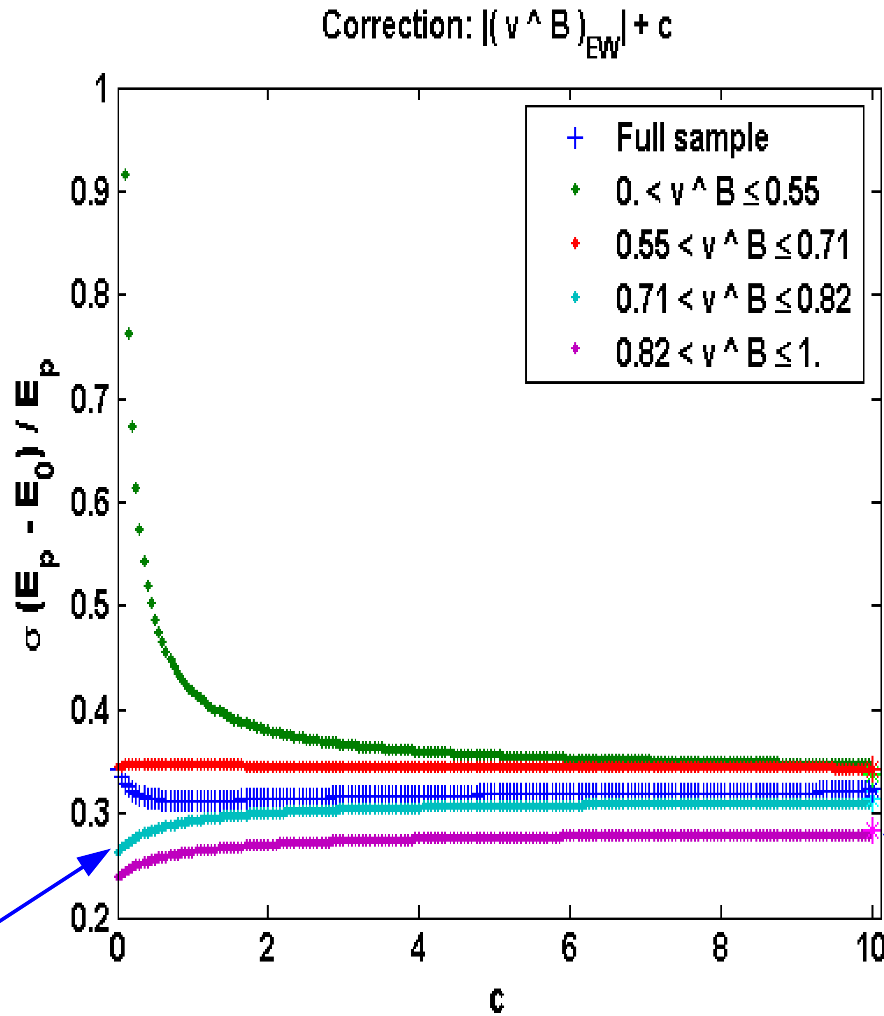
$\varepsilon_0 \rightarrow \varepsilon_0 /(|(\mathbf{v}\wedge\mathbf{B})_{EW}| + c)$

Range of the parameters

$0<|(\mathbf{v}\wedge\mathbf{B})_{EW}|<1$

$0<c<....$





c=0 => only geomag.

no correction

c large => “only c“→ no correction

<u>Full sample</u> => min=0.31 for c=0.95

<u>Sub-samples</u> => exhibit angular dependencies

- best result obtained for |v^B|>0.82 and c=0 => geomagnetic dominates
- for low |v^B| => best result with large c=> E.c dominates

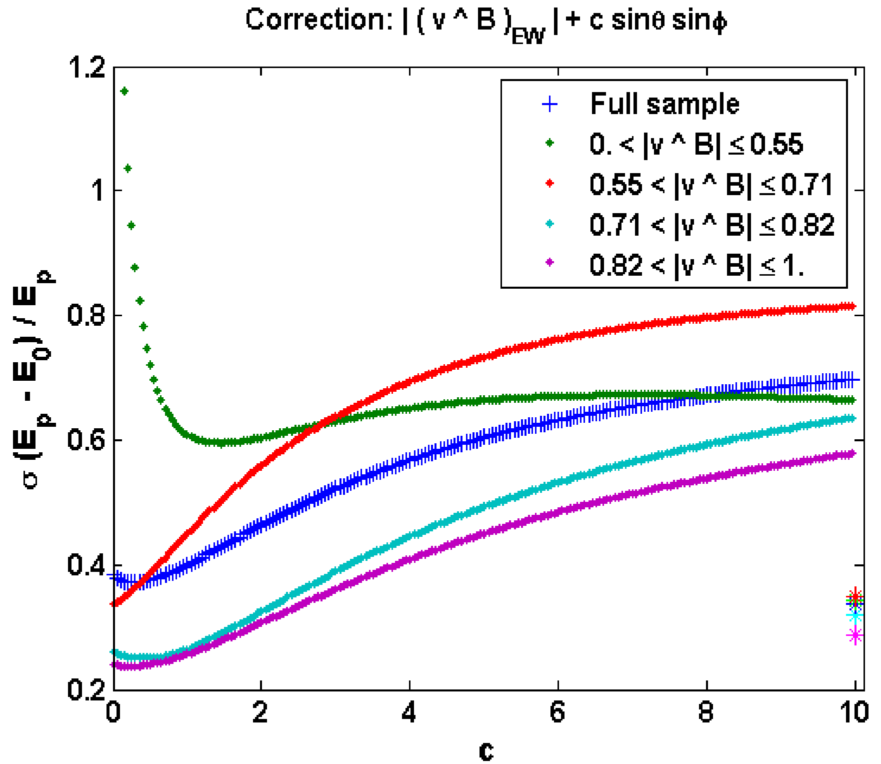
Association of the second term to an existing electric field

- Component ⊥ shower axis ?
- Component // shower axis ?
-

$\Rightarrow \varepsilon_0 \sim E.|(\mathbf{v}\wedge\mathbf{B})_{EW}| + E.c.|\sin\theta \sin\phi|$

(zenith θ, azimuth ϕ)

=> not favored



=> Possible interpretations (with the present statistic)

$\varepsilon_0 \sim E.|(\mathbf{v}\wedge\mathbf{B})_{EW}| + E.c$ => indicates a mix of effects ?

Second term depends on the charge of the shower

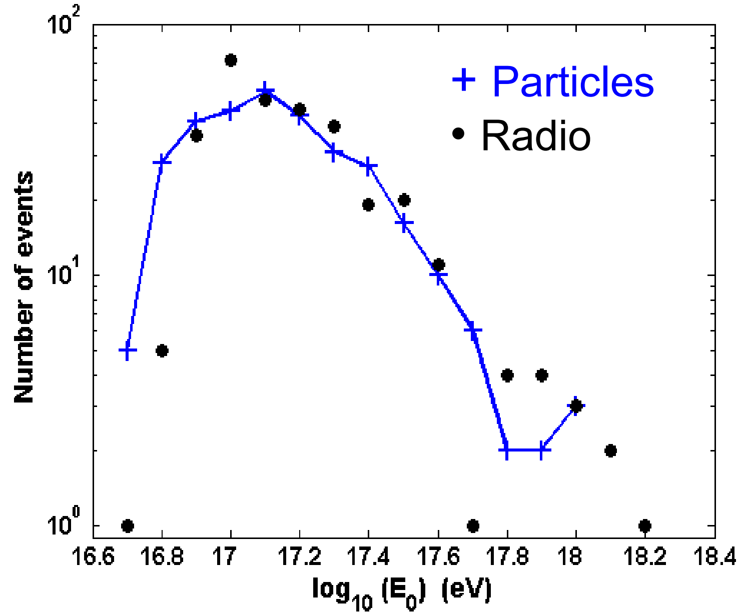
Greater weight of c when $|(\mathbf{v}\wedge\mathbf{B})_{EW}|$ decrease...

- Charge excess mechanism ?

$\varepsilon_0 \sim E.|(\mathbf{v}\wedge\mathbf{B})_{EW}|.(1 + c/|(\mathbf{v}\wedge\mathbf{B})_{EW}|)$

Analog to deflection with a magnetic dipole ? => charged particles deviate more when $|(\mathbf{v}\wedge\mathbf{B})_{EW}|$ increase ? => distances between the particles increase ?=> decreases coherence ?

- Coherence effect ?

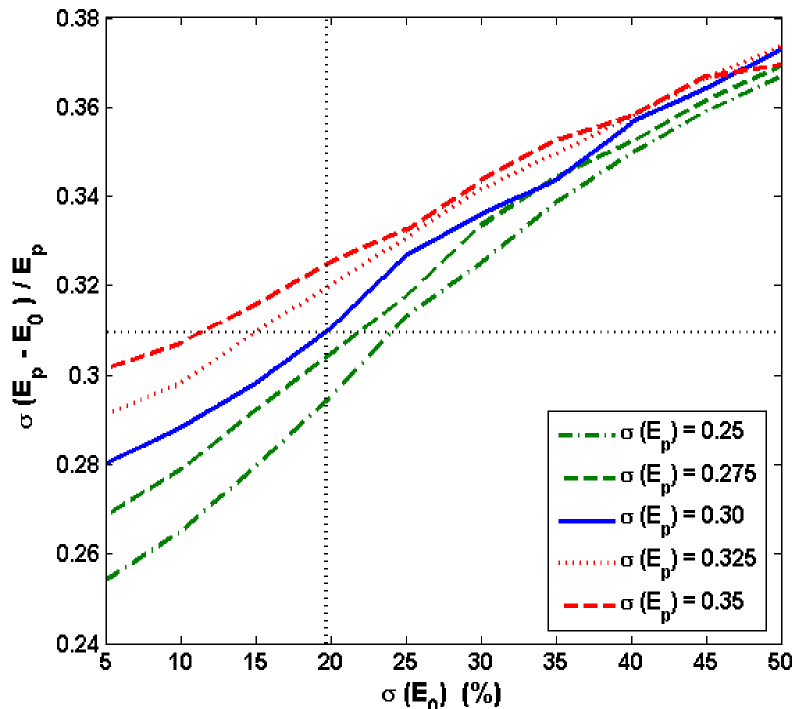


Result of the calibration (without correction)

Attempt to estimate an energy resolution for radio

Monte Carlo => distribution in energy of the events in coincidence
=> random E
=> Random E_p in 3σ with $\sigma(E_p)/E_p$ fixed (25%, 30%,...)
=> Random E_0 in 3σ by varying $\sigma(E_0)/E_0$.
Construction of the distribution $(E_p-E_0)/E_p$

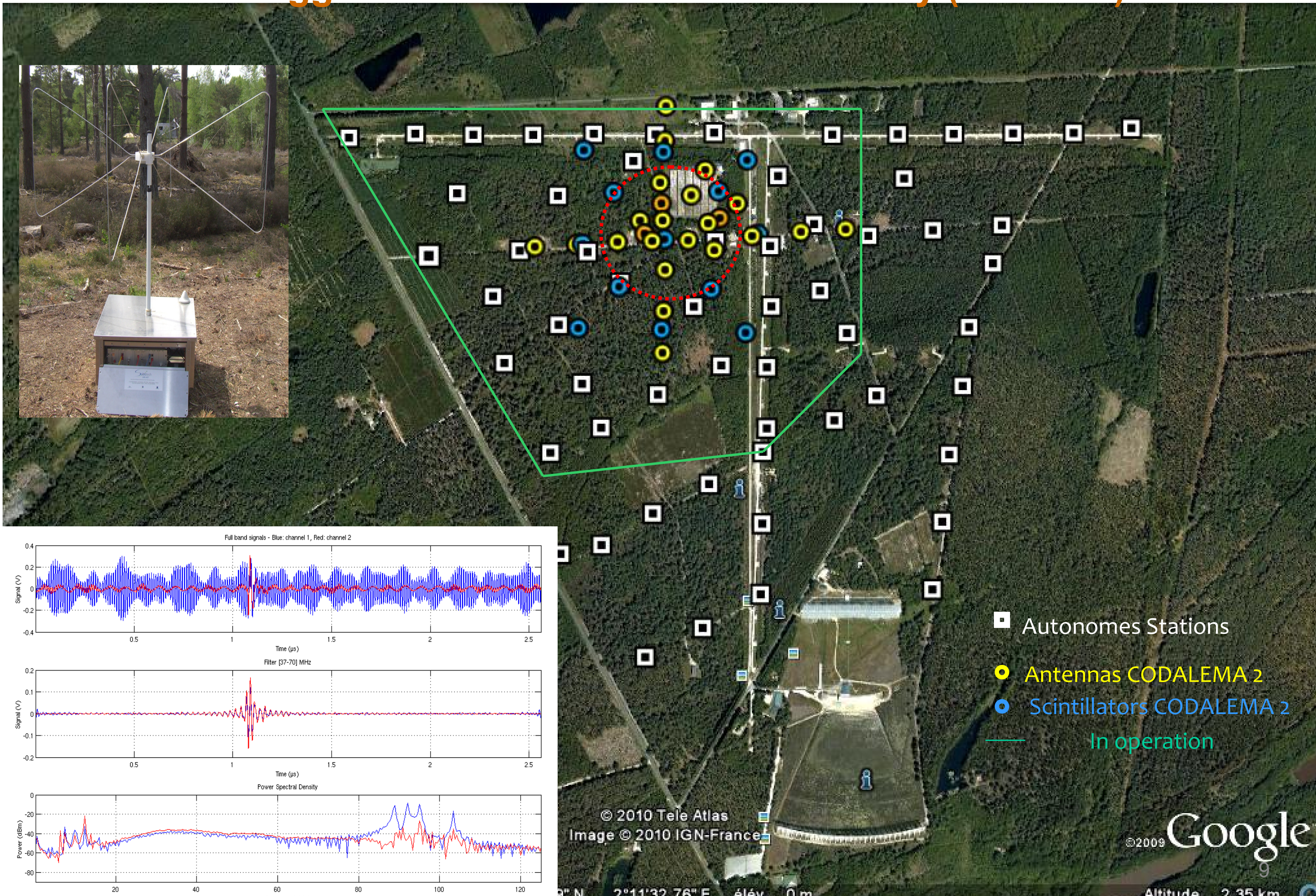
Without correction: $\sigma(E_0)/E_0 = 20\%$



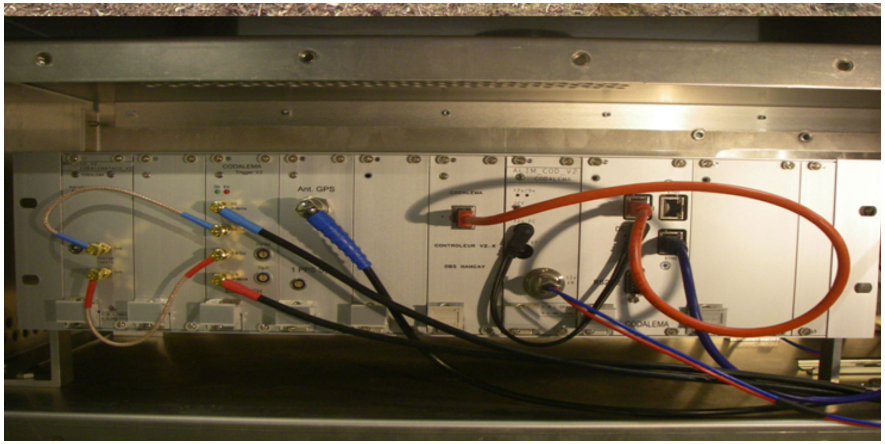
=> an underestimated performance ?
=> More relevant RLDF will increase the correlation ?
=> Principle of the correction doesn't depend on form of the RLDF

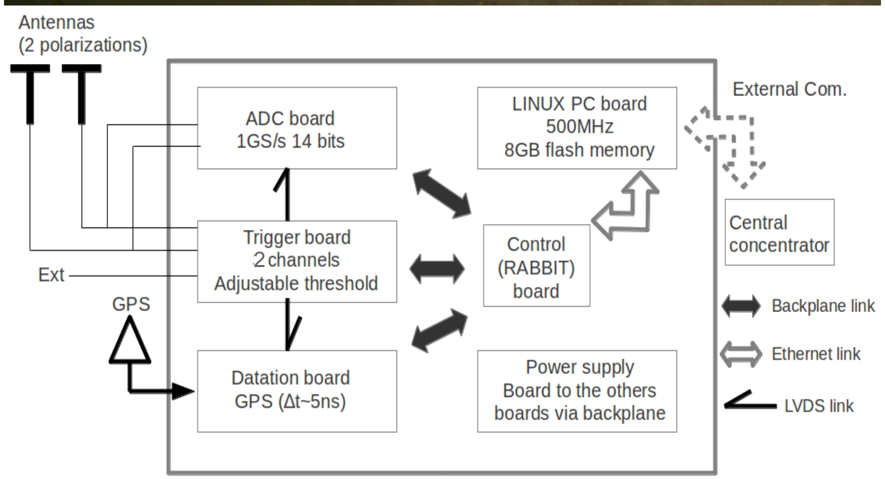
CODALEMA 2011... @ Nançay

Self-triggered antennas + multi-scale array (=> 1 km²)



The CODALEMA stand-alone station





Electronic crate (backplane supplying and linking boards)

- 1 ADC board : 14 bits waveform, 1GS/s, 2.5 μs , 1-250 MHz BW
- 1 dating board : GPS timing resolution: < 5 ns
- **1 trigger board** : 1st level of trigger @ galactic threshold
- **1 PC** board : 2nd level of trigger in embedded PC + Data management + 8GB flash memory
- **Acq. rate**: 25 evt/s
- Consumption: 20 W

Implementation of the trigger

1st trigger level (hard)
based on analog filtering in the trigger board+ amplitude threshold
=>Waveform digitization in ADC

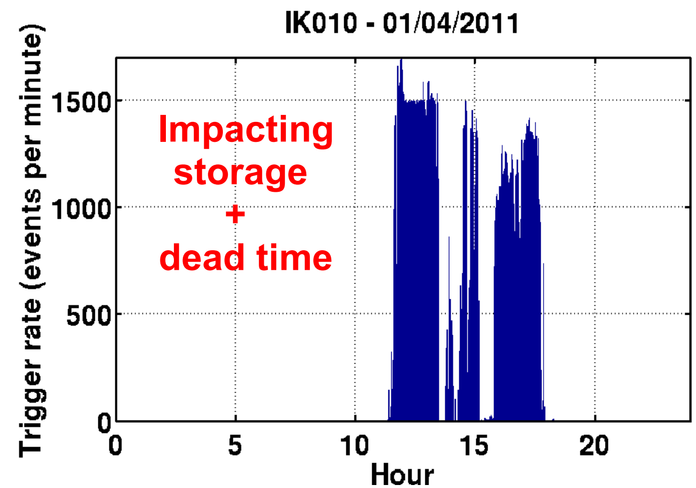
Send to CPU →

← Threshold update
+ Possible selections
Max of amplitude
Standard deviation
Duration
Recurrence

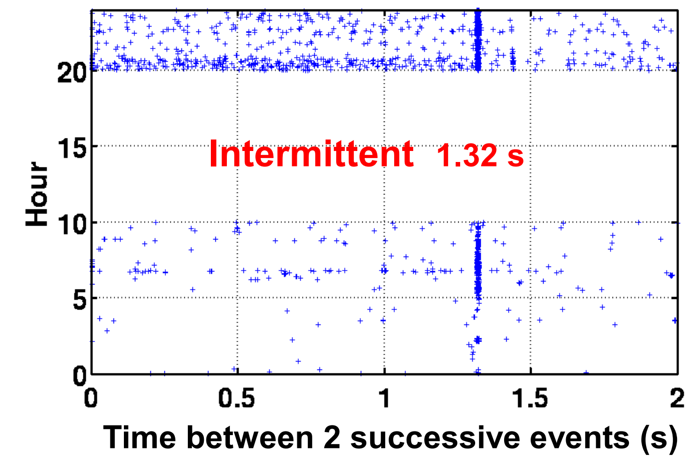
2nd trigger (soft)
based on waveform analysis through PC embedded
=> Data storage

Features of the detected events

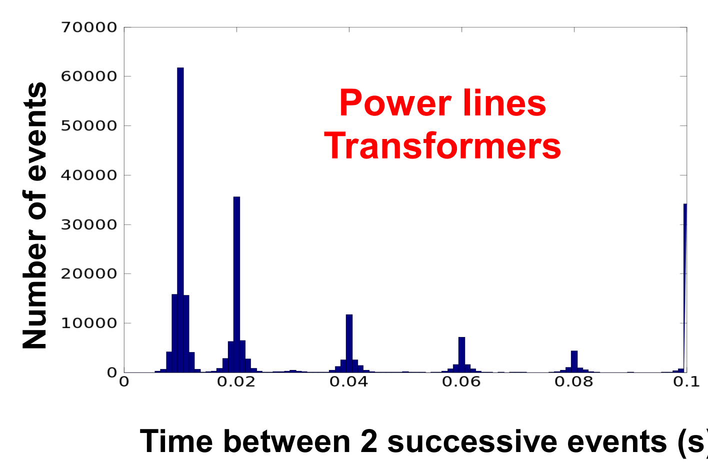
Dominated by anthropic emissions



Intermittent emissions: eg. T=1.32 s, 1.4 s,... Filtering in the PC at level 2 (wave form analysis, recurrence transients...)
=> Reduce only storage, not the dead time

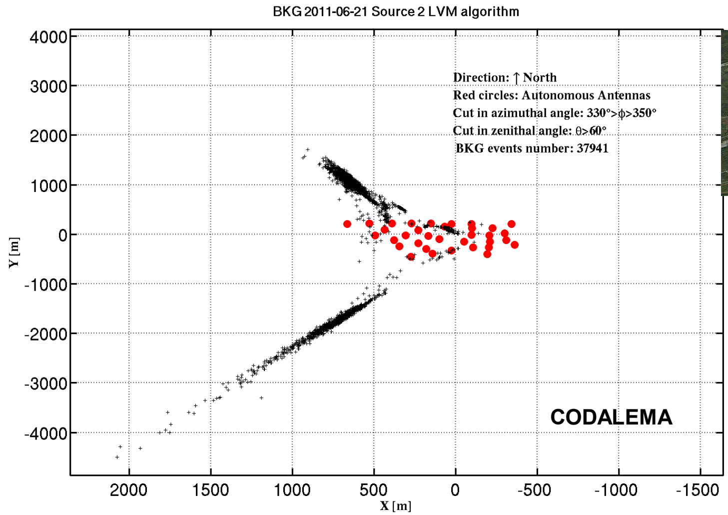


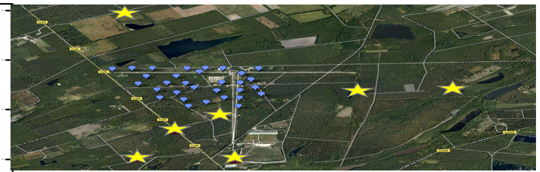
Daily recurring emissions (very annoying): @ 50 Hz & 100 Hz emissions affect most strongly the duty cycle
=> Power lines + transformers identified as major problem !

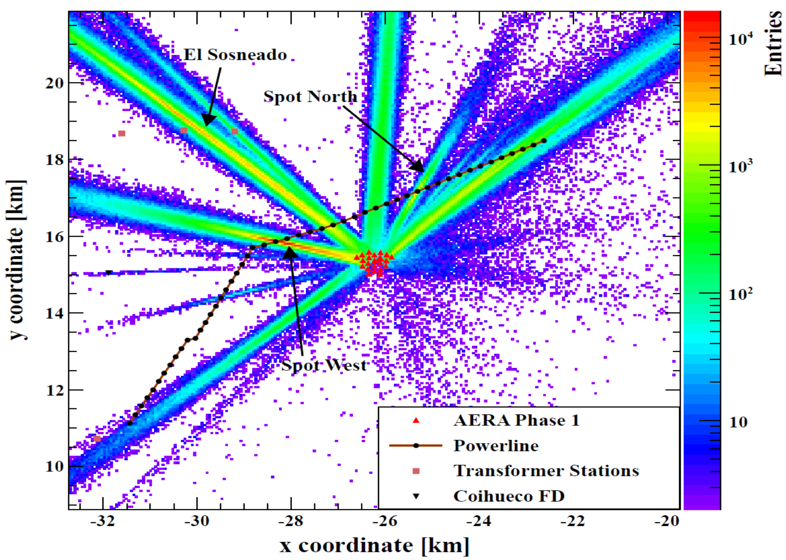


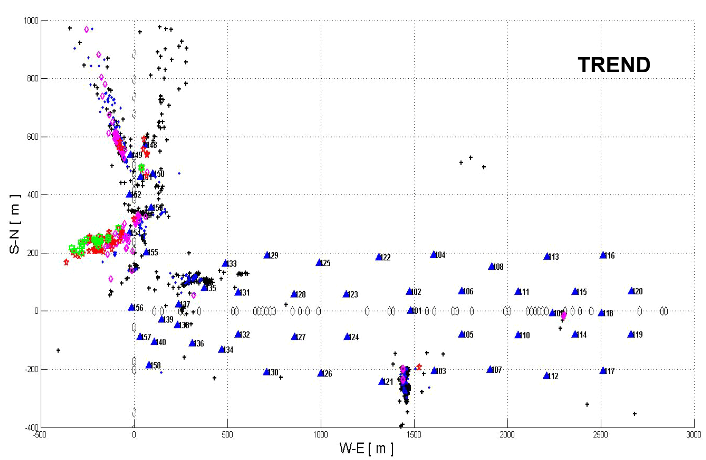
How to mitigate these effects ?

- **Improving level 1 trigger card => identifying the recurrences before encoding ?** => understand the mechanism of emission ahd its features
- **Trying to solve the emission at the source level** =>modification of the power devices ?









=> Observations of these RFI emissions by several experiences

=> Accurate source localizations expected using spherical reconstruction methods (Fixed source positions) (Number of events)

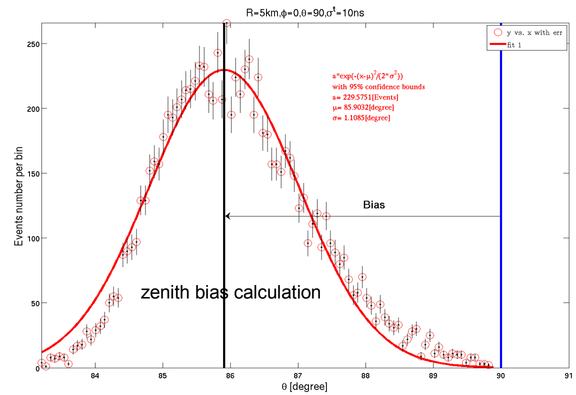
The problem will be analogous for shower events

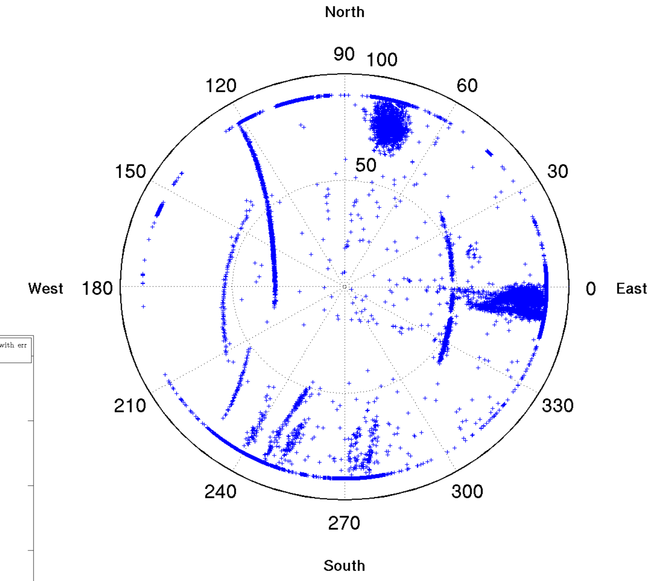
Except that in this case it is a single realization of the event parameters => Avoid a statistical estimate of the emitting center

Adjustments by planar wave fronts not relevant

=> Provides only arrival direction angles

- No localization of point-like sources
- Increasing bias with the zenith angles

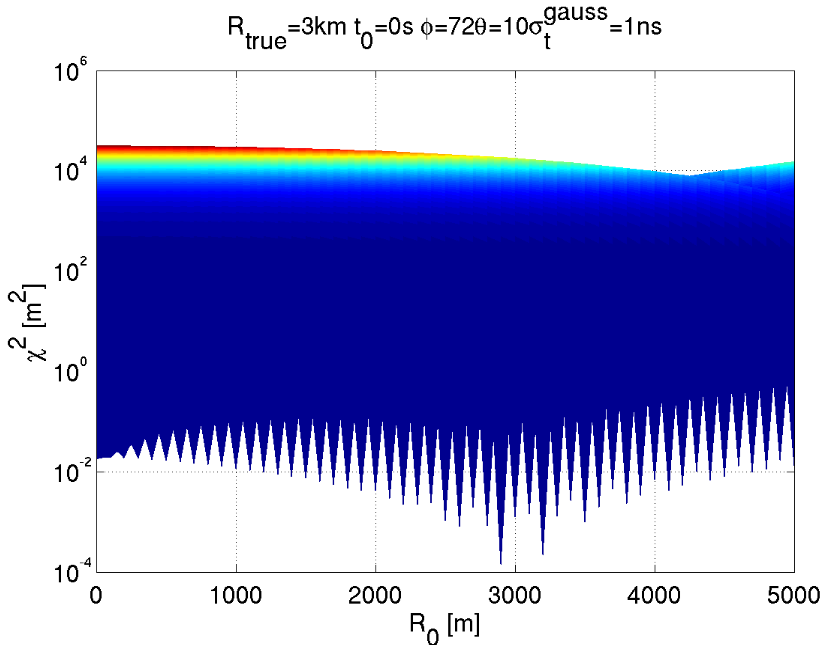


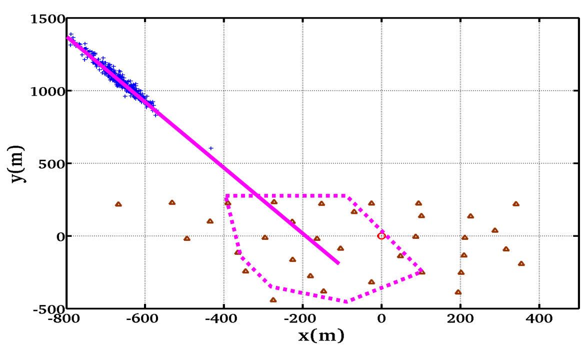


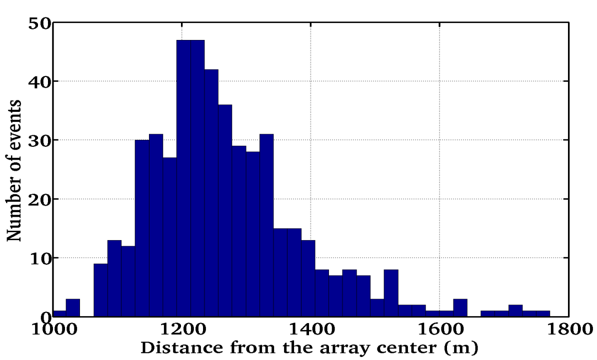
Simulation of source reconstructions using spherical waves

=> Not only time resolutions are in question
=> Also standard minimization methods are in question
+ results sensitive to
=> Algorithms (Simplex, Levenberg-Marquardt, Linear-search)
=> Initial values or the convergence

=> Detailed study of the minimization methods for the spherical reconstruction







=> Study of the objective function

(A. Rebai PhD thesis)

$$\chi^2 = \frac{1}{2} \sum_{i=1}^{N} \left[\|\vec{r_s} - \vec{r_i}\|_2^2 - (t_s^* - t_i^*)^2 \right]^2$$

Mathematical advanced analyzes

Study of Coercivity & Convexity (Hessian matrix)

χ^2 defined positive => at least one minimum exists

Local non-convexity

=> Existence of local minima

Not succeed to treat analytically the general case (3D array + source in sky) but some properties derived from particular cases

- Convex hull of the detector array

unique solution for the sources included

Degeneracies for external sources

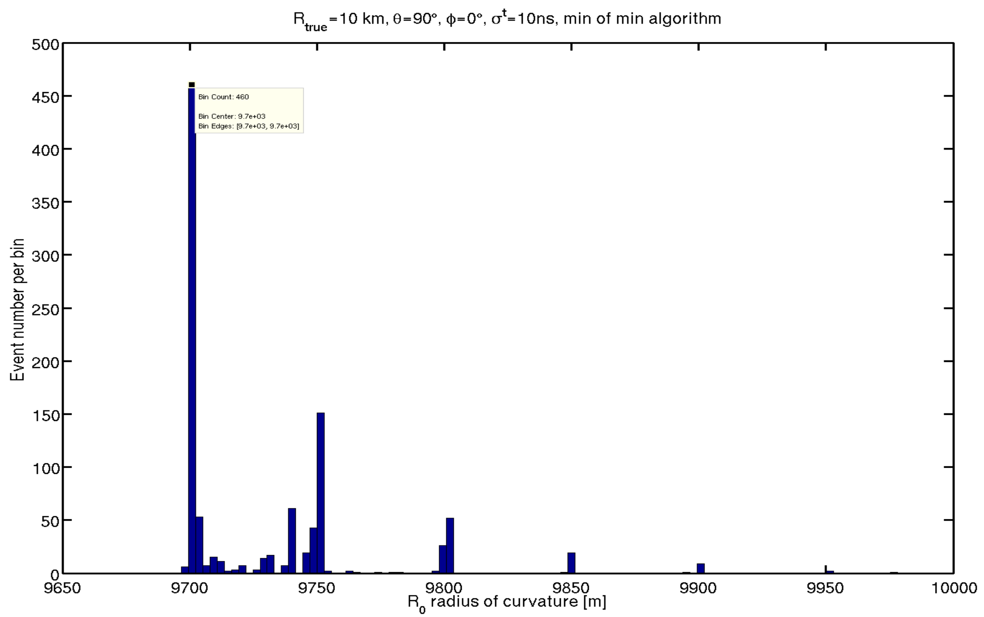
- Critical points on a line (fired antenna barycenter-source location)

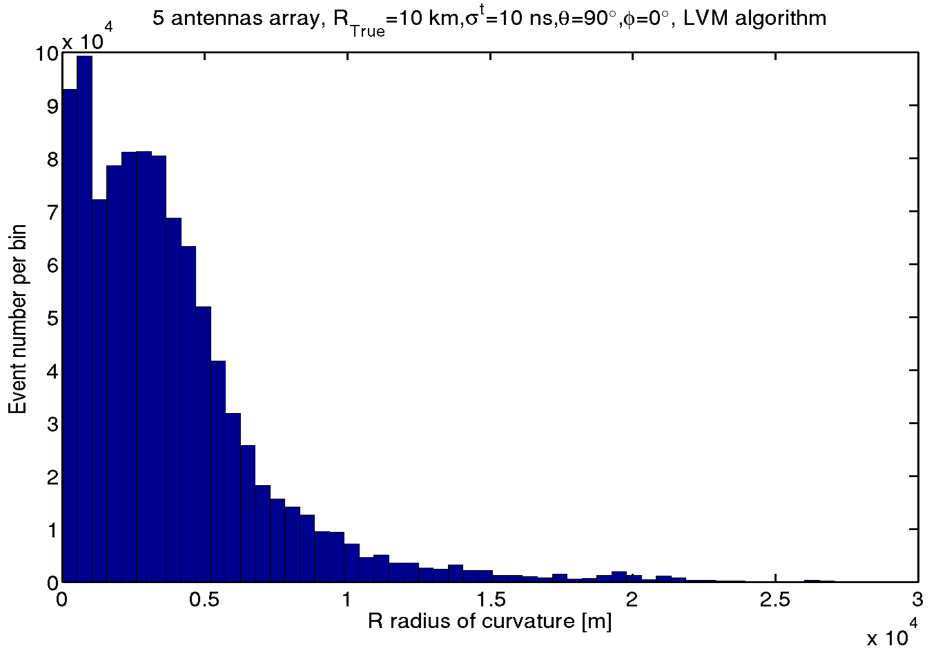
Conclusion => In this approach, spherical reconstruction seems an ill-posed problem !

Best method to bypass this problem not yet found...

=> Try to avoid trapping in some local minima => Search for the minimum of the objective function using a grid calculation

Simulated shower events





+ need bias estimation: in progress

- Try different approaches ?
- Use advanced statistical theories => additional information (signal amplitudes + functional of the RLDF, $\chi^2_{Global}=\chi^2_{Time}+\chi^2_{Ampl}$) ?

Work in progress...

Conclusion

Some earlier analyzes have been more deepened.... leading to possible refinements of the interpretations

=> The electric field at shower core seems a relevant observable => provides an usable energy estimation after calibration by another detector

This observable « radio » of the energy could include a mix of several emission process (Charge excess ?, Coherence ?)

Triggering is challenging in autonomous mode
Recognition of emitting point sources is also challenging

Spherical reconstruction seems an ill-posed problem
=> Need to work further and maybe to interact with other disciplines (applied mathematics, earth sciences, GPS technics...)

Thank you for your attention