Investigation of extensive air shower properties with the CODALEMA experiment : tackling the challenges of a radio-detection cosmic ray observatory.

- Introduction
- CODALEMA 3
- EAS properties from radio signal
- Outlook

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ECOLE DES MINES DE NANTES
cnrs IN2P3 Les deux infinis
UNIVERSITÉ DE NANTES

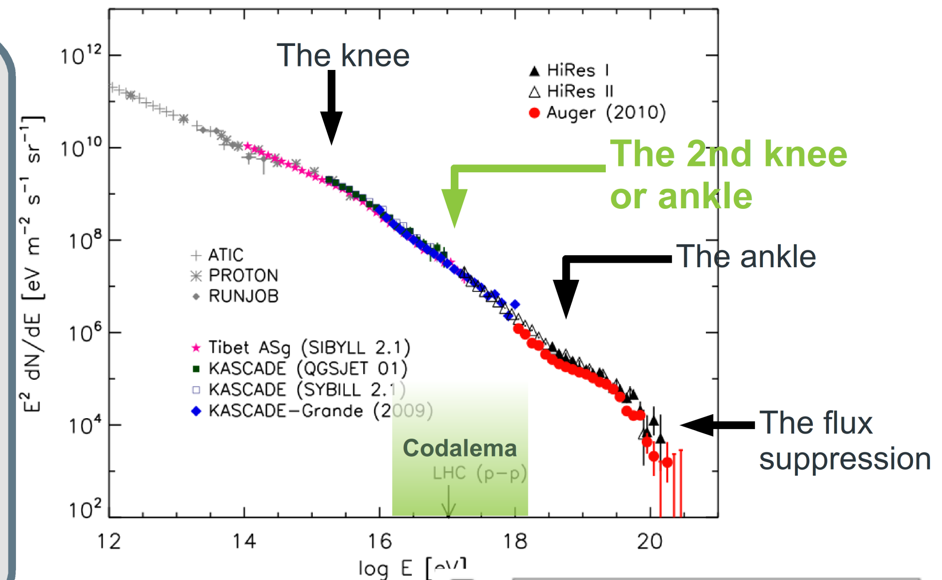
Why UHECR observation ?

Old field but still mainly unknown field :

- What is the nature of the CR ?
- What are the sources of CR ?
  - What is the mechanism giving their energy
  - Galactic vs extra-galactic origin

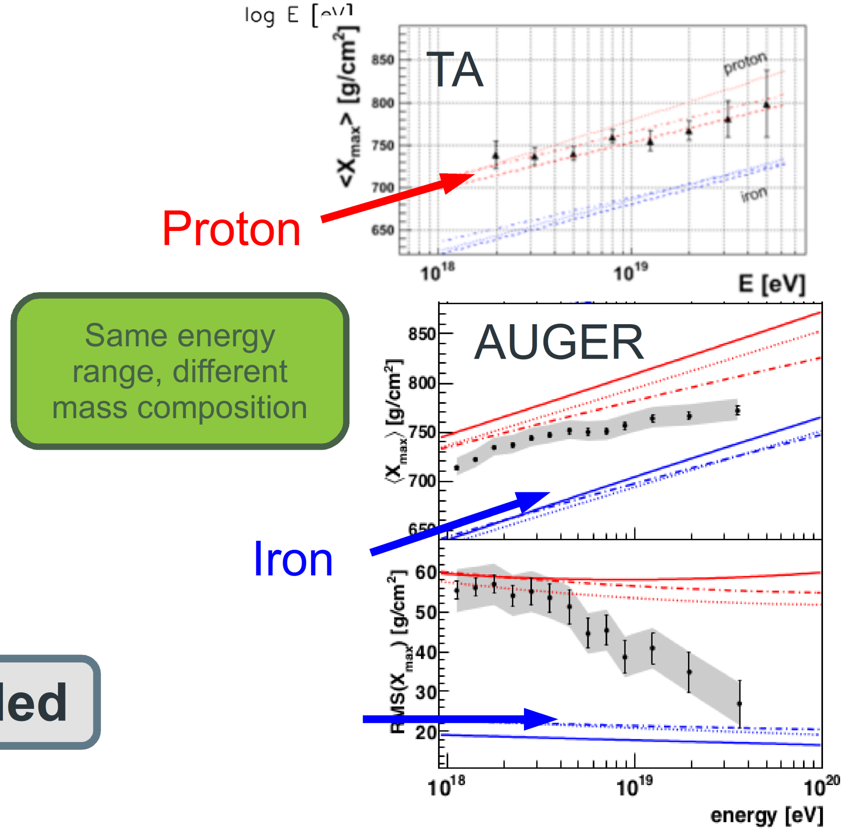
Some significant progresses :

- The spectrum is ending !
- The high energy part of the spectrum has features
- The sky seems anisotropic



Still facing open questions :

- Origin of the spectrum ultra-high energy fall out : GZK cutoff or source limits ?
- Nature of cosmic rays : protons (TA) or heavy ions (Auger) ?
- Isotropic sky ? No source pointing capabilities (yet or if any ?)



Larger statistic AND particle identification needed

Why radio detection of UHECR ?

Limitations of current detection techniques

- Particle detectors (SD) : only the end of the EAS
- Fluorescence telescope (FD) : too sensitive to the environment (light, atmosphere)

Attracting features of radio detection

- Combining SD+FD advantages
- High duty cycle, low cost...

Already long story (late 70' and early 00')

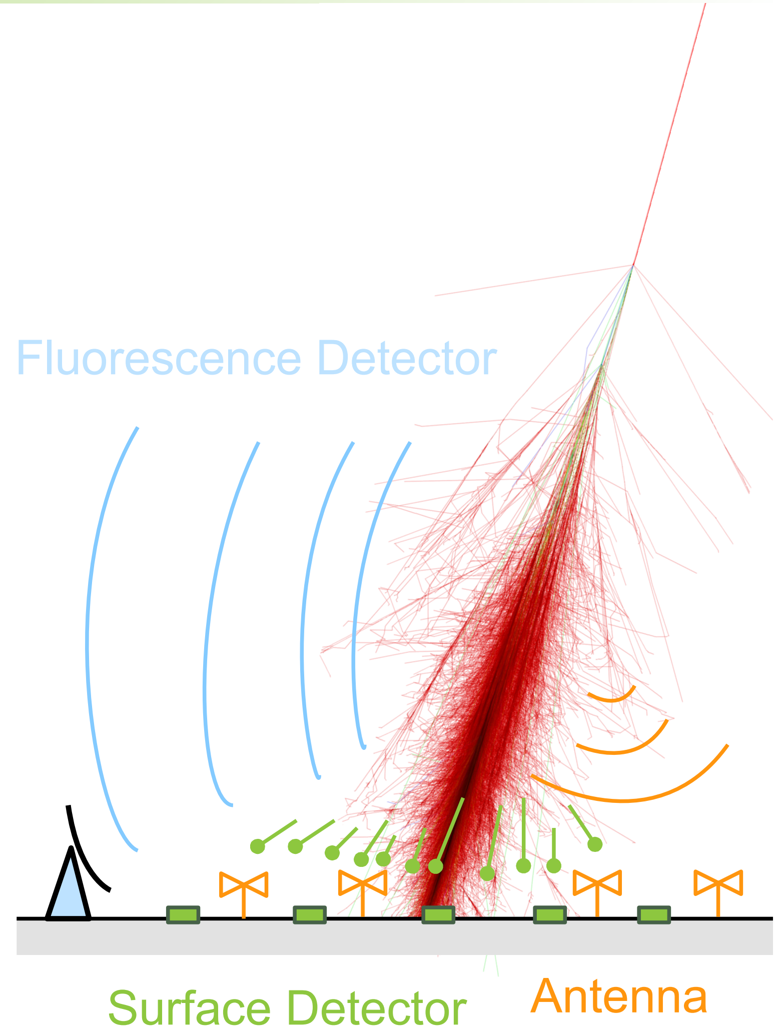
- Jodrell Bank in 1964

Experiments are multiplying

- LOPES, CODALEMA : 00'
- AERA, LOFAR, TUNKA, … : 10'

Already successful but need to reach further milestones

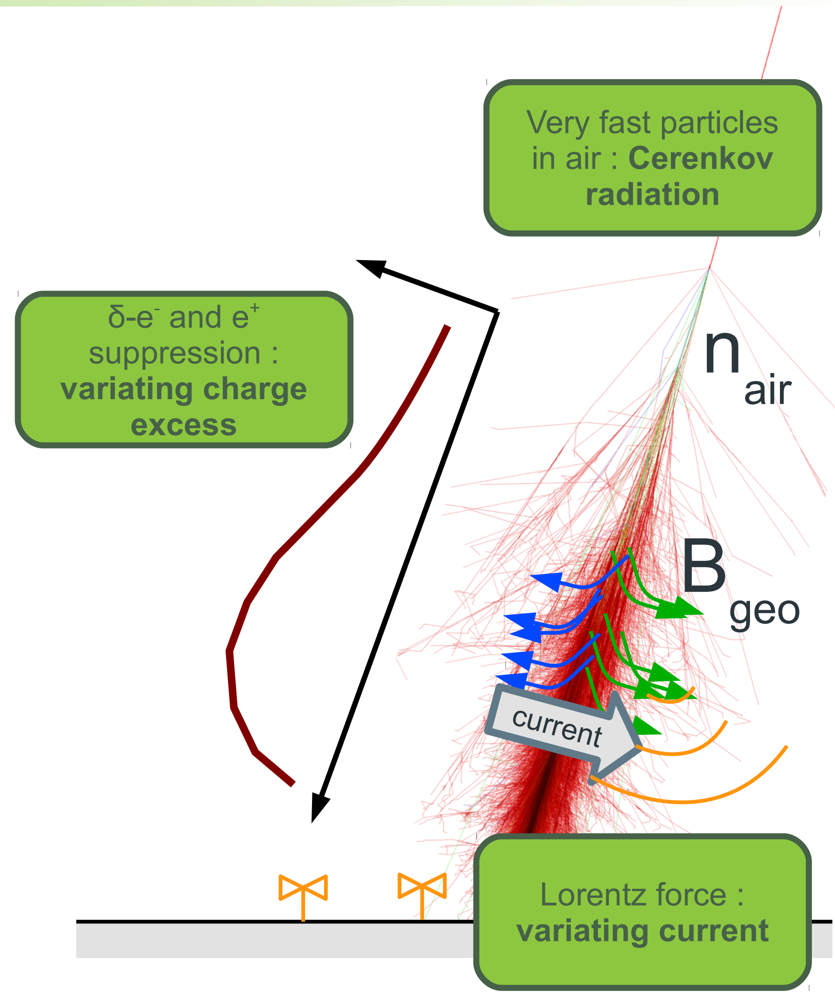
- Refine knowledge on sensitivity of radio to EAS properties
- Develop and master a prototype array
- Pursue R&D efforts (next gen. antenna)



Radio detection of EAS

EAS : flux of (dis)-appearing accelerated particles produces radiation

- Cerenkov signal was first searched
- Geomagnetic effect is usually dominant in the MHz domain
- The charge excess variation gives the second contribution to the signal
- Cerenkov effect can appear at high frequency, various distances



Radiation = Mixture of several effects

- Drawback : complicate the interpretation
- Advantage : rich information in a single or few antennas

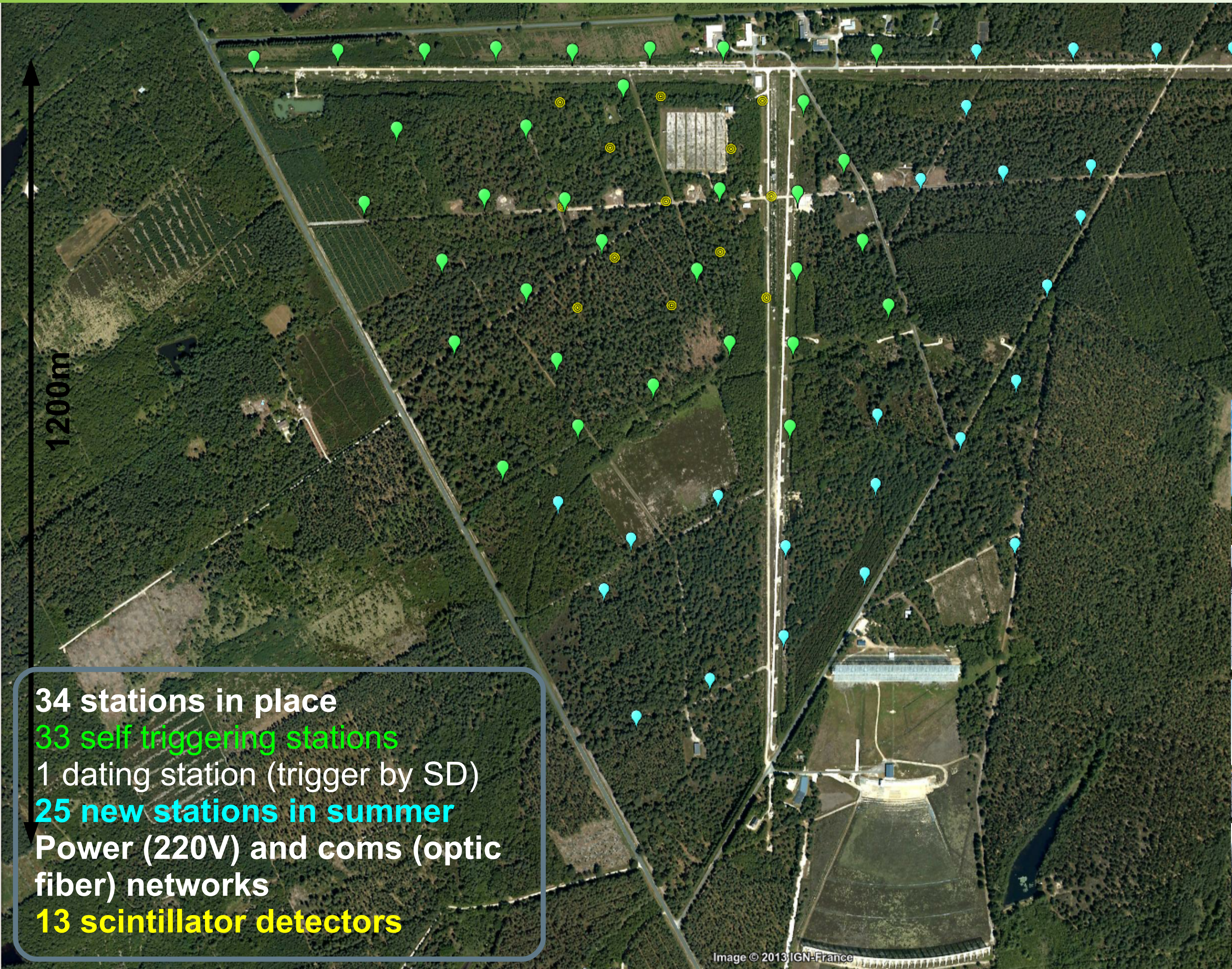
Theoretical descriptions are converging

Antenna and electronics back-end are getting more sensitive

Very fast transient (few hundreds ns)
Largest spectral fraction in the decametric band (few tens MHz)

CODALEMA3 : a dedicated radio detection station

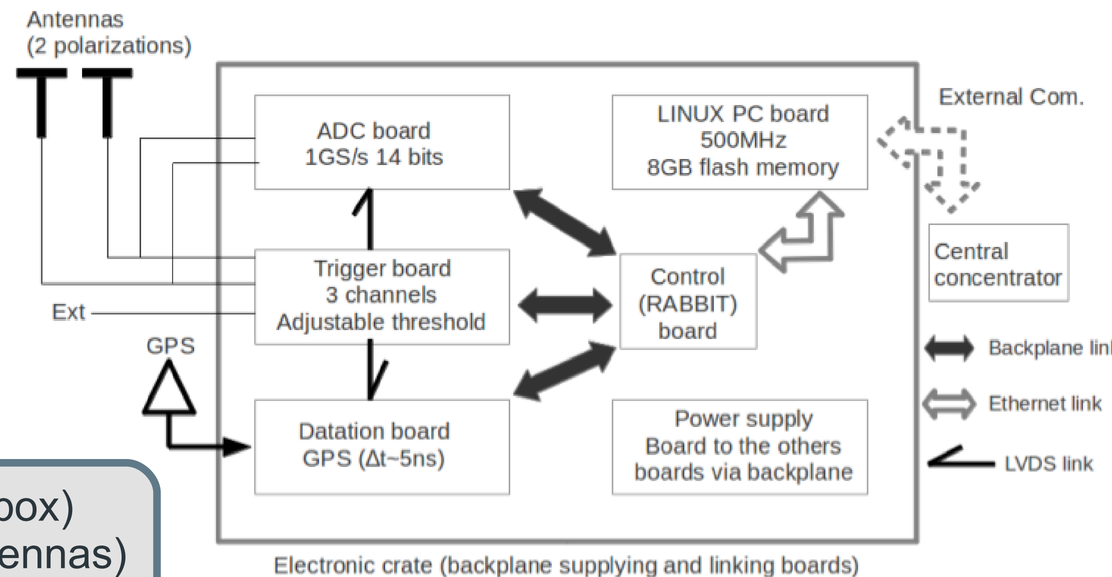
The CODALEMA3 array

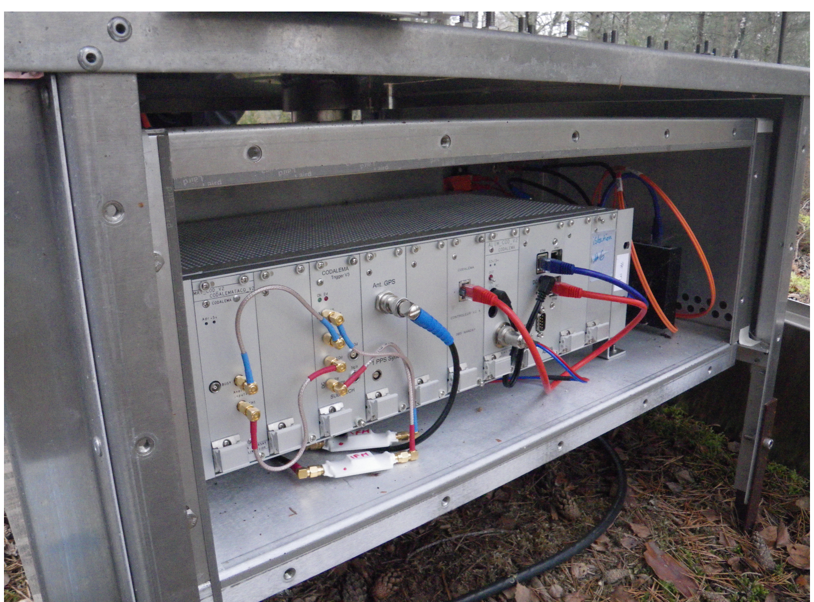


34 stations in place
33 self triggering stations
1 dating station (trigger by SD)
25 new stations in summer
Power (220V) and coms (optic fiber) networks
13 scintillator detectors

CODALEMA 3 : the detection station

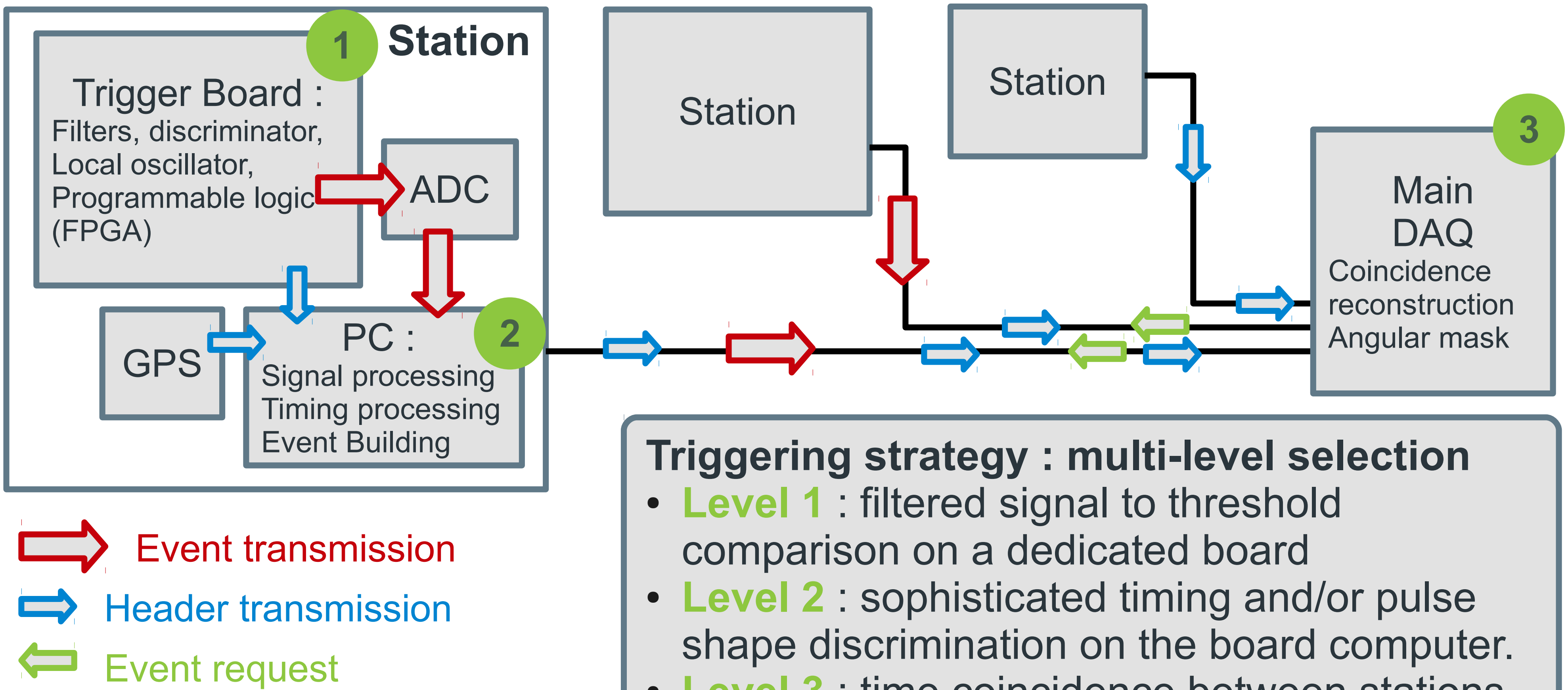
1m x 1m (box)
2m x 2m (antennas)
1.5m height





- **Autonomous station** : signal detection, selection, digitization, dating, event building, storage **in the station**
- **Wide band antenna + high sampling rate ADC (1 GS/s)**
- Upgradeable elements and multi-lab project : one function = one board.
  Separated modules in Eurocard standard.
- Quiet electronics : **EMC box**
- Low power consumption (20 W)

CODALEMA 3 : the triggering strategy



Triggering strategy : multi-level selection

- **Level 1** : filtered signal to threshold comparison on a dedicated board
- **Level 2** : sophisticated timing and/or pulse shape discrimination on the board computer.
- **Level 3** : time coincidence between stations and angular reco. on a master computer.

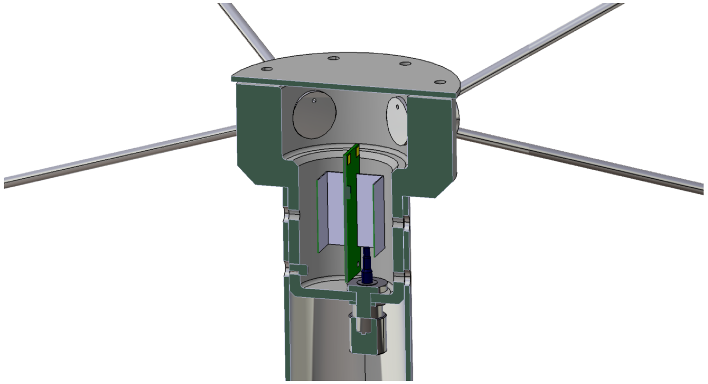
Storing and data saving scheme

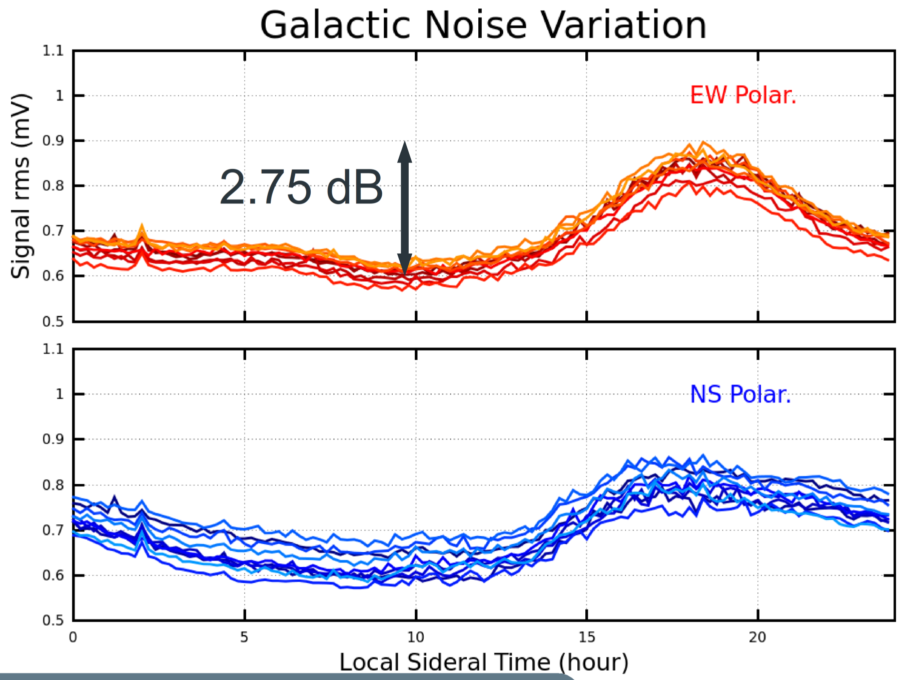
- After L1 : full event are stored locally
- After L2 : event header at sent by the station
- After L3 : full events are requested and sent by the stations involved in the coincidences

Data format developed for and adopted from AERA (PAO).
Data are stored offline in a Firebird db for monitoring, mining and archiving.

Antenna performances

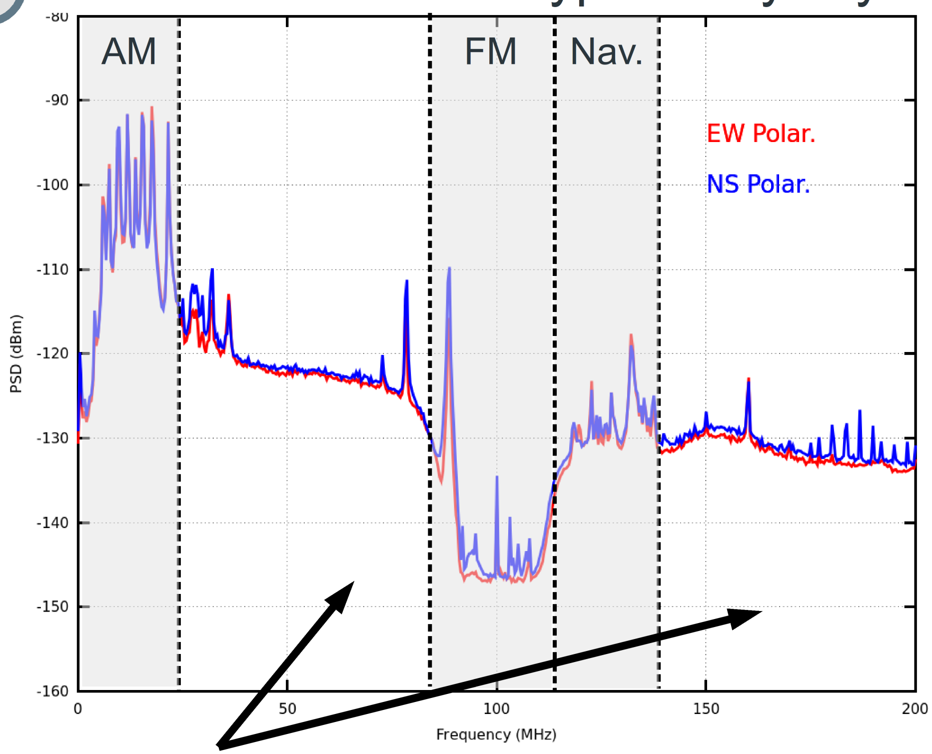
- Large band, sensitive, dual polarizations, dedicated LNA (IC, filtering).
- A performing antenna operated or tested by others : AERA, LOFAR Super Station, EASIER, IceCube, …
- A new LNA already in IC. Better linearity, earlier FM filtering.





Expected variations (antenna response and exposure)

A typical day sky



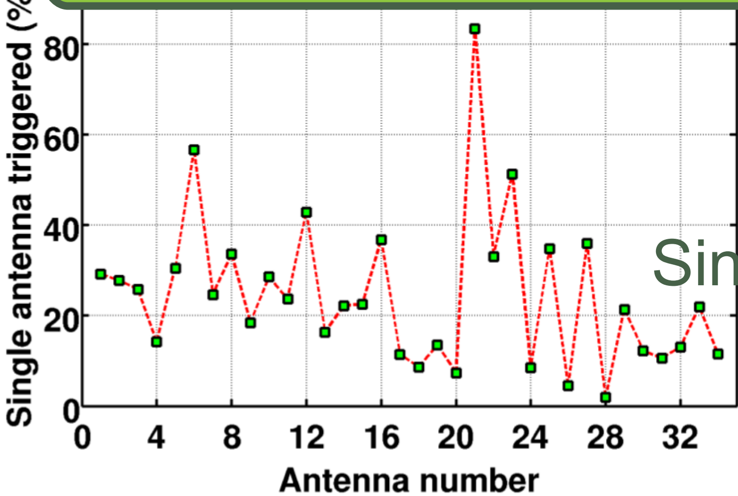
Typical useful bands (extended when the signal is large)

D. Charrier et al., Nucl. Inst. Meth. A662 S142 (2012)

A variating RFI environment

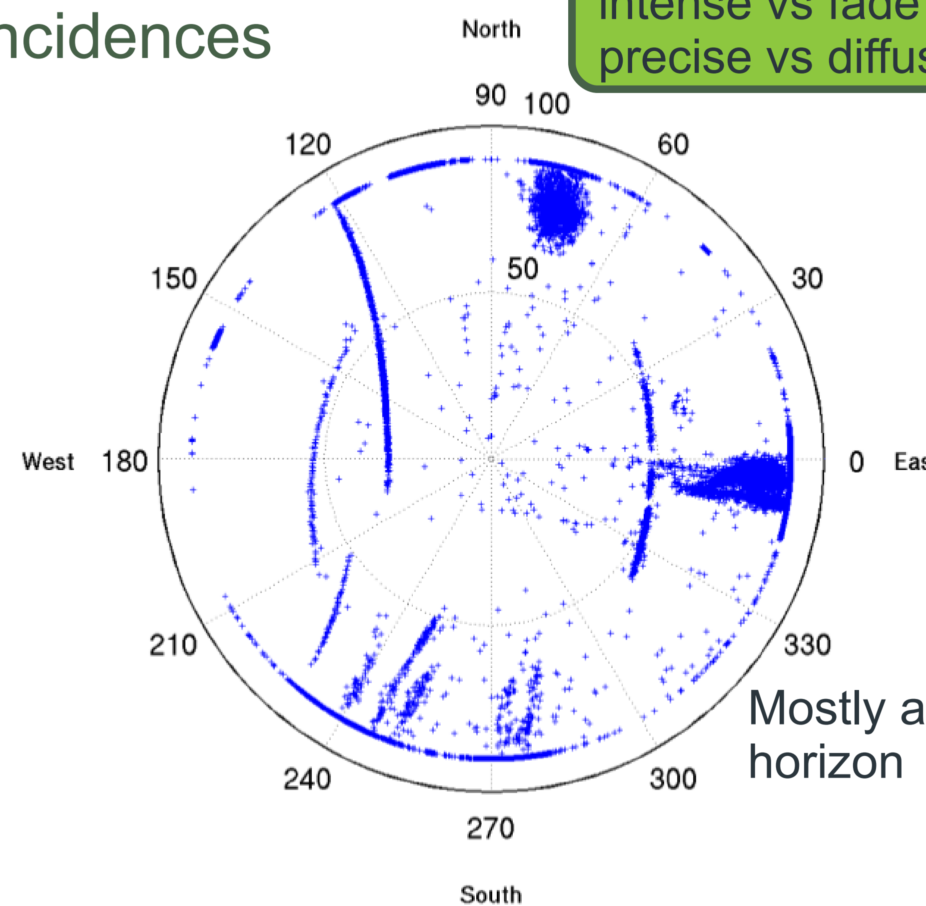
Despite law-enforced RFI restrictions the Nançay radio-astronomy station is surrounded by various variating transient sources.

A significant fraction of events are singles : very local transient sources



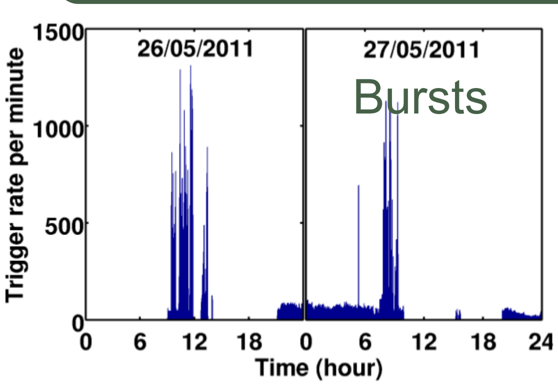
Singles vs Coincidences

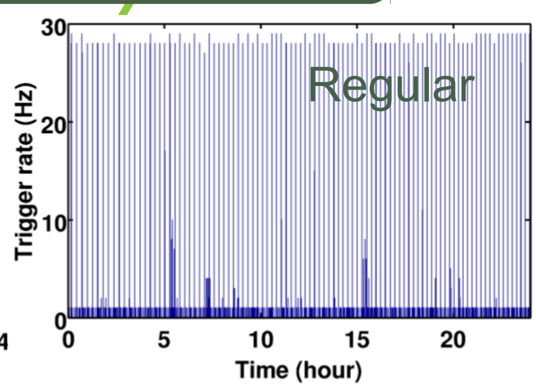
A typical day :
moving vs static
intense vs fade
precise vs diffuse



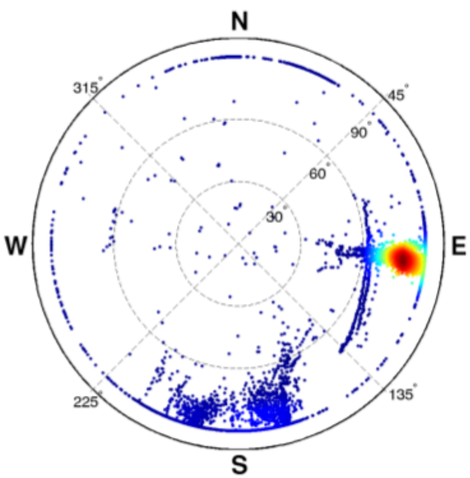
Mostly at horizon

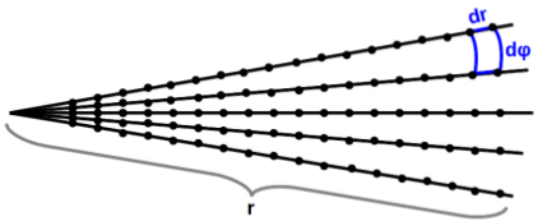
Permanent signals or regular bursts : identity of the sources

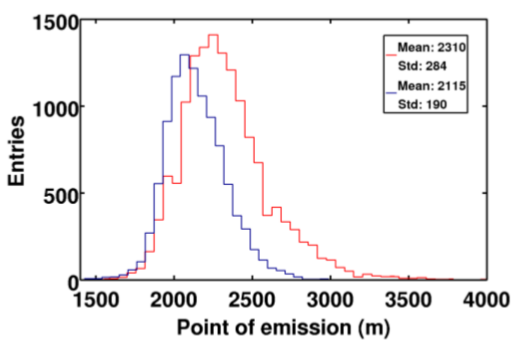




Identification, localization of noise sources

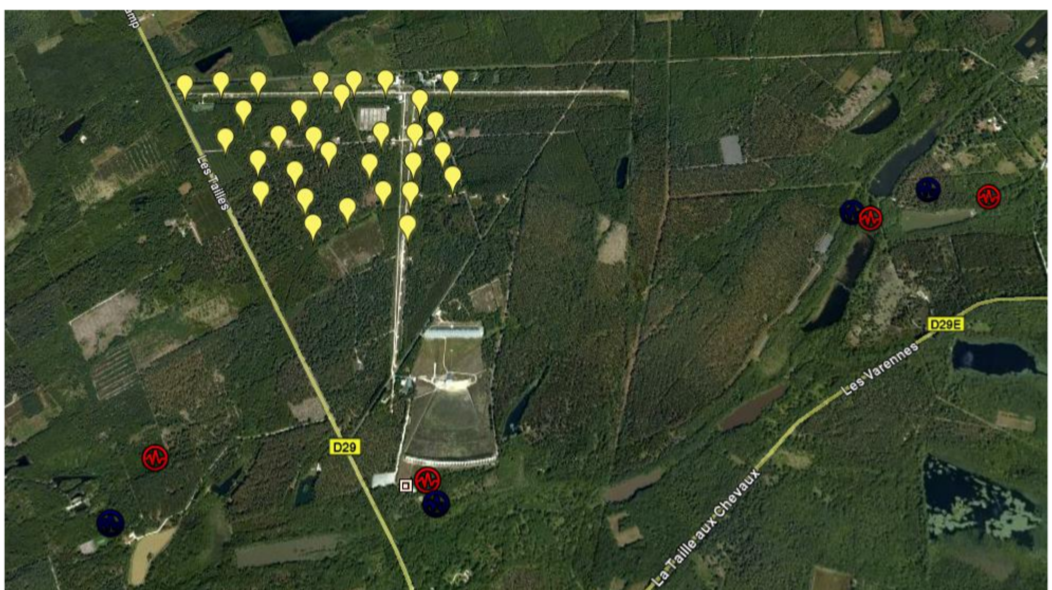






Source identification and localization :

- Source at the horizon and spherical wave front approximation
- Finding the smallest χ^2 by scanning the expected (R,φ) phase space
- Resulting locations associated with human-made objects (electric transformer, electrical power line)
- Position resolution limited by the extrapolation outside the array

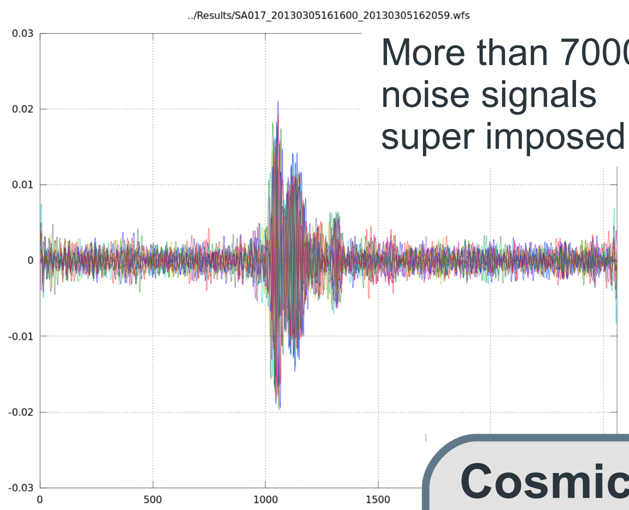


Strong and clearly identified sources are been chased but...

… main sources can hide secondary sources
… the environment is evolving (Cell phone network, digital TV and radio, RF meter reading) and is different over a large surface

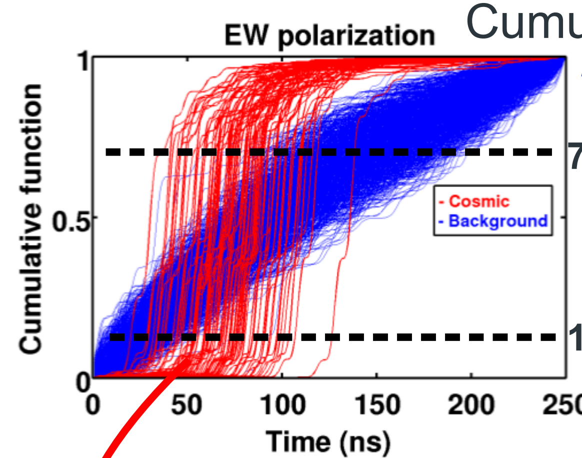
Better reject the parasitic transient online

Mastering the data load on the array



More than 7000 noise signals super imposed

Pulse shape selection

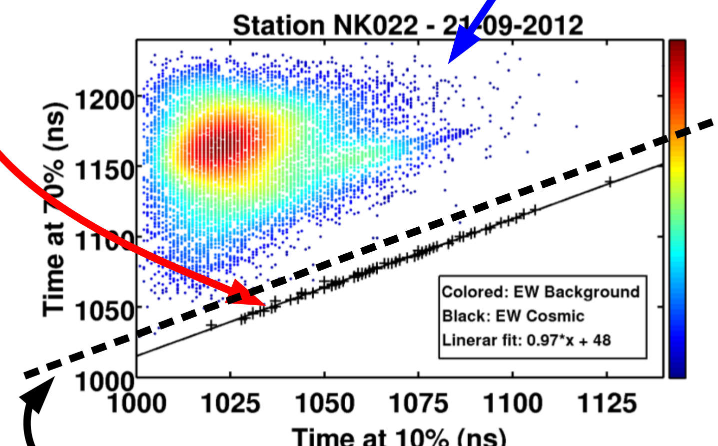


Cumulative V^2

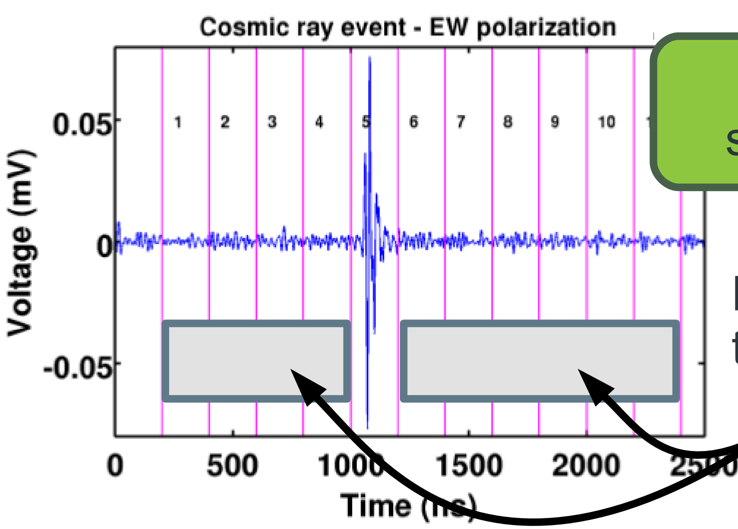
Noise

Cosmic signals are rather short
Noise signals are often similar
Noise signals can be long or with secondary pulses
Noise signals are often regular

Cosmics



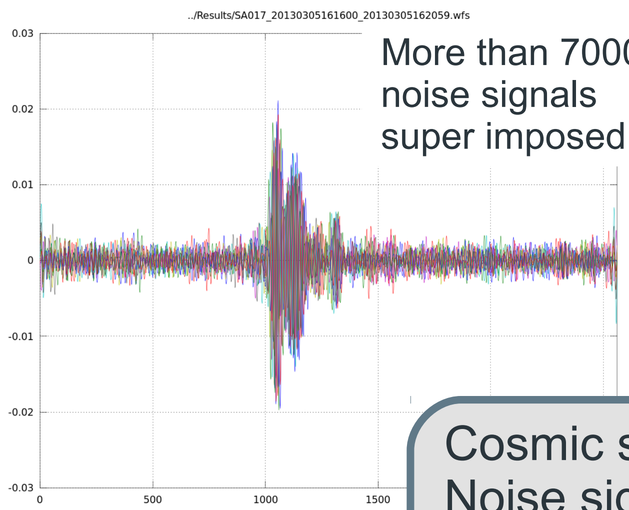
Rejection above the cosmic time line



Energy selection

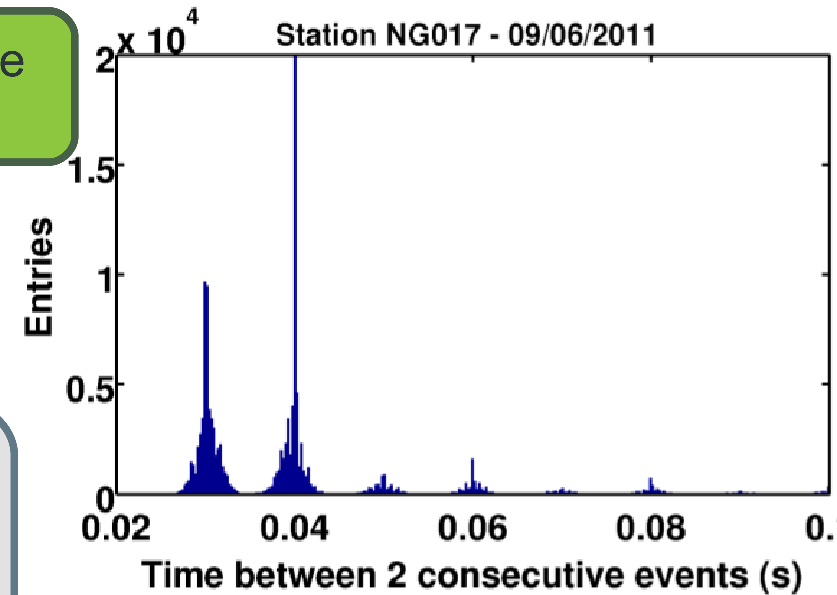
Rejection if signal in the outer windows

Mastering the data load on the array



More than 7000 noise signals super imposed

Occurrence selection



Cosmic signals are rather short
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Noise signals are often regular

Rejection at particular time differences :

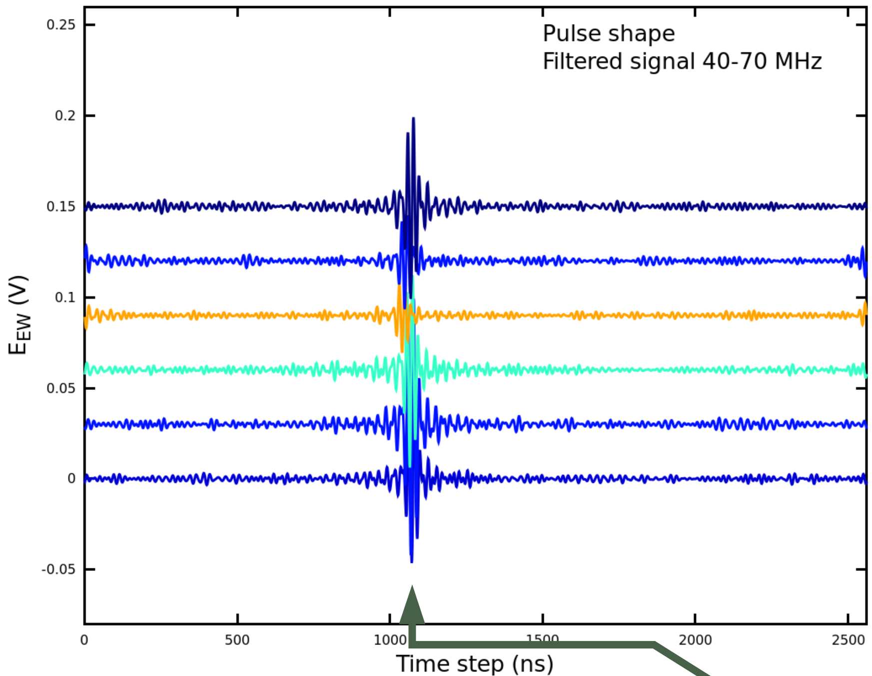
- Multiple of 10 ms
- 1.32s, ...

Selection	**Shape**	**Energy**	**Occurrence**
Efficiency	Excellent. Low cosmic event loss	Good. Suppress cosmic in a noisy sky	Low. Phase shift and mixed period
Analog/Online implementation	Hard. Needs a clock, a integrator, a time analysis. (2)	Difficult. Needs a clock, an integrator. (1) (2)	Easy. Needs a clock and a time table (1) (2)

Almost 95% of the noise signal is rejected

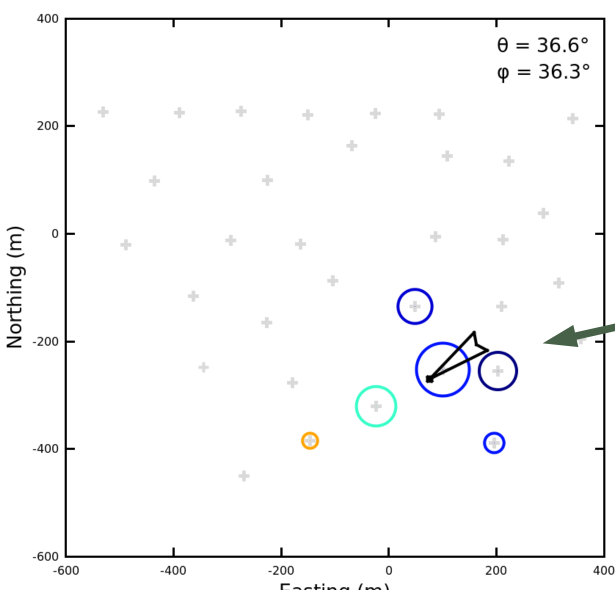
R&D for a simplified analog version (1)

Reconstructing the EAS



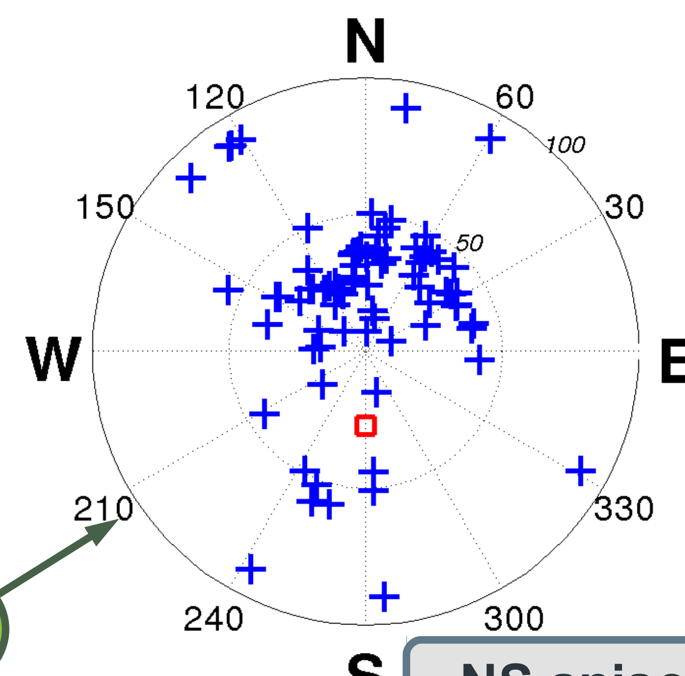
EAS transient are unambiguously identified
- Pulse shape and spectral signature
- Timing consistency within the stations
- Time coincidence with the SD array in the dating station
- Arrival direction above horizon
- Angular coincidence with the SD array
- Basic properties are emerging : arrival direction anisotropy, LDF

Station
GPS time



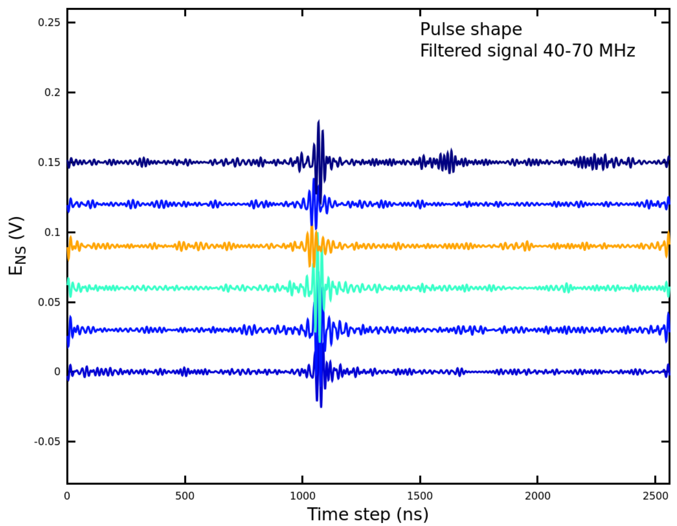
Event
Arrival
direction

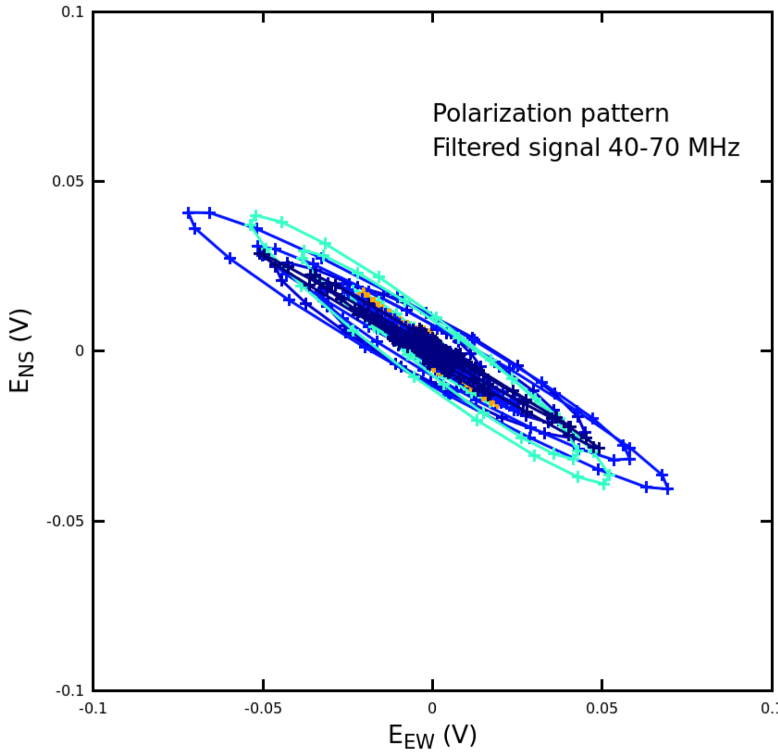
Dataset
Sky map



NS anisotropy

Polarization pattern



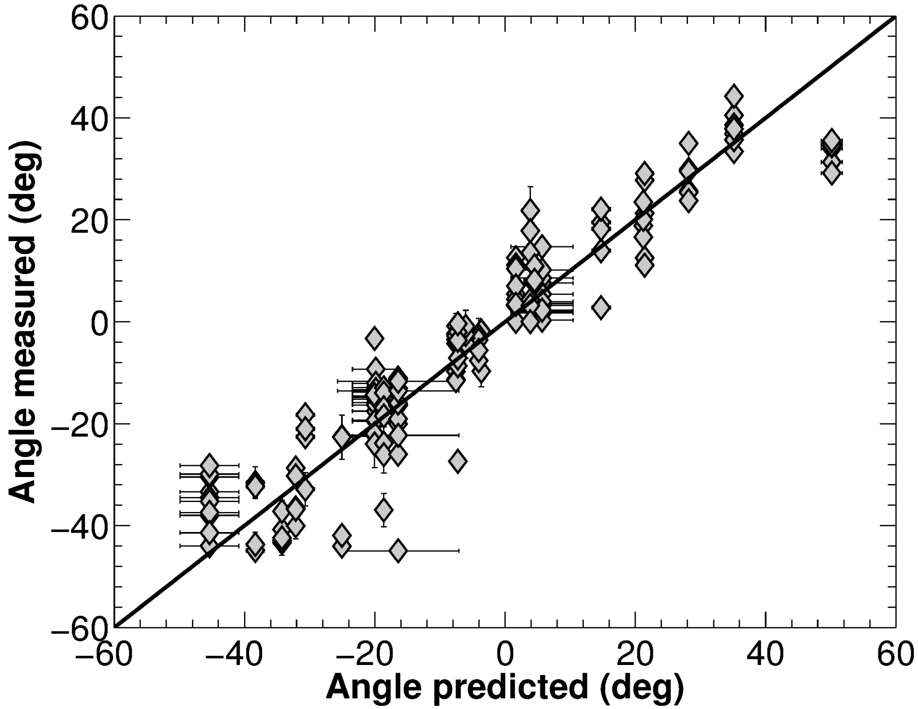


Assuming a pure geomagnetic effect :

- **E** α **n** x **B** , linearly polarized
- Φ_{exp} = atan((**n** x **B**)$_{NS}$/(**n** x **B**)$_{EW}$)
- Φ_{exp} given by the arrival direction

The antenna measured the polarized signals E_{EW} and E_{NS}

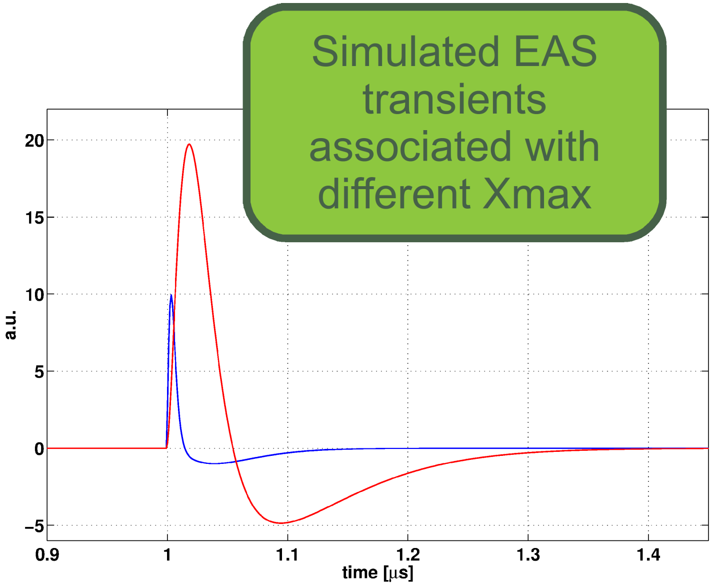
- Φ_{meas} = atan(U/Q)/2 where U,Q are the Stokes parameters

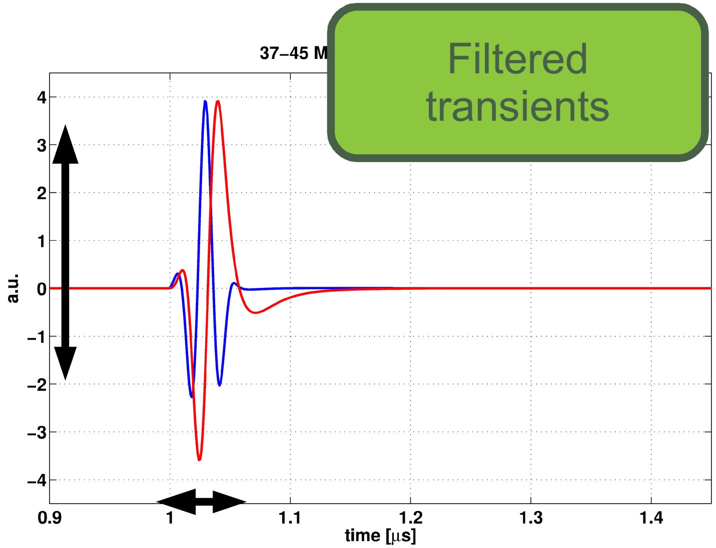


- Coarse pattern : the data follows the rule : $\Phi_{exp} = \Phi_{meas}$
- Fine pattern : the dispersion shows the charge effect

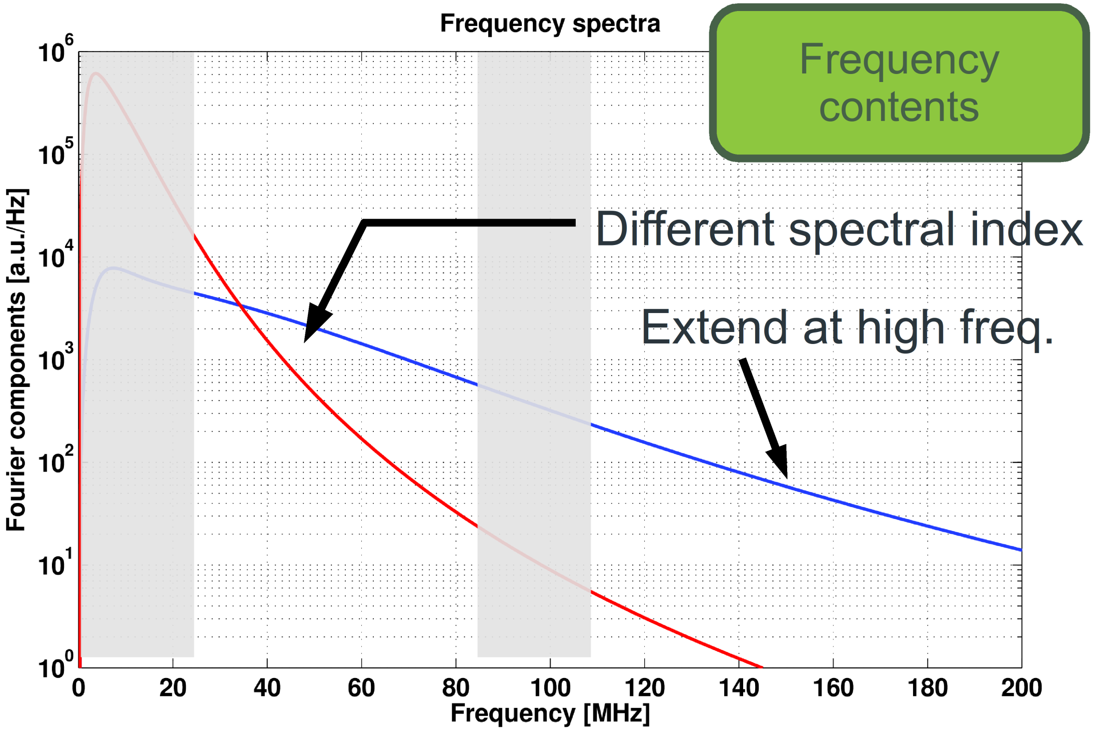
A. Belletoile et al., ICRC'11, D.Torres et al., ECRS'12

Pulse shape and spectral contents





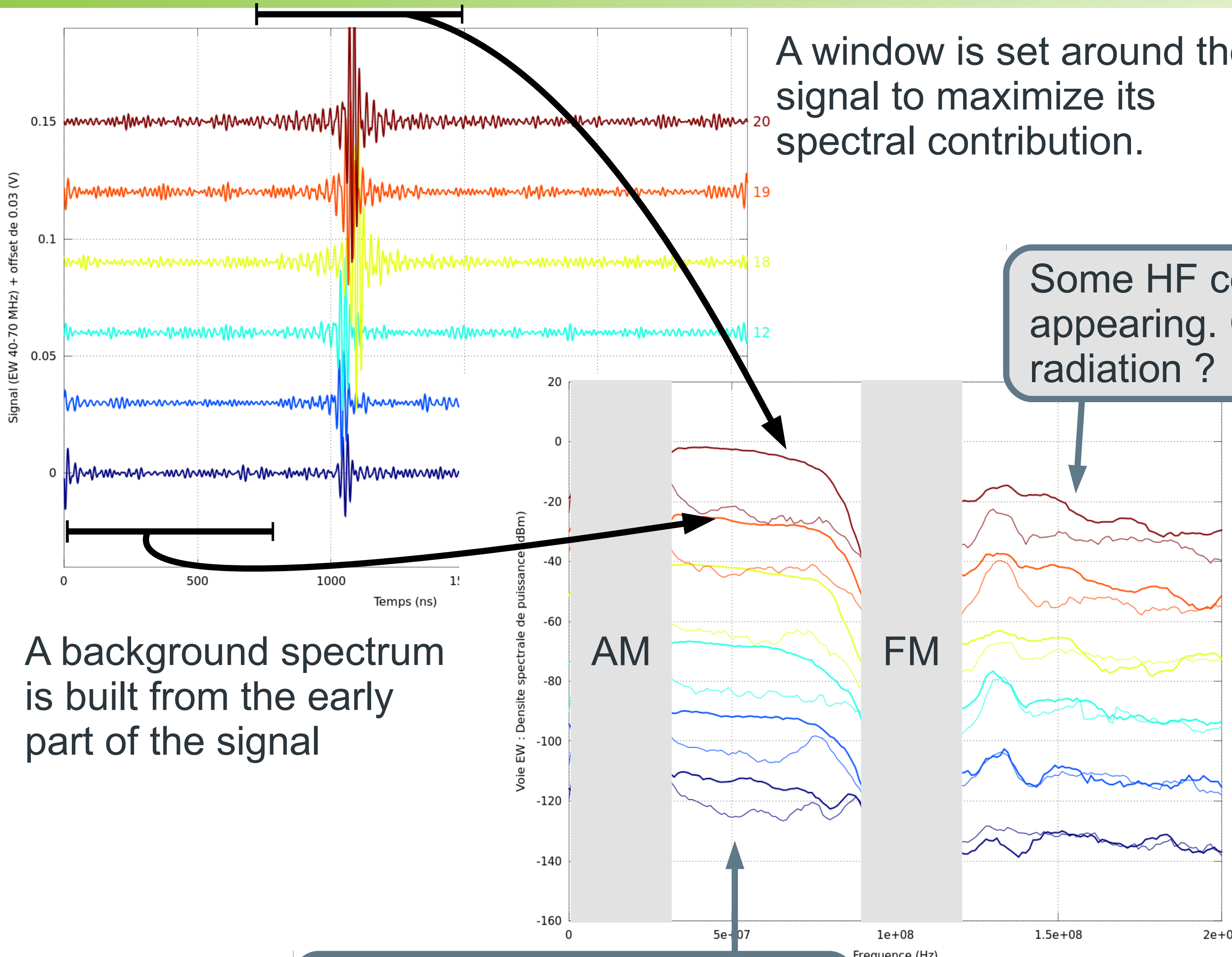
Similar amplitudes and time widths



Different **EAS features** :
energy, inclination, mass (Xmax)
Or **observation conditions** :
impact parameter, orientation, under/above
induces different **pulse shapes** :
Amplitude duration, bi-polarity
Filtering the signals kills the differences
Measuring the spectrum over a wide-band preserves the sensitivity

Pulse shape and spectral contents

A window is set around the signal to maximize its spectral contribution.

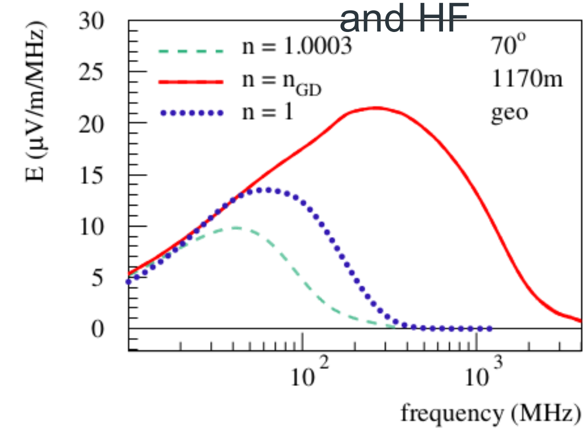


A background spectrum is built from the early part of the signal

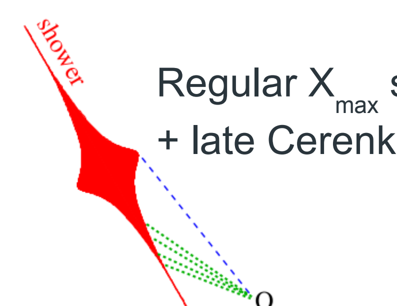
Some HF contribution is appearing. Cerenkov radiation ?

The signal is clearly emerging above the noise ! Price : freq. resolution lost

The Cerenkov can be strong and HF

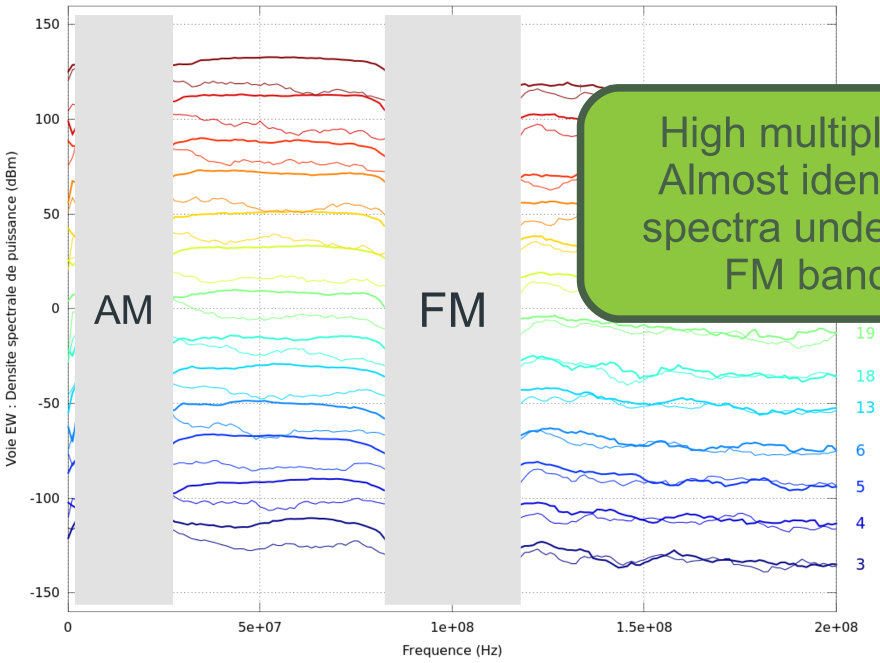


Regular X_{max} signal + late Cerenkov

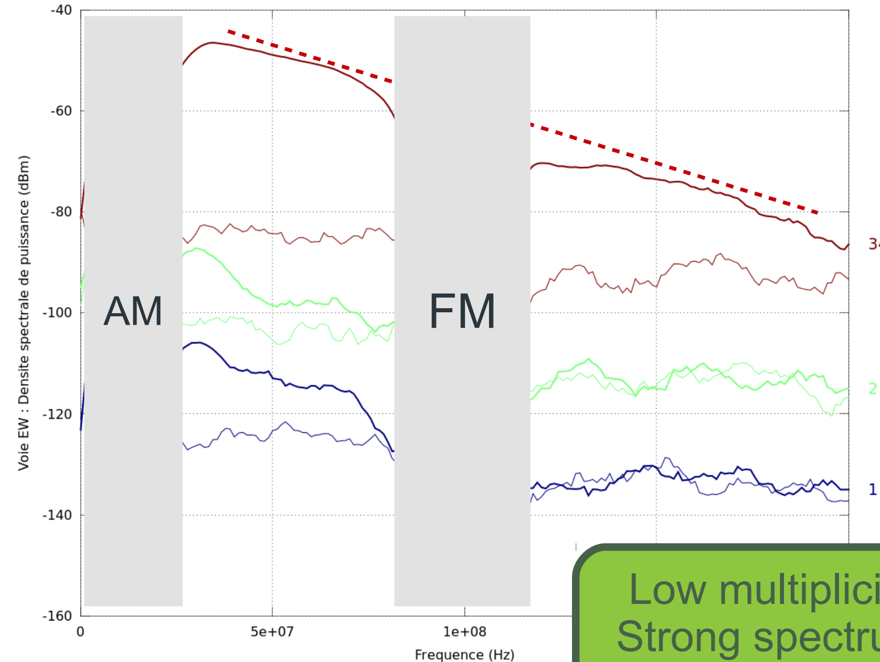


From K.Werner et al. ArXiv 1201:4471v2

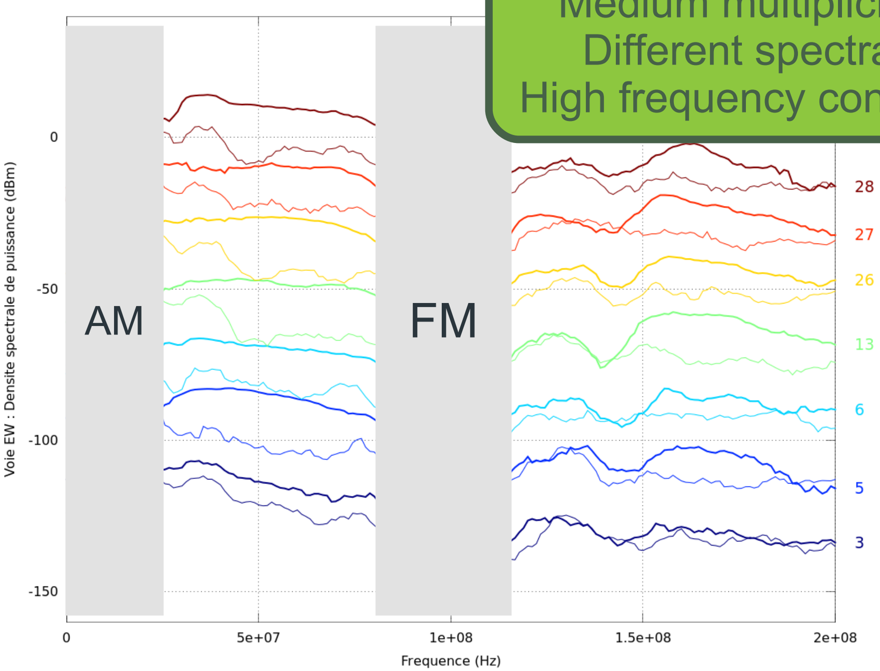
Spectral contents : a variety to explore



High multiplicity
Almost identical spectra under the FM band



Low multiplicity
Strong spectrum variations



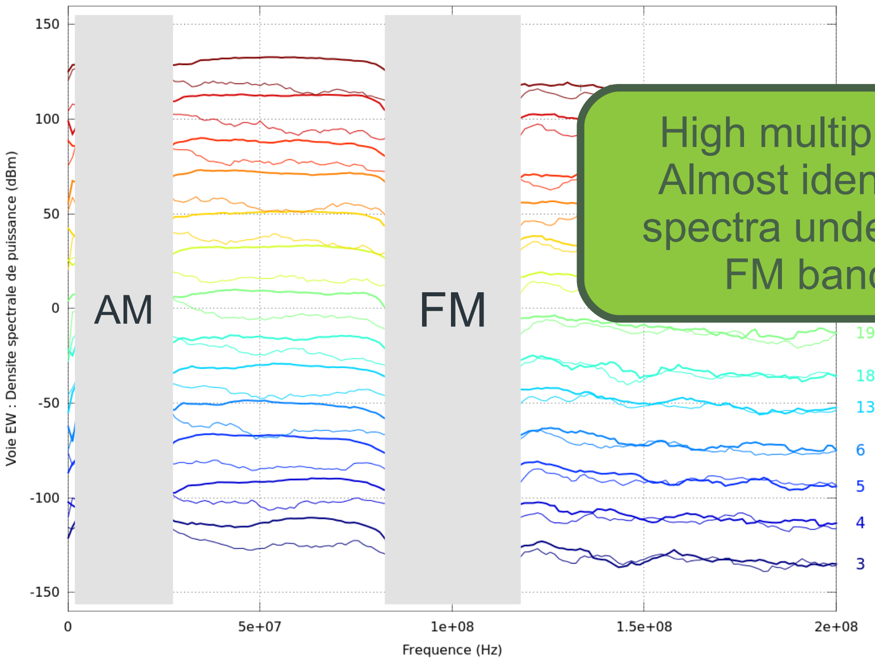
Medium multiplicity
Different spectra
High frequency content

The dataset shows very rich content.
The events are very difference in :

- Multiplicity
- Spectral extent and spectral index
- Polarization
- Lateral distribution

A detailed de-convolution of the full elect. chain (antenna+LNA+ADC) is needed. Ongoing work. Quantitative analysis in progress. D.Torres PhD thesis.

Spectral contents : a variety to explore



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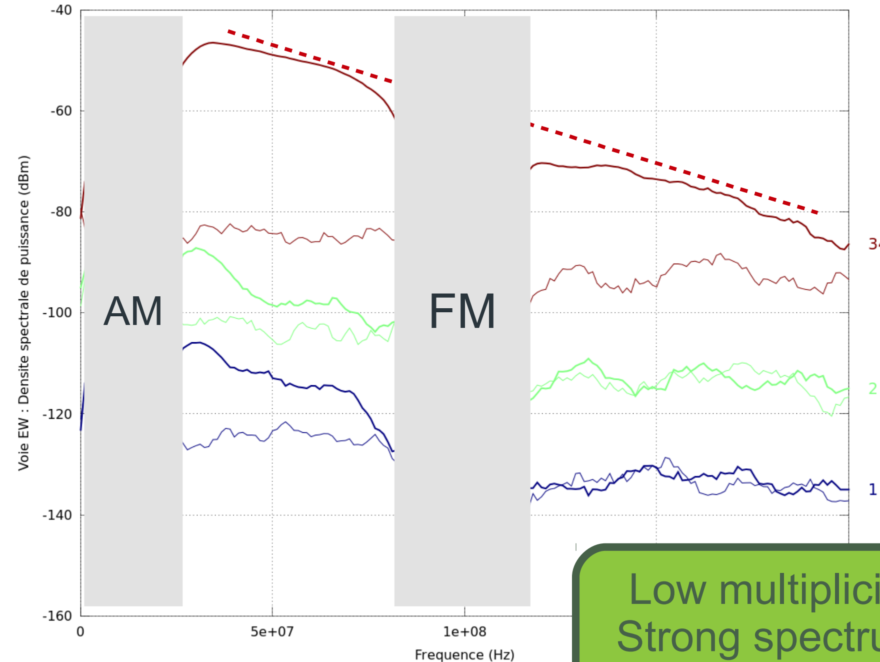

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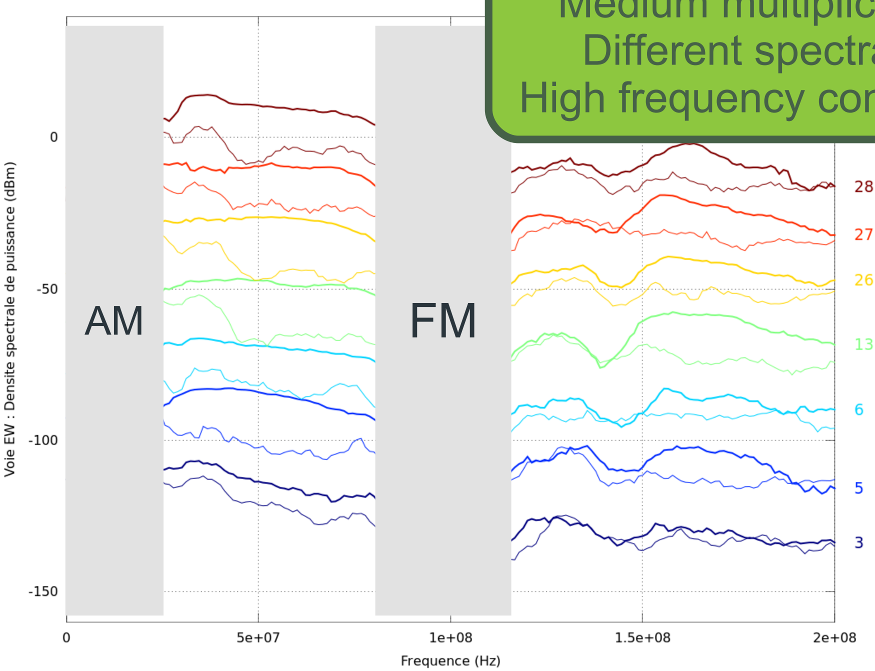

Medium multiplicity
Different spectra
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The dataset shows very rich content.
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- Spectral extent and spectrum slope
- Polarization
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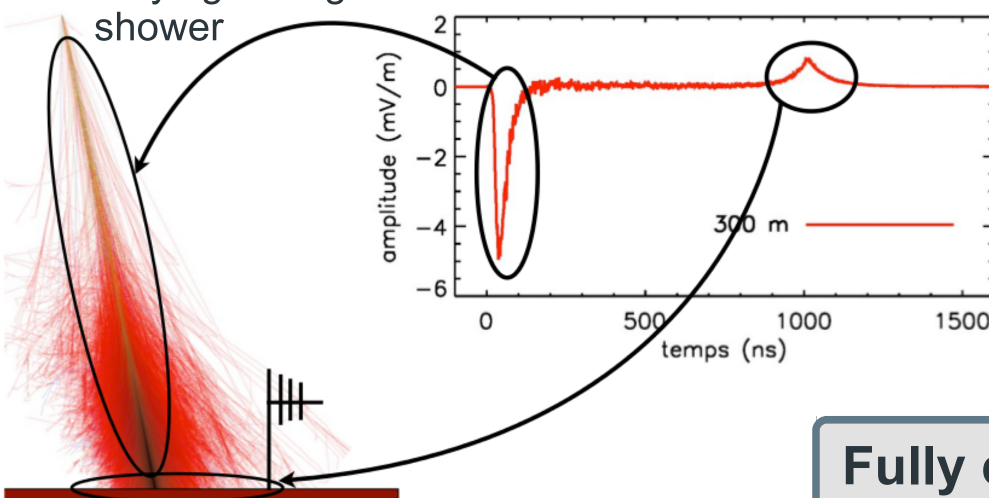
On going R&D efforts

Improve the antenna+LNA sensitivity
- Better linearity : smaller inter-modulations
- Increase BW in the NW polarization
- Already in use in the LOFAR Super Station

Extend the frequency bandwidth
- High frequency up to 400 MHz :
  - higher spectral sensitivity,
  - look for Cerenkov contribution.
- Low frequency down to 5 MHz :
  - higher sensitivity at larger distance,
  - look for other mechanisms : **shower death signal**

The net charge is varying during the shower



The net charge may also strongly vary when it reach the ground

V.Marin, 2012 (SELFAS)

Fully characterize the radio electric field
- Implement a vertical polarization measurement
- Perform a 3D measurement of the E field : balloon-borne station with the CNES

Conclusions and outlook

Mastering a large array
- Move Level 2 strategy into Level 1 dedicated board.
- Optimize Level 3 strategy

Transient from EAS are unambiguously identified
- Understand pulse shape and frequency content of the EAS radio transients
- Assess radio detection sensitivity to RC energy
- Quantify radio detection sensitivity to RC mass (lateral distribution and longitudinal development)
- Increasing statistics (stability and extension of the array)

On going R&D to improve radio detection performance and sensitivity
- Complete the polarization measurements (vertical)
- Increase the band width at both higher and lower frequencies
- A compact phased array for further triggering developments

Spare slides

Radio detection resultss

Geomagnetic contribution
- E field α X B
- Polarization f(θ,φ)

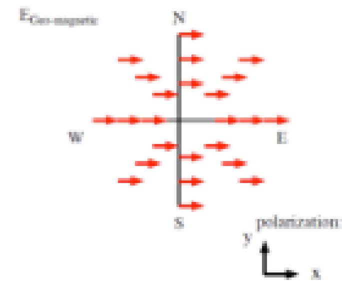
Lateral distribution function

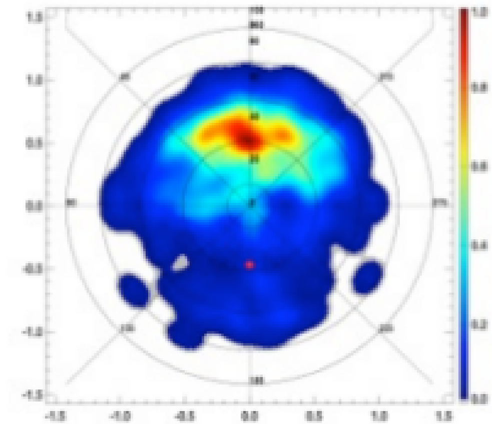
E_0, d_0, x_0, y_0

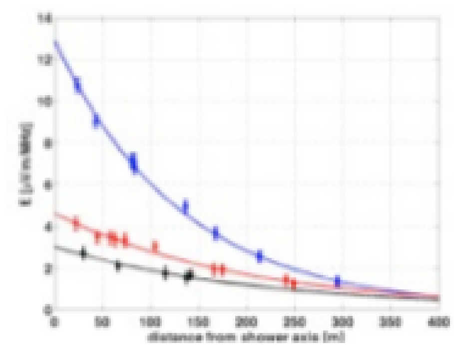
E_0 α E_p

Charge excess contribution
- 2nd order effect
- Radial polarization
- Radio shower core offset with respect to the particle shower core.

Observed in CODALEMA !







$$E_i(d) = E_0.exp(-d_i/d_0)$$