The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

SMR/1842-7

International Workshop on QCD at Cosmic Energies III

28 May - 1 June, 2007

the CODALEMA Experiment

R. Dallier
SUBATECH, Nantes, France

Radio detection of extensive air showers: The CODALEMA experiment

COsmic ray **D**etection **A**rray with **L**ogarithmic **E**lectro**M**agnetic **A**ntennas

The CODALEMA collaboration:
3 french institutes – 8 laboratories
SUBATECH Nantes (IN2P3, 2002)
Obs. de Paris-Meudon (INSU, 2002) - Station de Nançay (INSU, 2002)
LAL Orsay (IN2P3, 2004) - ESEO Angers (2004)
LPSC Grenoble (IN2P3, 2005)
LAOB Besançon (INSU, 2006) - LPCE Orléans (INSU, 2006)
+ support of the Lab. of AUGER-France for the tests @ AUGER-South

CODALEMA: 2 sites

Working @ NANÇAY
Currently 16 dipoles, 13 scintillators
45 dipoles foreseen end 2008

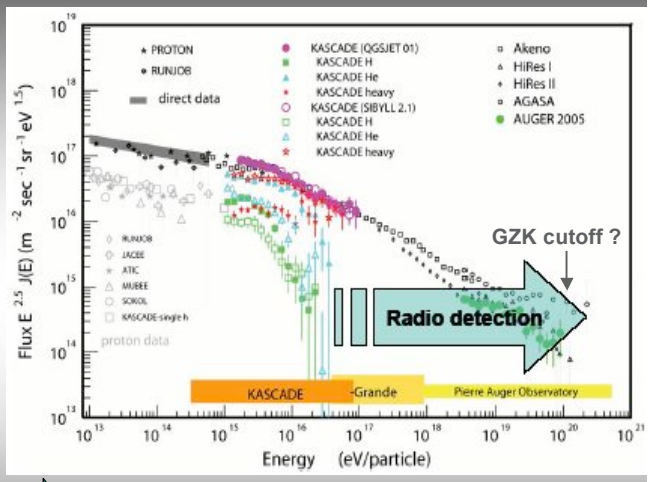
Tests @ AUGER-South
3 stations of 2 dipoles in 2007

Phase 1-2 (2002-05): Enlightenment of the method
Phase 3-4: (2006-08): Energy calibration from 10^{16} to 10^{18} eV

UHECR studies

Problematic of
ORIGINE
&
NATURE
of the cosmic rays

Radio-detection:
longitudinal development, macroscopic observables, long range detection, inclined showers, cheap, high duty cycle…



Complementary to hybrid techniques
Fluorescence, surface particles detectors

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Radiodetection of cosmic rays

1962:	Theoretical prediction - Askar'yan effect
1964-65:	First experiment - T.C. Weekes
Mid 70's:	Abandoned (difficulties of interpretation and detection + success of other techniques)
End 90's:	Re-investigated in dense media (ice, salt) ⇒ neutrinos
In 1999:	Proof of principle on accelerator (sand, D. Saltzberg,)
In 2000 :	Experience on CASA-MIA (K.Green et al., 2003, N.I.M. A, 498)
In 2002	LOPES Experience on KASCADE CODALEMA Experience of SUBATECH

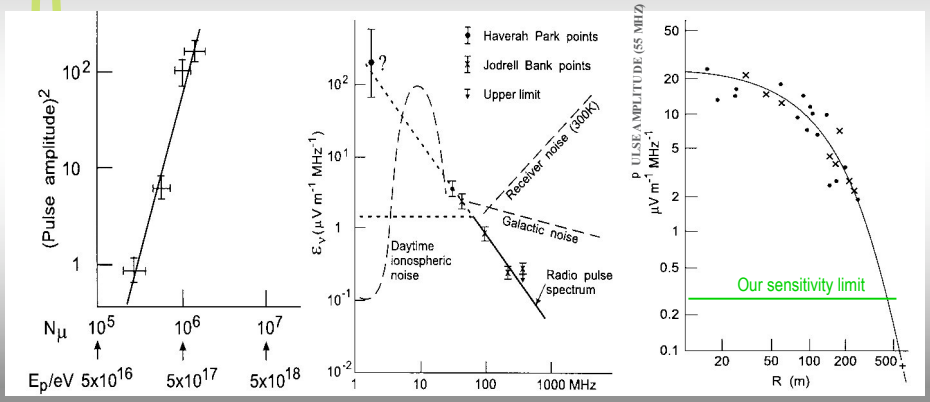
In 2005 : H. Falcke et al., Nature, May 19, 2005
D. Ardouin et al. NIM A555 2005 & astro-ph/0504297

In 2006: Prospectives on AUGER-South

Experimental results of 1970

H.R Allan, Prog. in Elem. Part. Cosmic Ray Phys., 10 (1971), p.171

- Theoretical assessments based on a frequency analysis of the signal
- 1 resonant antenna (Δf = 1 MHz)
- In coincidence with ground charged particle detectors



Some certainties but … some inconsistencies (Haverah Park, Yakutsk,…)

Origin of the electric field

Recombination of positrons in the atmosphere

Negative charge excess (~10% @ 10^{20}eV)**: monopolar emission**

Separation of charges due to the geomagnetic field

Dipolar emission

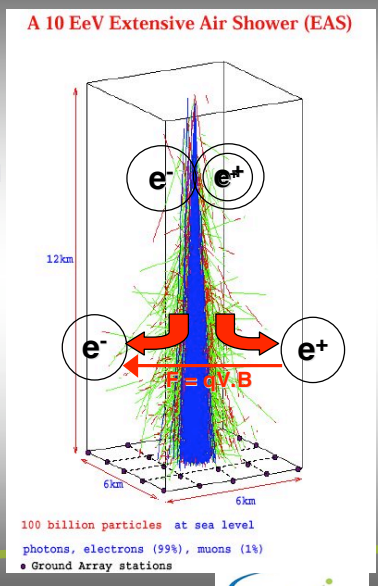
Creation of charges along the shower path

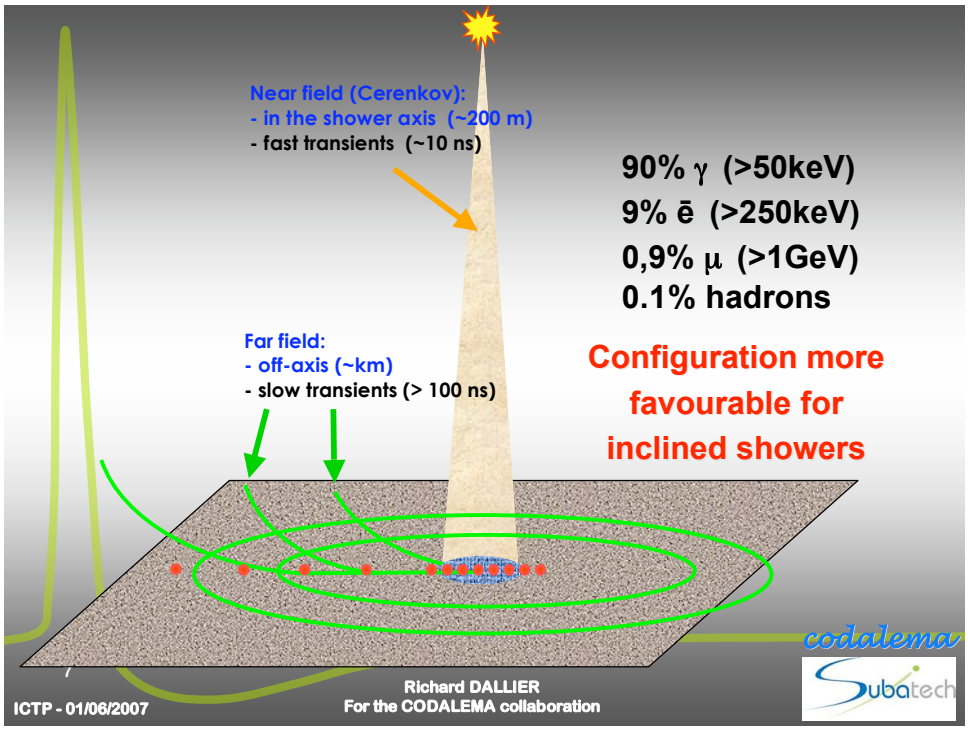
Dipolar current

Deflection of charges in the geomagnetic field

Synchrotron emission

+ Cerenkov emission (on axis)




Near field (Cerenkov):
- in the shower axis (~200 m)
- fast transients (~10 ns)
Far field:
- off-axis (~km)
- slow transients (> 100 ns)
90% γ (>50keV)
9% ē (>250keV)
0,9% μ (>1GeV)
0.1% hadrons
Configuration more favourable for inclined showers
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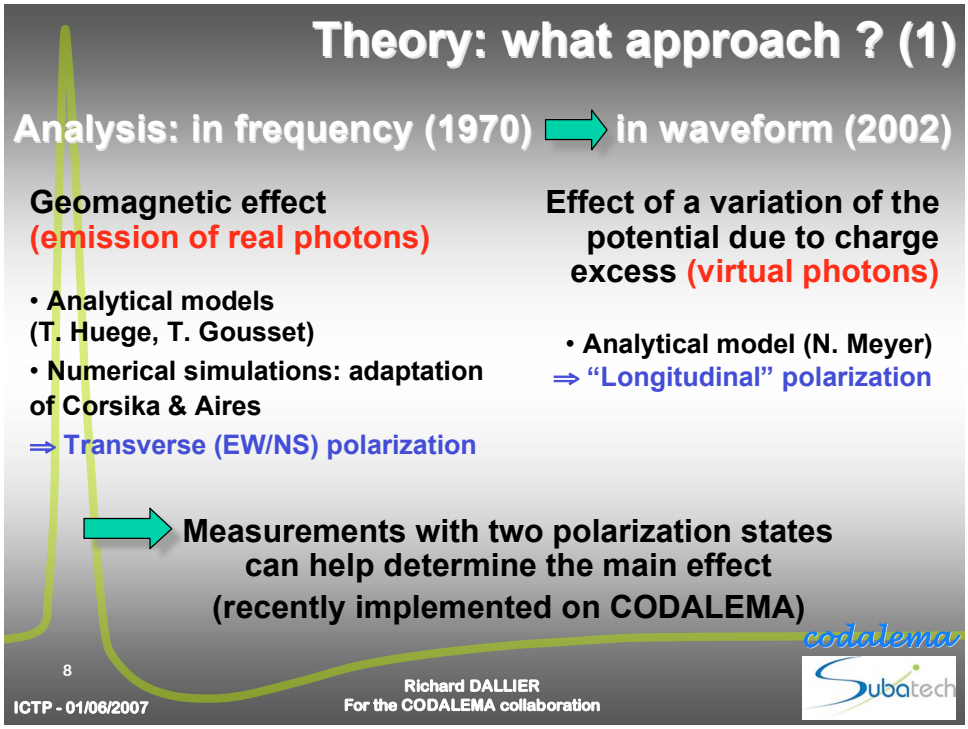
Theory: what approach ? (1)
Analysis: in frequency (1970) in waveform (2002)
Geomagnetic effect
(emission of real photons)
• Analytical models
(T. Huege, T. Gousset)
• Numerical simulations: adaptation of Corsika & Aires
⇒ Transverse (EW/NS) polarization
Effect of a variation of the potential due to charge excess (virtual photons)
• Analytical model (N. Meyer)
⇒ "Longitudinal" polarization
Measurements with two polarization states can help determine the main effect
(recently implemented on CODALEMA)
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Theory: what approach ? (2)

- **Semi-empiric:**

Macroscopic description (calorimetry) with simple laws? ⇒ analytical models ? (SUBATECH, Obs. de Paris)

- **Monte-Carlo:**

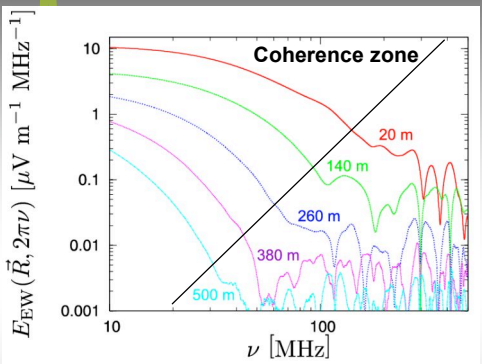
CORSIKA, AIRES, CONEX & semi-analytical models? (SUBATECH, LAL, LPSC)

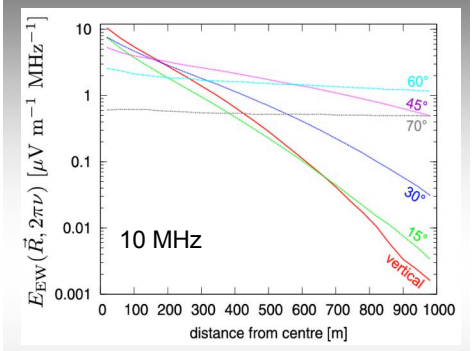
OR **Dedicated code** as for LOPES (T. Huege, FZK)

Questions:

- Inclined showers (neutrino detection)?
- Effects of positive ions queue? Of pancake geometry? Of atmospheric electric field (stormy weather)?

T. Huege: Frequency spectra @ 10^{17} eV



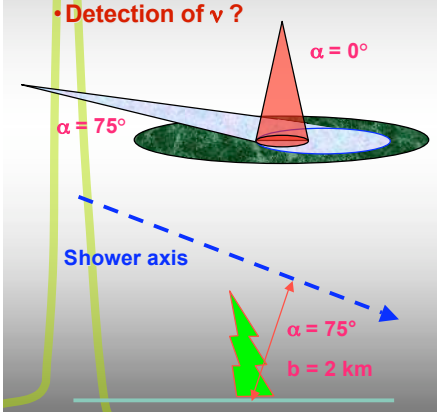


- For vertical showers
- 10 MHz: very coherent
- 55 MHz: coherence only up to ~ 300 m

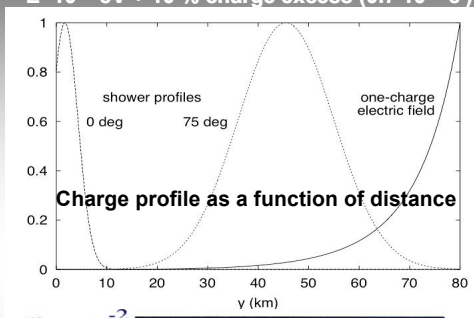
- Favourable for inclined showers
- Approx. Exponential scaling

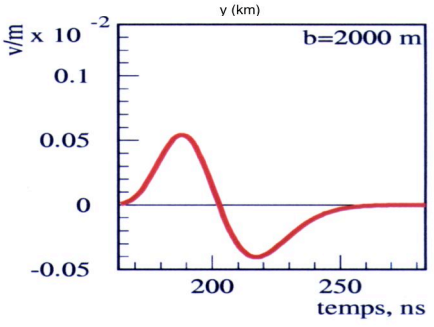
T. Gousset *et al.*: simulations of horizontal showers

Very long range detection
- Illumination cone
- Amplitude + arrival time
- Detection of ν ?



E=10^{20} eV + 10 % charge excess (0.7 10^{10} e^-)





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Radiodetection capabilities with CODALEMA

2002 • Trigger capabilities
(1 ant. + narrow band)

2003 • Shower direction: triangulation
(several ant. + time tagging)

2005 • Field topology: extent & core location
(several ant. + field distribution on the ground)

2006 • Primary particle energy : ∝ total charge ∝ electric field
(amplitude of the signal)

2007 • Nature : longitudinal profile, X_{max}
(shape of the signal)

To demonstrate

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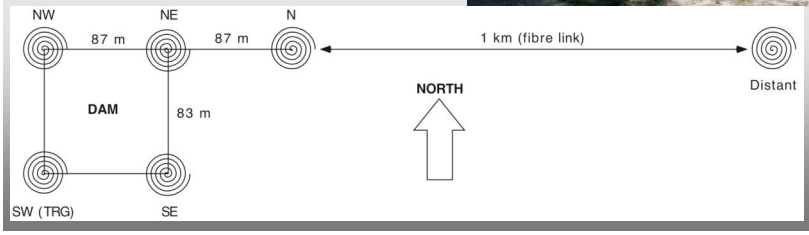
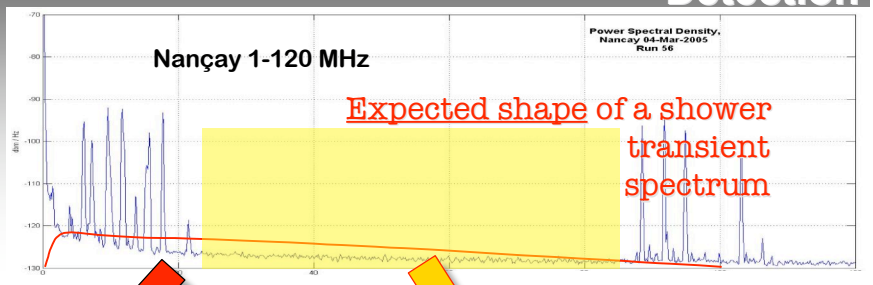
Radio triggered system: 2003 – 2004

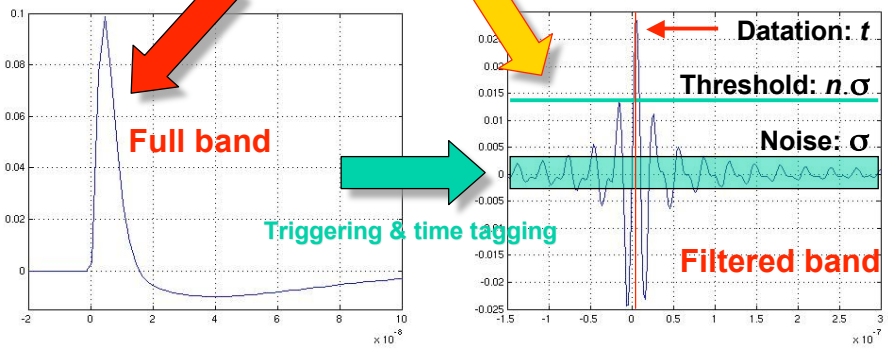
DAM: (Decametric Array) of the Radio Observatory of Nançay

- **Spiral log-periodic ant., 1-100 MHz (3dB), 90° lobe, circular polarization**
- **One trigger antenna filtered in 33–65 MHz, the 5 other full band**
- **Waveform 8 bits, 500 MS/s, 10 µs**



The CODALEMA Technique for Transient Detection





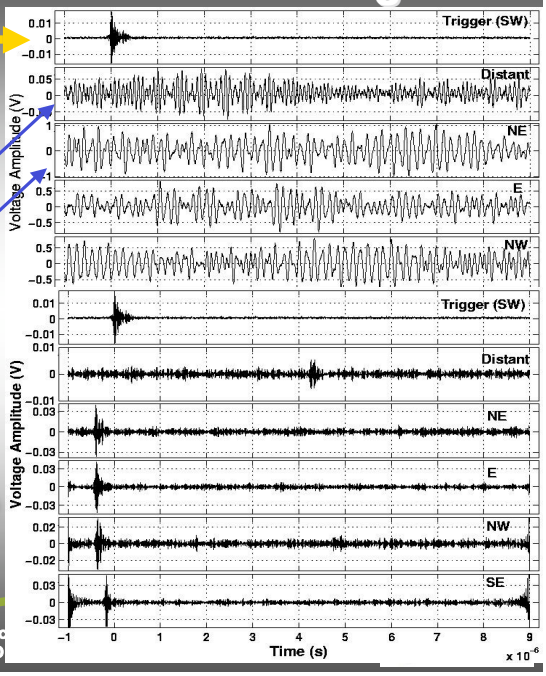
Transient recognition

1 Trigger Antenna
Voltage threshold on a devoted filtered antenna (33-65 MHz)

1 distant antenna (1 km) @ 10-100 MHz
+ 4 broad band antennas (1-100 MHz)

With Flash ADC 8bits - 500 MS/s - 10µs

After 33-65 MHz off-line numerical filtering



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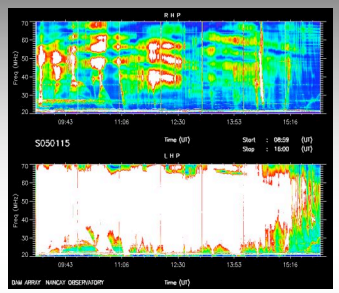
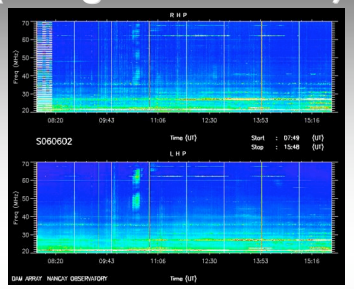
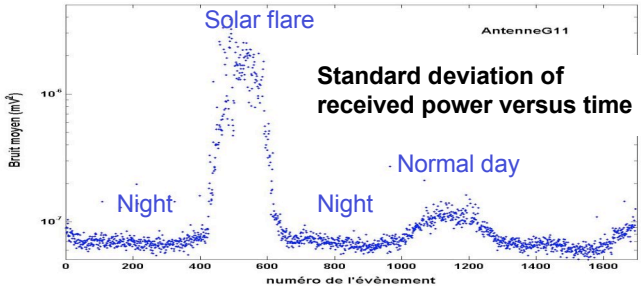
Triangulation performances (1)
(using Solar bursts)

DAM sun survey
15/01/05
&
02/06/06

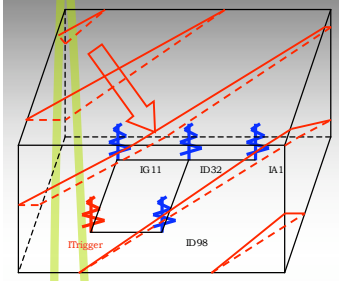




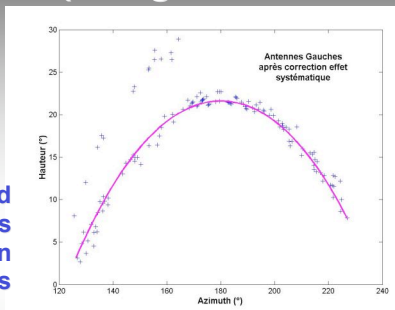
solar flare in active region AR10720 on 2005 Jan. 15



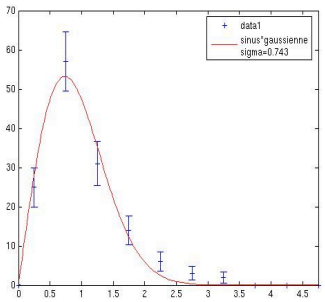
Triangulation performances (2)
(using Solar bursts)



Principle of the triangulation



Reconstructed directions versus sun ephemerids



Distribution of the residuals

Direction accuracy

σ = 0.74 °

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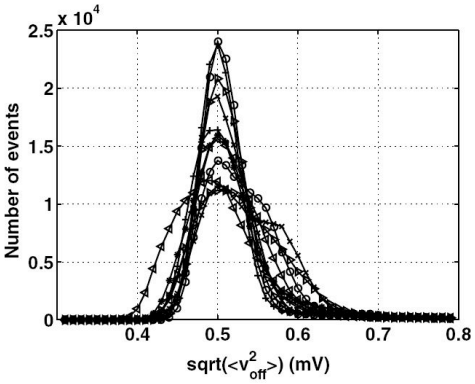
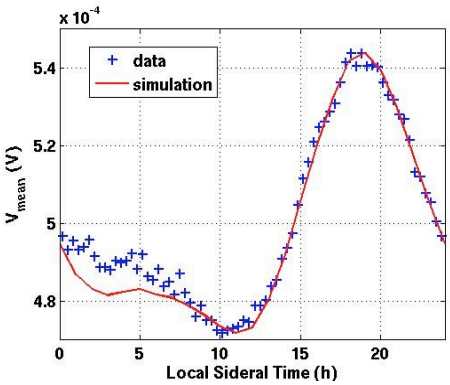
Signal sensitivity



Distributions of the ground floor signal in the 40-70 MHz band after cross calibration of the antennas gains

Time evolution of the mean ground floor **compared to** the galatic background + Cas.A simulated contributions seen through 45° lobe antennas



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Small antenna array: expected signal @ 10^{17} eV

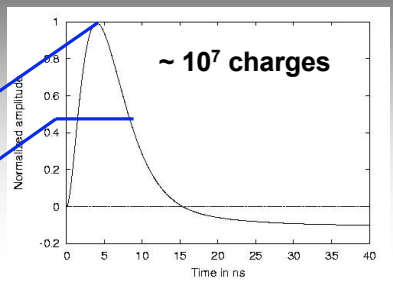
Vertical shower @ *small impact parameter*

Following H. R. Allan (1971)

Signal simulation:

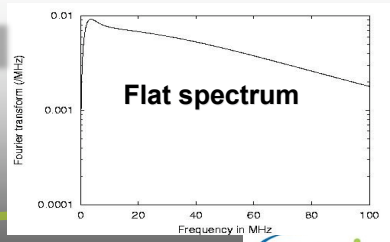
e_{pk}~150 µV/m

FWHM duration ~ 8 ns



- **Narrow-band antennas (improved sensitivity)**
- **Small antenna array**

2004-2005 setting @ Nançay



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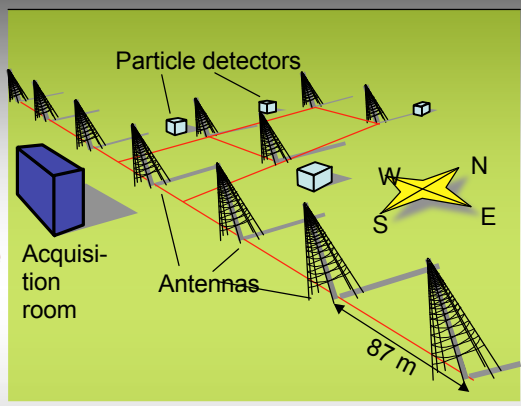
Narrow band and particle trigger: 2005 - 2006

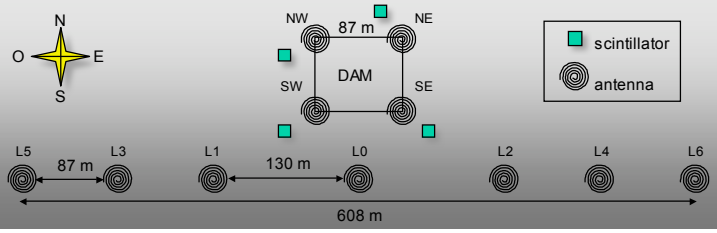
DAM: (Decametric Array) of the Radio Observatory of Nançay

- **Spiral log-periodic ant., 1-100 MHz (3dB), 90° lobe, circular polarization**
- **FILTERED IN 24-82 MHz**
- **Waveform 8 bits, 500 MS/s, 10 µs**

TRIGGER: 4 stations of scintillators (2 m²) in coincidence

- **Signal recording + time of flight analysis**
- **Reconstruction of the shower direction**
- **Comparison with radio**





Scintillators events

Reconstruction of the particle pancake arrival direction

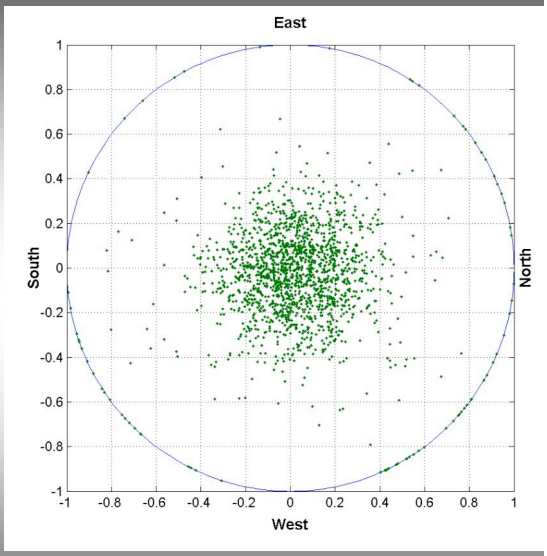
Active area: 7000 m²

Counting rate: 0.7 evt/min

Zenital limit : 0° < θ <60°
No azimutal limit

Estimated acceptance:
16000 m².sr

⇒ Trigger energy threshold : 1.10¹⁵ eV



Time distribution for antenna events

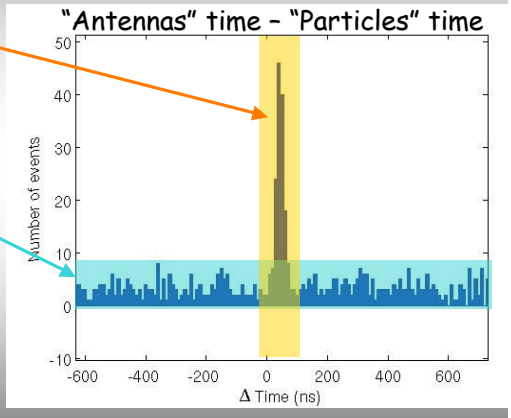
Coincidence rate: 1 Antenna + Trigger = 1 event / 1 h

3 Antennas + Trigger = 1 event / 2 h (~200 evts)

Sharp peak (< 100ns)
= EAS candidates
Coincidence rate:
1 event / Day

Flat distribution
= Fortuitous events

Using scintillators acceptance ⇒ Energy threshold ~ 5.10¹⁶ eV

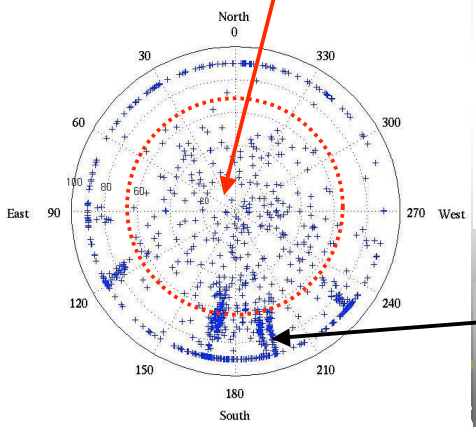


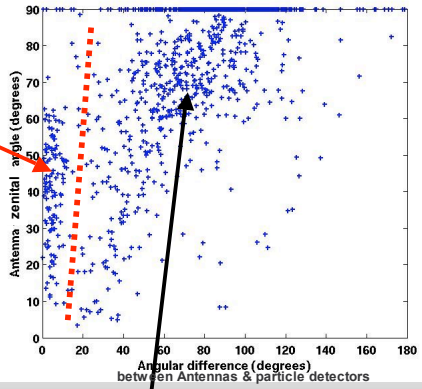
Coincidence characteristics

All events in a 2 µs window around the particle trigger

Selection Procedures

EAS candidates in the peak



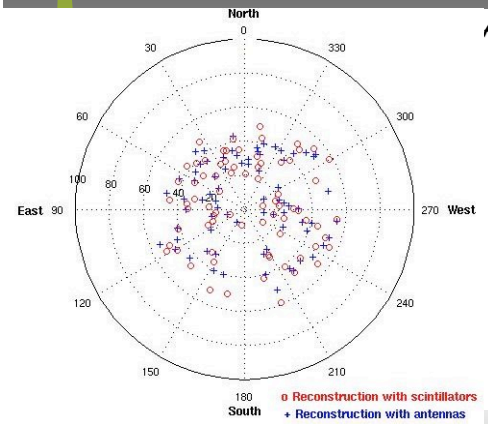


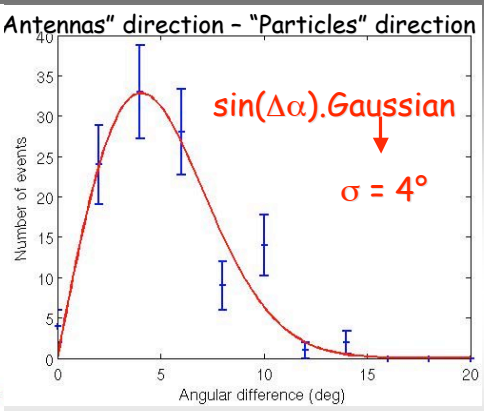
Noise events (in & outside the peak)

(Anthropic + solar + storms +….)

(generally coming from the horizon)

Correlation of Arrival directions



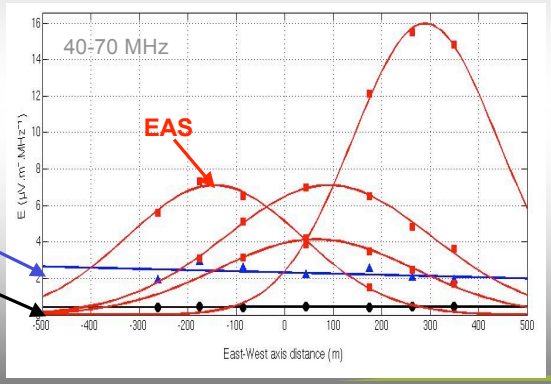


Reconstruction of EAS arrival direction is confirmed via Radio-Detection

Electric Field topologies

Variable antenna multiplicity (limited array)
Field amplitudes from 250 μV/m to 1.2 mV/m in 40 - 70 MHz

The entire shower development is seen by every antenna



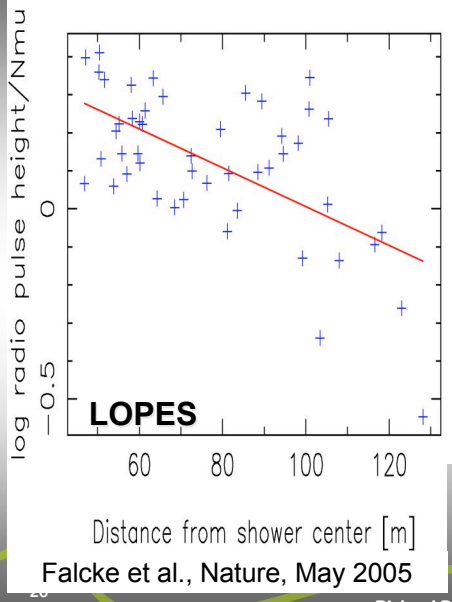
Far Transient

Ground Noise

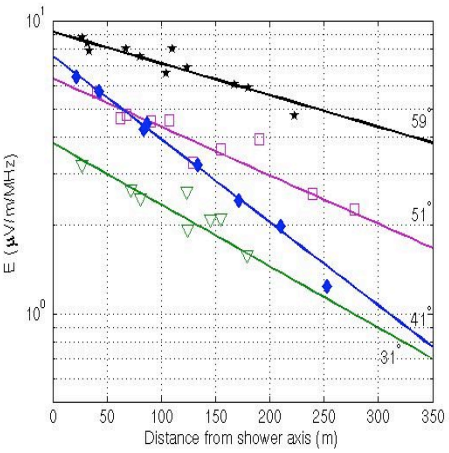
Free of particle ground density fluctuations

Field topology is a decisive criterion of selection in stand alone mode

Shower reconstruction



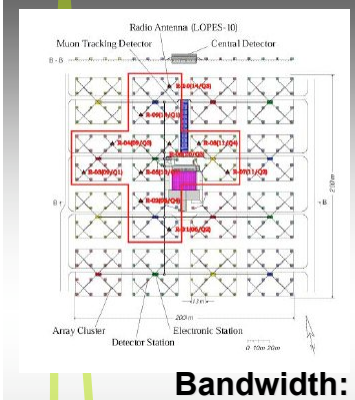
Falcke et al., Nature, May 2005



Field Measurements

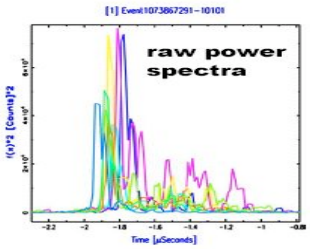
~ 600 m @ ~ 5.10^{16} eV

LOPES

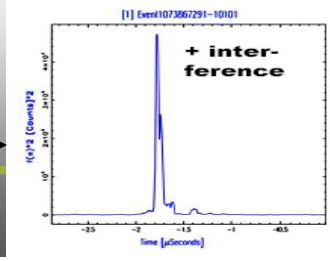


10 LOFAR antennas
Trigger: KASCADE

Bandwidth: 40-80 MHz + Sampling: 80 MS/s



Numerical phasing



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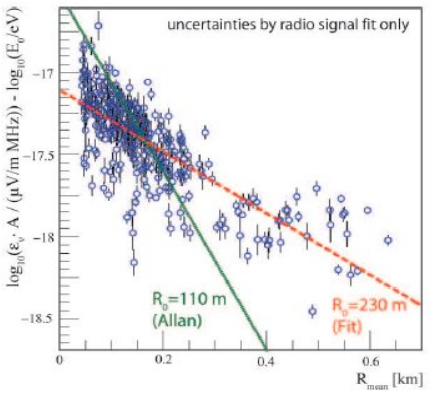
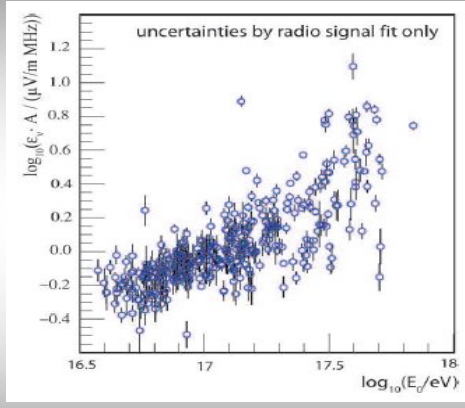
LOPES 10: Results with KASCADE-Grande



Correlation of the radio pulse height with the mean distance of the shower axis



Correlation of the radio pulse height with the primary energy of the shower

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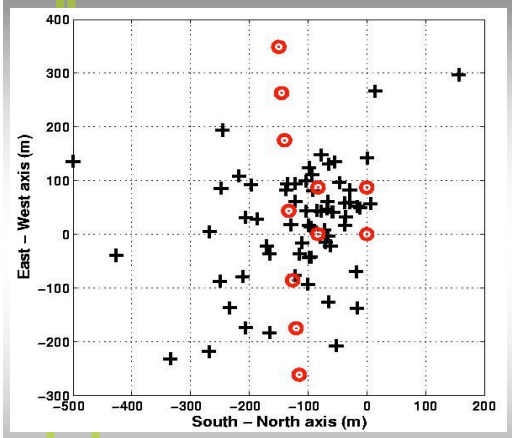
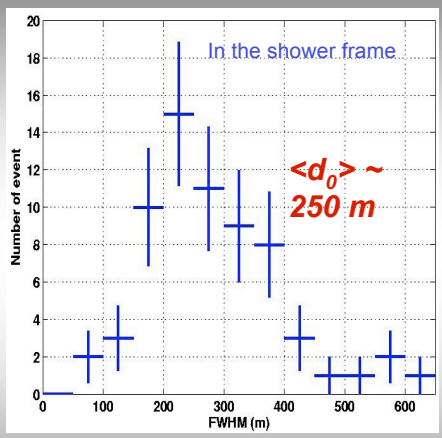
Extraction of the Parameters

If the maximum of the electric field is measured on 1 of the sampling axis:





Core positions (X0,Y0)

Extent of the field

FWHM extent of the field

~ 250 m @ ~ 5.10^{16} eV

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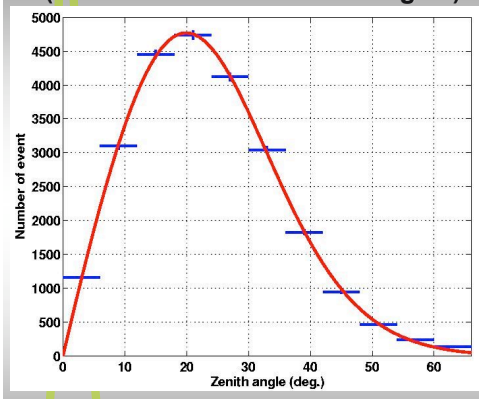
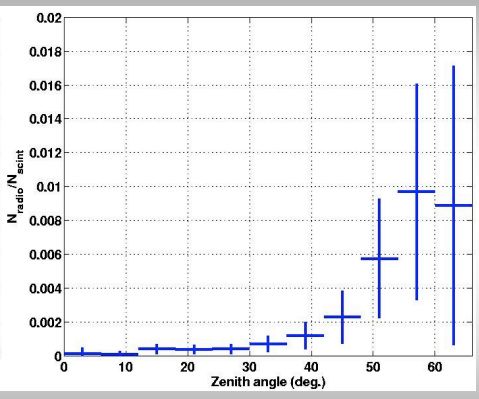
Detection of horizontal EAS

Trigger Counting
(not corrected from solid angles)

Radio / Trigger Acceptance





Radio-detection could be naturally adapted to the detection of atmospheric neutrinos ?

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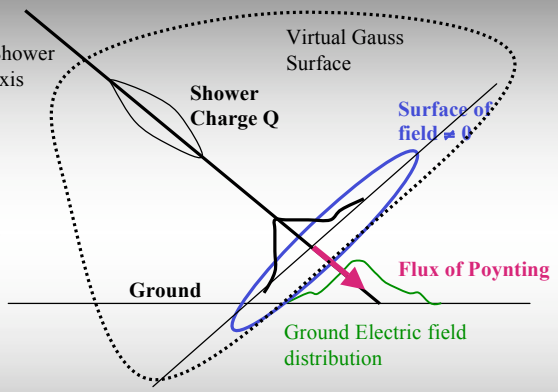
Tentative of energy estimation (1)

(via the global features of the EAS)

In the shower frame:
$E(d) = E_0.\exp(-d/d_0)$

γ: geomagnetic angle with the shower



GAUSS FLUX (charge excess…) ??

$\Rightarrow E_{Primary} \sim Q / e = \int E(d) \cdot dS = E_0 \cdot d_0^2$??

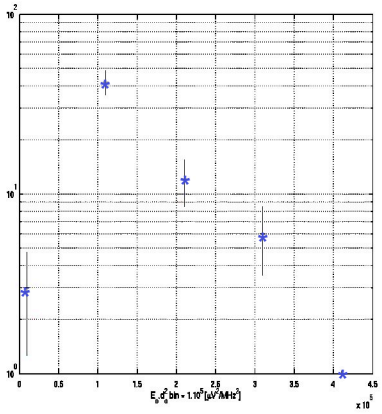
RADIATED ENERGY (geosynchrotron,…Poynting) ??

$\Rightarrow E_{primary} \sim \int P \cdot dS = E_0^2 \cdot d_0^2 / \sin^2(\gamma)$??

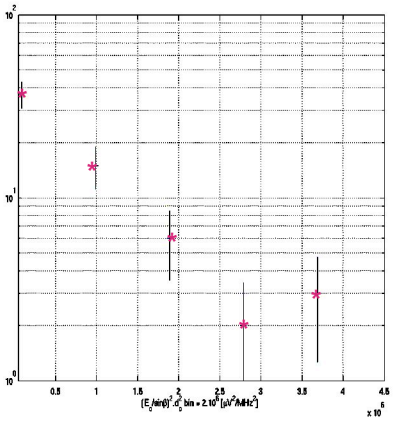
Tentative of energy estimation (2)

(very preliminary)

$E_0 \cdot d_0^2$ spectrum (a.u.)



$E_0^2 \cdot d_0^2 / \sin^2(\gamma)$ spectrum (a.u.)



Need more statistics

Signal simulation @ 10^{20} eV

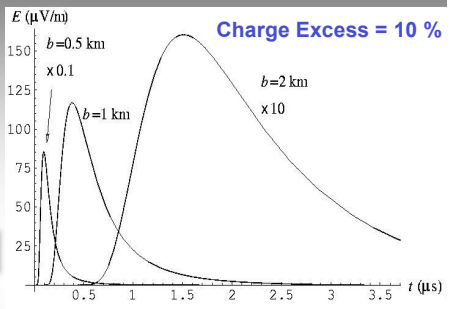
Vertical shower (charge excess only)

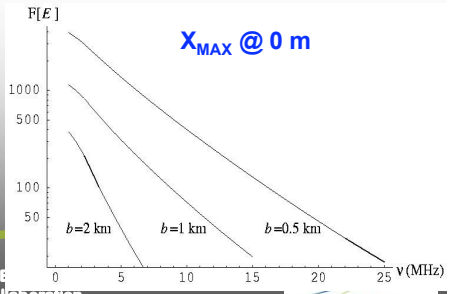
amplitude ⇒ energy
duration ⇒ impact parameter
shape ⇒ primary nature

SENSITIVE to X_{MAX}

For detection at large distance

Broad-band dipoles





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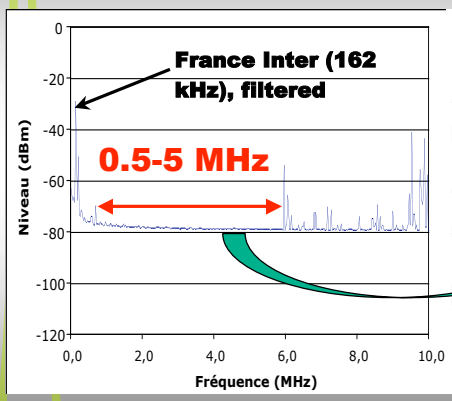
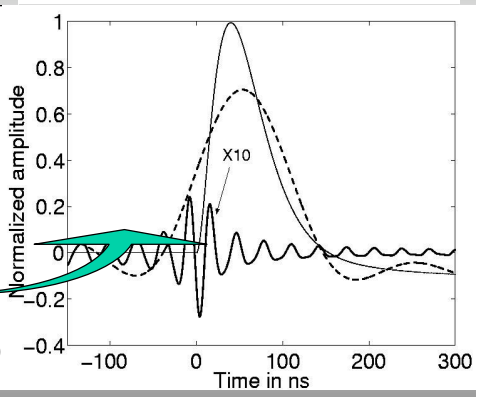
Constraint on the signal shape at low frequencies

Enlarge Frequency Band: from filtered Log-Periodic(24-82 MHz) ⇒ Broad Band Dipoles (0.2-100 MHz)

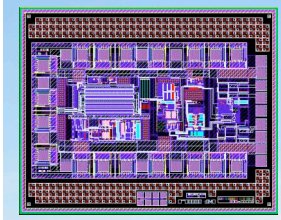




Required @ Nançay for 10^{17} ⇒ 10^{18} eV and also for PAO tests @ 10^{20} eV

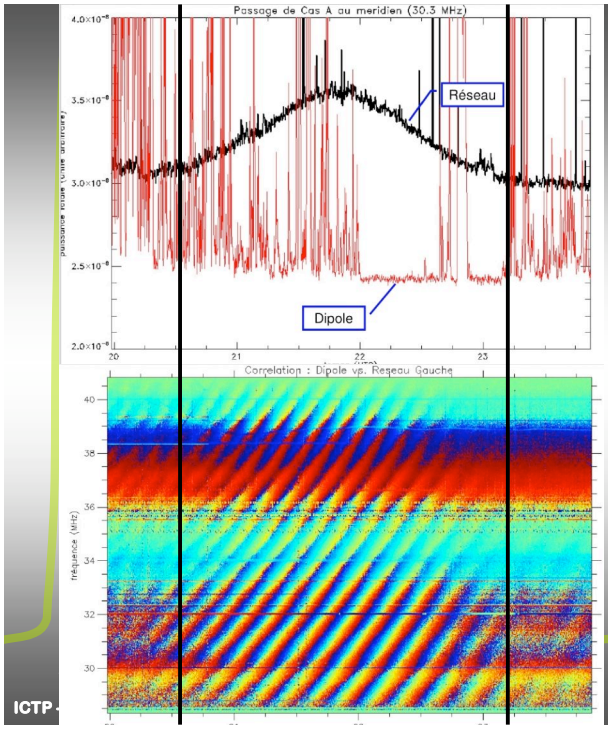
The CODALEMA short active dipole (1)

A dedicated LNA(ASIC)



Constant directivity

+ ADC MATACQ (12 bits, up to 1 GS/s, 2500 Samples)
+ Full Bandwidth (0-250 MHz)



The CODALEMA Short active Dipole (2)

Good astronomical performances on a wide band (pointed out as a real enhancement by astronomers)

(Interférometry Dipole-DAM on Casiopea A)

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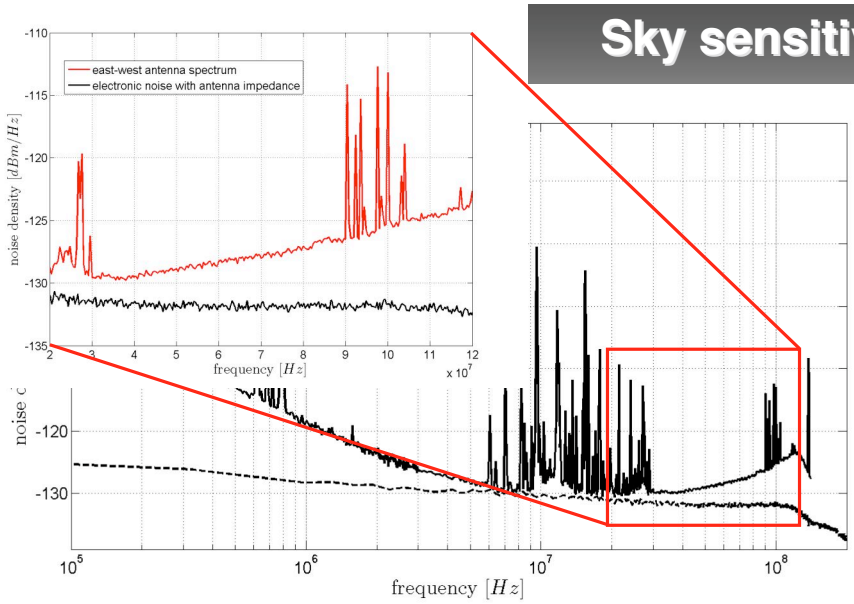
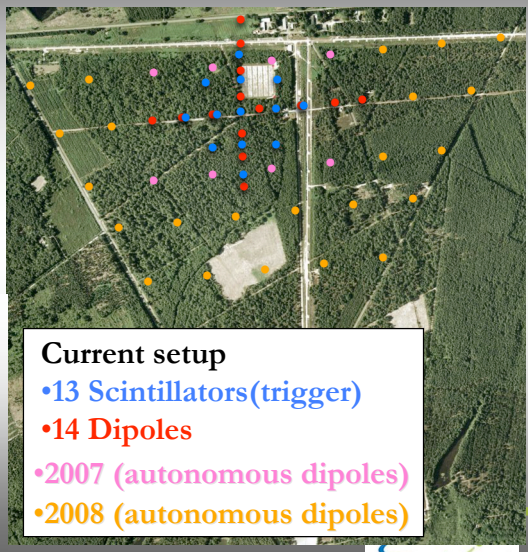
Sky sensitivity



Broadband dipoles: schedule @ Nançay (2006-2008)

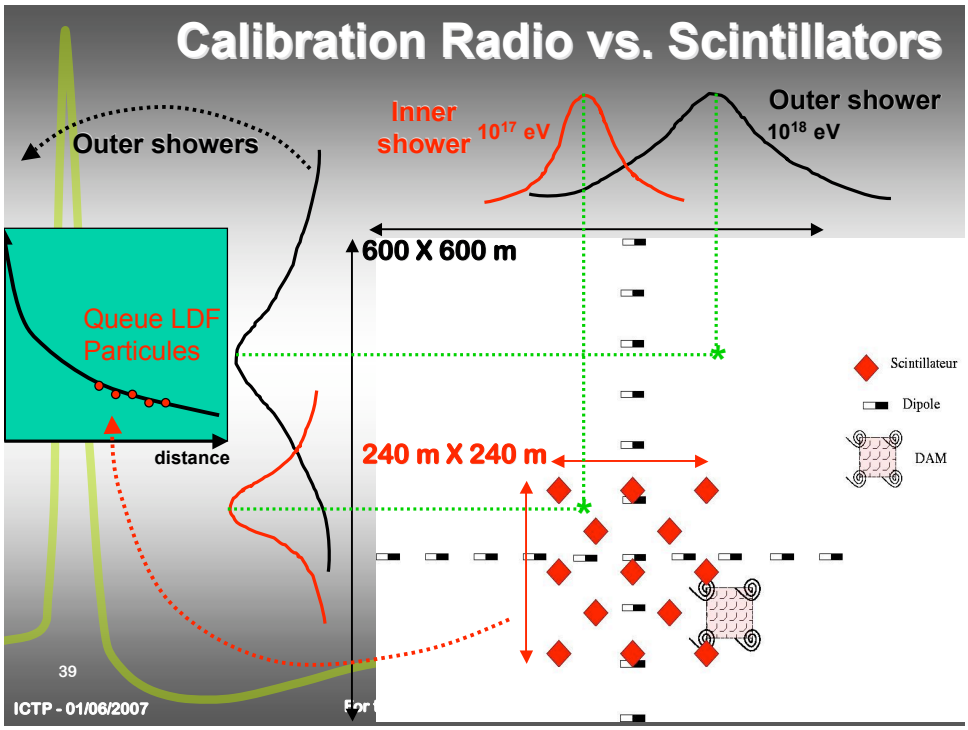
Evt by evt energy calibration < 10^{18} eV before end of 2008

Setup of a 1 km² engineering array for a future giant radio-detector



Current setup
- 13 Scintillators (trigger)
- 14 Dipoles
- 2007 (autonomous dipoles)
- 2008 (autonomous dipoles)

Autonomous dipoles:
- Trigger,
- Data taking (ADC MATACQ 12 bits, Full Bandwidth 0-250 MHz)
- Time tagging
- Data transmission,
- Power supply


Calibration Radio vs. Scintillators
Outer showers
Inner shower 10^17 eV
Outer shower 10^18 eV
600 X 600 m
Queue LDF Particules
distance
240 m X 240 m
Scintillateur
Dipole
DAM
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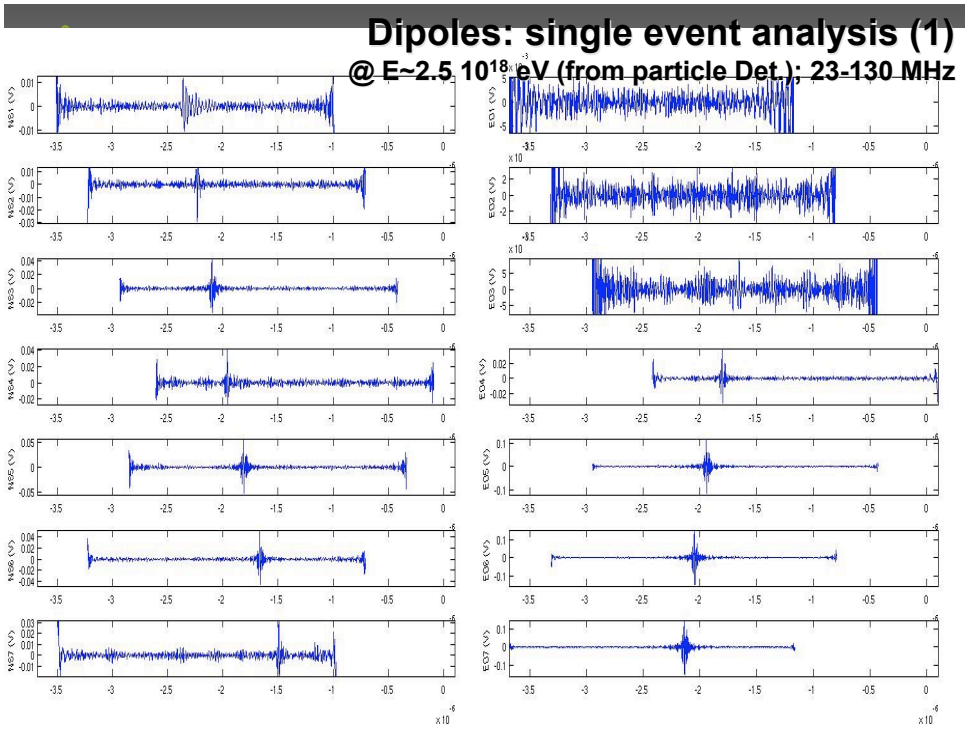
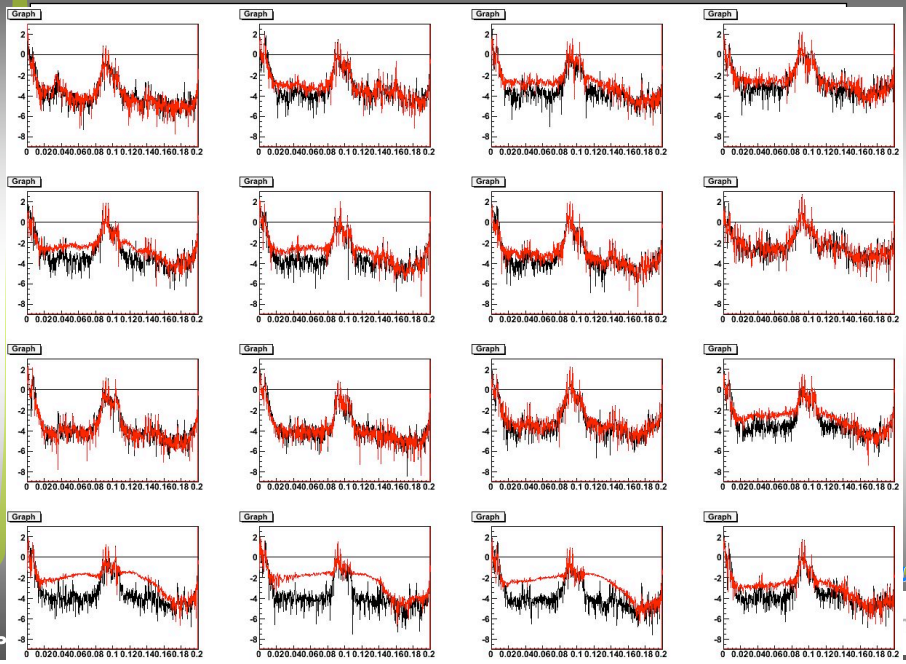
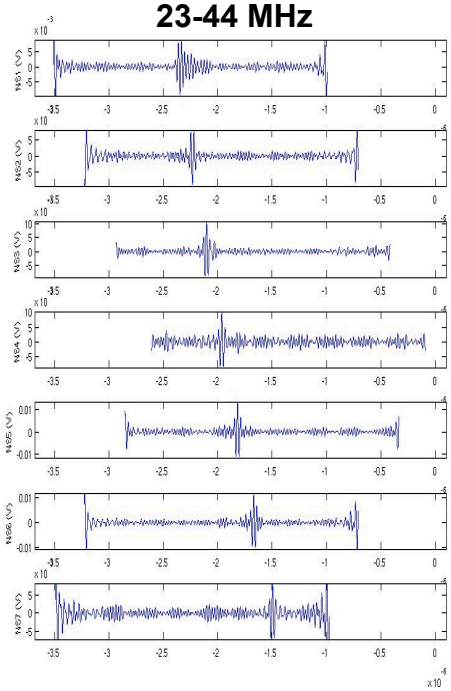

Dipoles: single event analysis (1)
@ E~2.5 10^18 eV (from particle Det.); 23-130 MHz

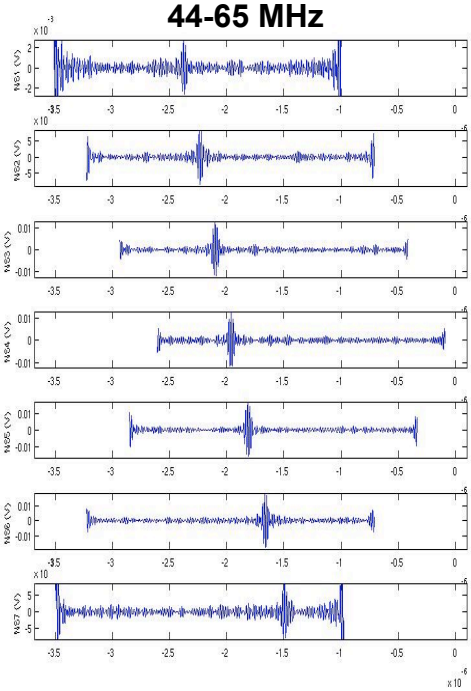
Single Event Analysis (2)

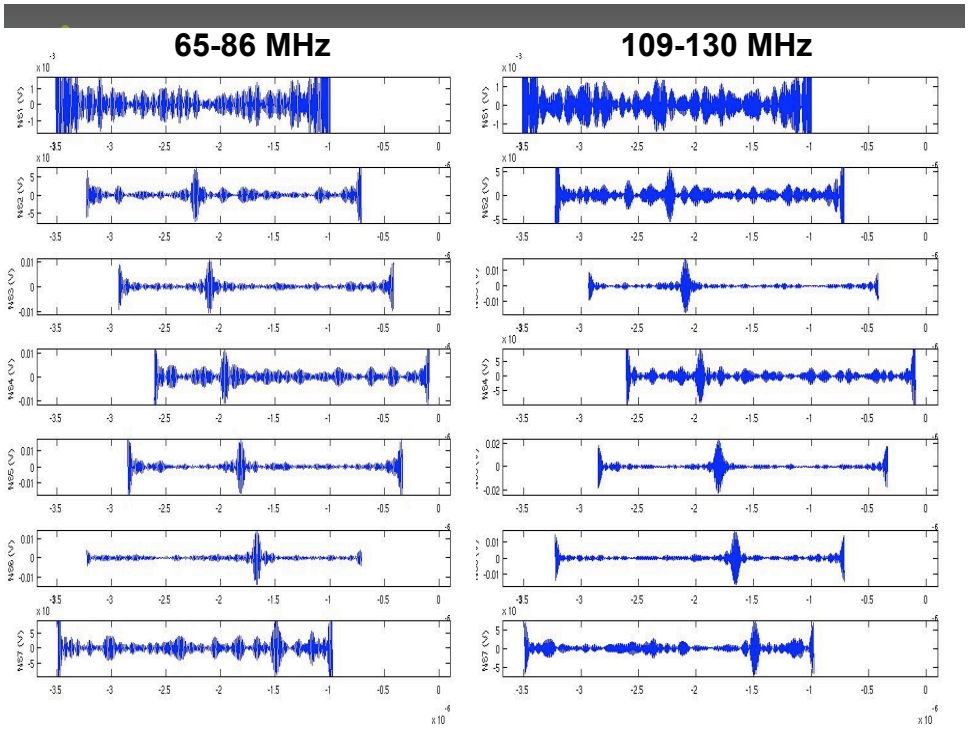


23-44 MHz

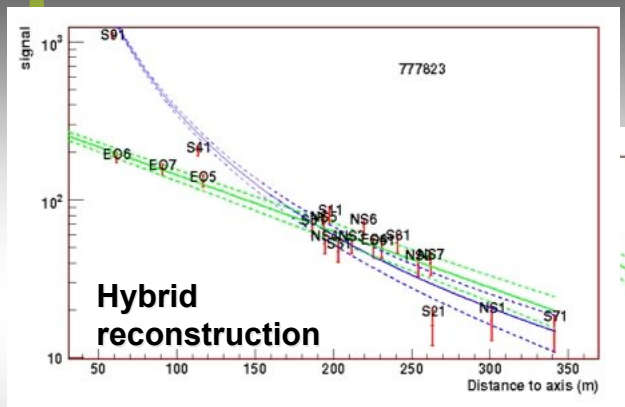


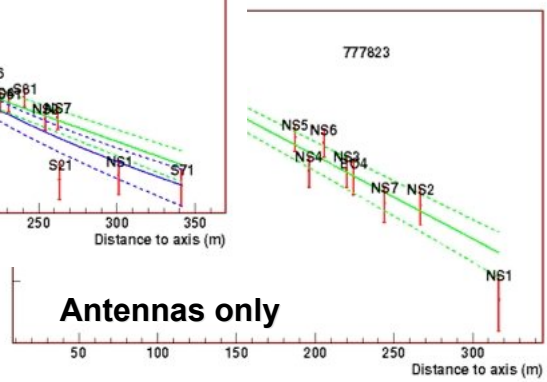
44-65 MHz





Single Event Analysis (3): LDF / field profiles





RAuger: Radio @ Auger

To mimic the problematics of a large array of autonomous antennas

To deliver useful information on radio signal @ 10^{18} eV

Auger is the only place in the world to do that

Instrumental objectives

- **Tests of single detector performances**

  Antennas, Front End electronics , noise level, trigger rate, trigger level, dead time, time tagging

- **Tests of autonomy**

  Power, data transmission

- **Tests of array operation**

  Coincidences between antennas, multi-trigger building, Radio Frequency Interference studies (local noise sources, noise transient counting rate)

Radio R&D objectives

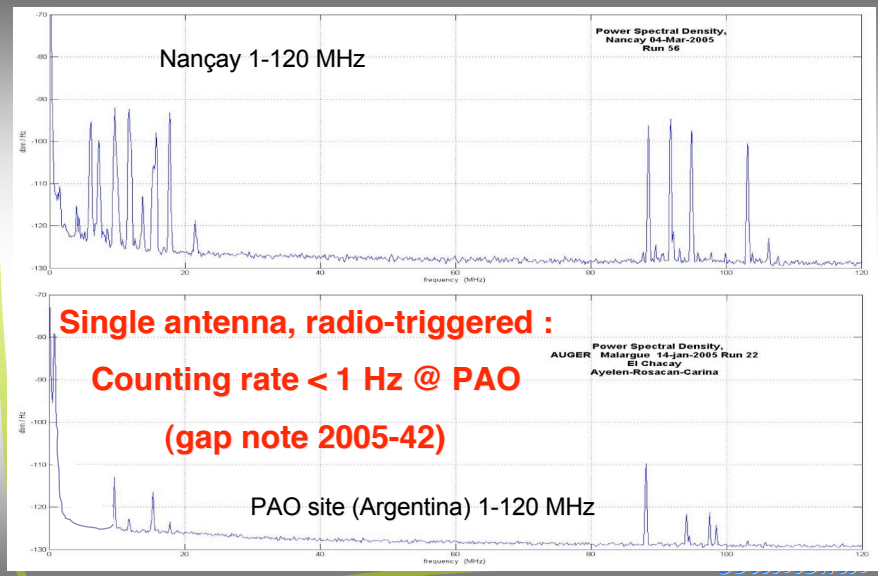
- Full band waveform @ > 10^{18} eV
  - Short & long distance observation, pulse shape recovery
- Detection in coincidence with Auger
  - Shower direction and datation with radio signals, shower parameters from Auger
- Electric Field Distribution = f (distance to core)
  - EF strength on ground at Auger site
- To give simulation and extension inputs
  - Array pitch determination, link with CODALEMA and LOPES @ 10^{17} eV

Means

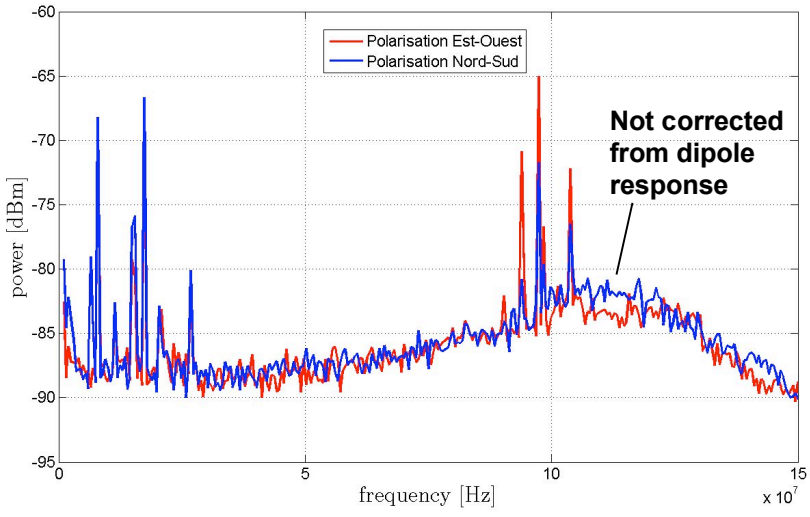
3 autonomous, self triggered antennas

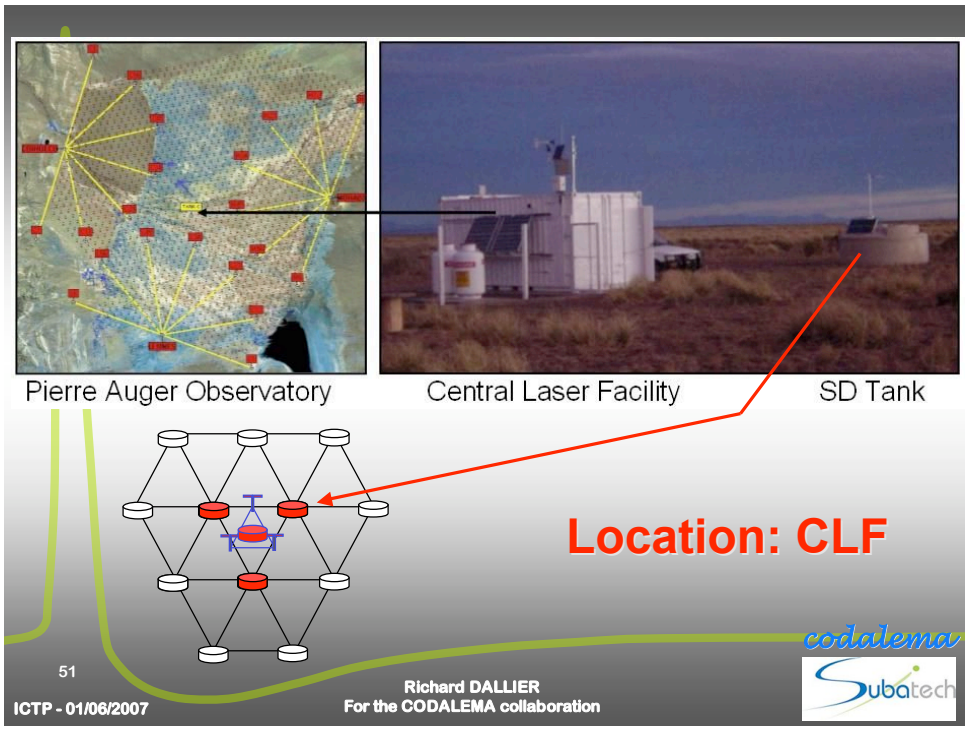
- Independent trigger
- Can be tested @ home
- Placed and displaced easily
- Triangulation, statistics increase
- No interference with Auger completion

Sky background @ PAO (2005)



With the active dipole




Pierre Auger Observatory
Central Laser Facility
SD Tank
Location: CLF
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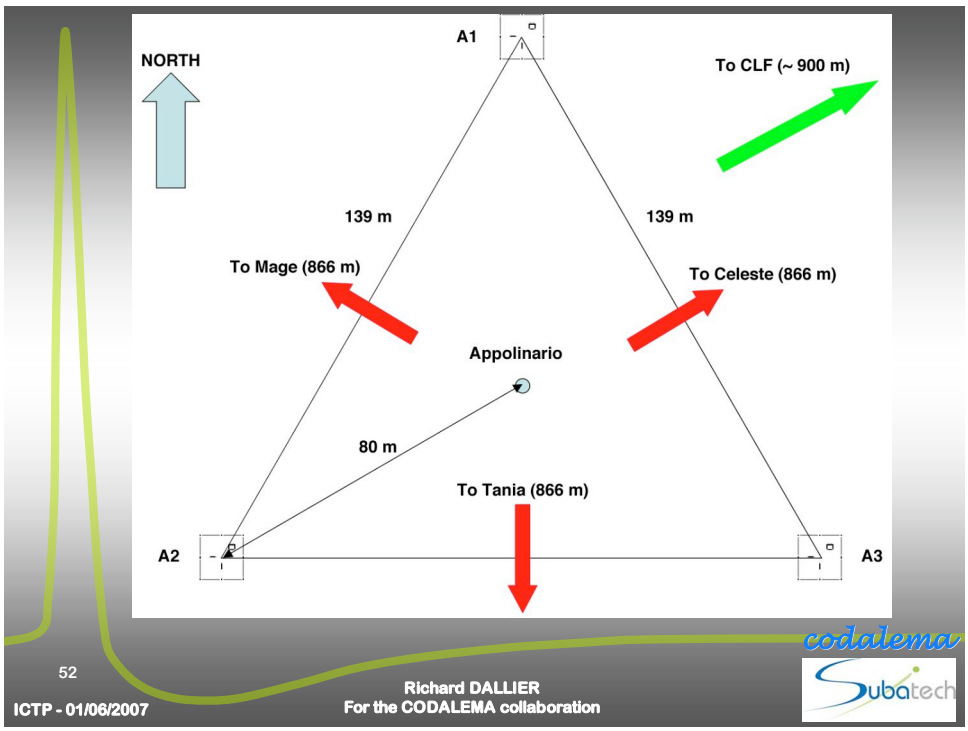
NORTH
A1
To CLF (~ 900 m)
139 m
139 m
To Mage (866 m)
To Celeste (866 m)
Appolinario
80 m
To Tania (866 m)
A2
A3
52
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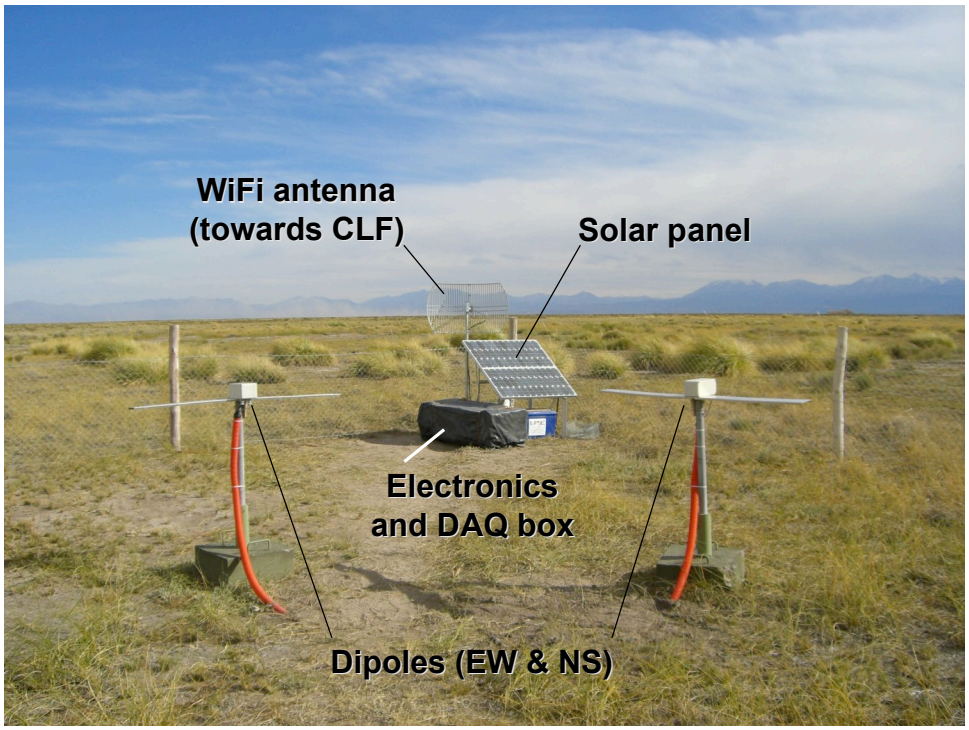
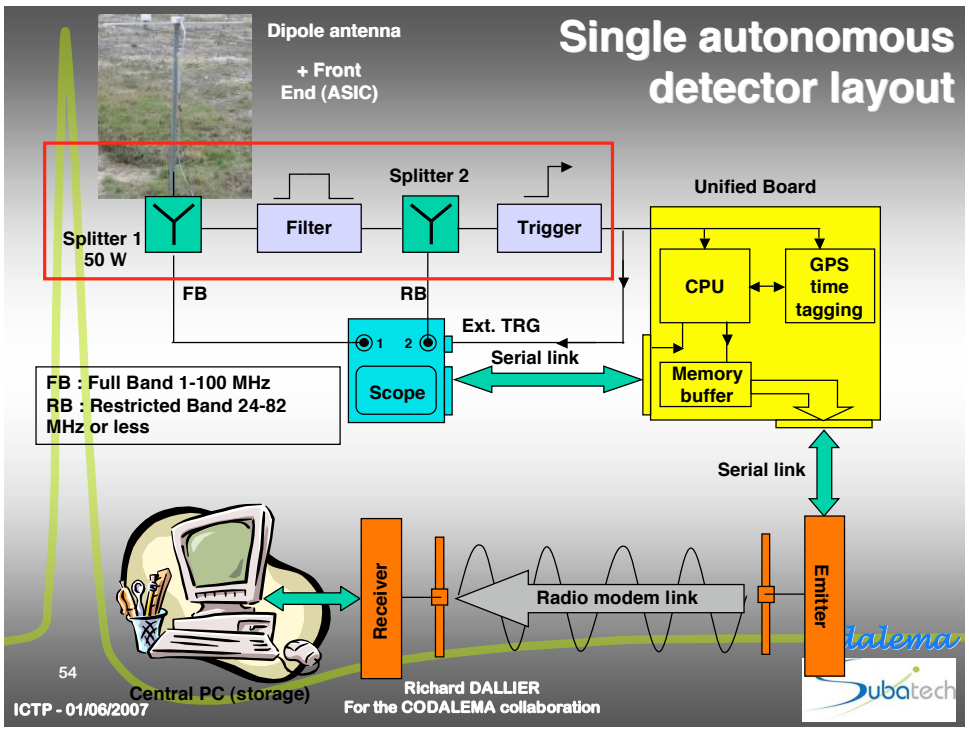

WiFi antenna
(towards CLF)
Solar panel
Electronics
and DAQ box
Dipoles (EW & NS)


Single autonomous
detector layout
Dipole antenna
+ Front
End (ASIC)
Splitter 1
50 W
Filter
Splitter 2
Trigger
Unified Board
CPU
GPS
time
tagging
FB
RB
Ext. TRG
Serial link
Scope
Memory
buffer
FB : Full Band 1-100 MHz
RB : Restricted Band 24-82
MHz or less
Serial link
Receiver
Radio modem link
Emitter
Central PC (storage)
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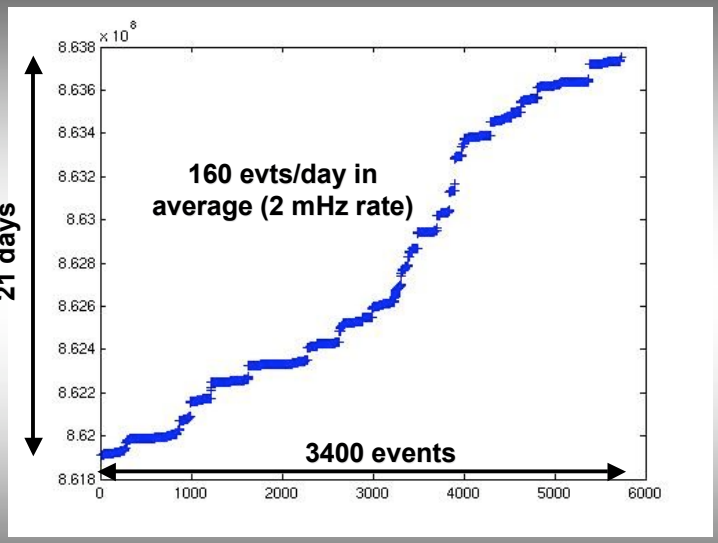
RAuger status

- Installed in December 2006
- Problems of noise and electromagnetic compatibility (shielding) ⇒ didn't work perfectly but greatly improved our knowledge on autonomous radio detection
- Problems fixed up in May 2007 ⇒ takes data, until end of the year

Trigger rate on 1 station



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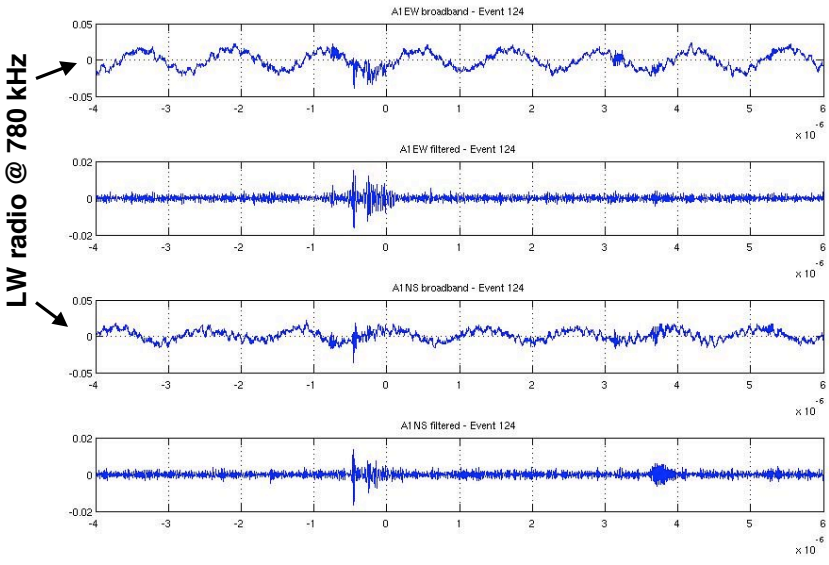
Zoology of events: 1- Fast "electronics" transients



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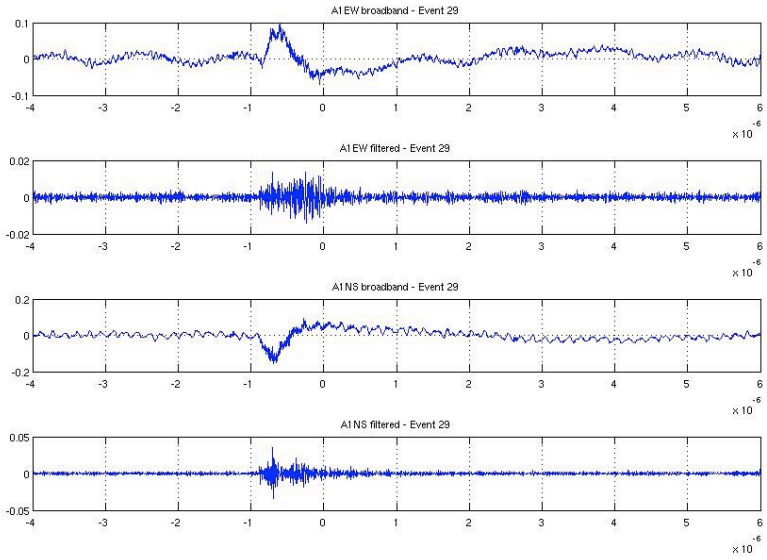
2- Slower “natural” - at least external - transients

Inverted polarity



3- (quite certainly) Far storm events

Lightning precursor ?