Radio detection of extensive air showers:

The **CODALEMA** experience

COsmic ray Detection Array with Logarithmic ElectroMagnetic Antennas

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

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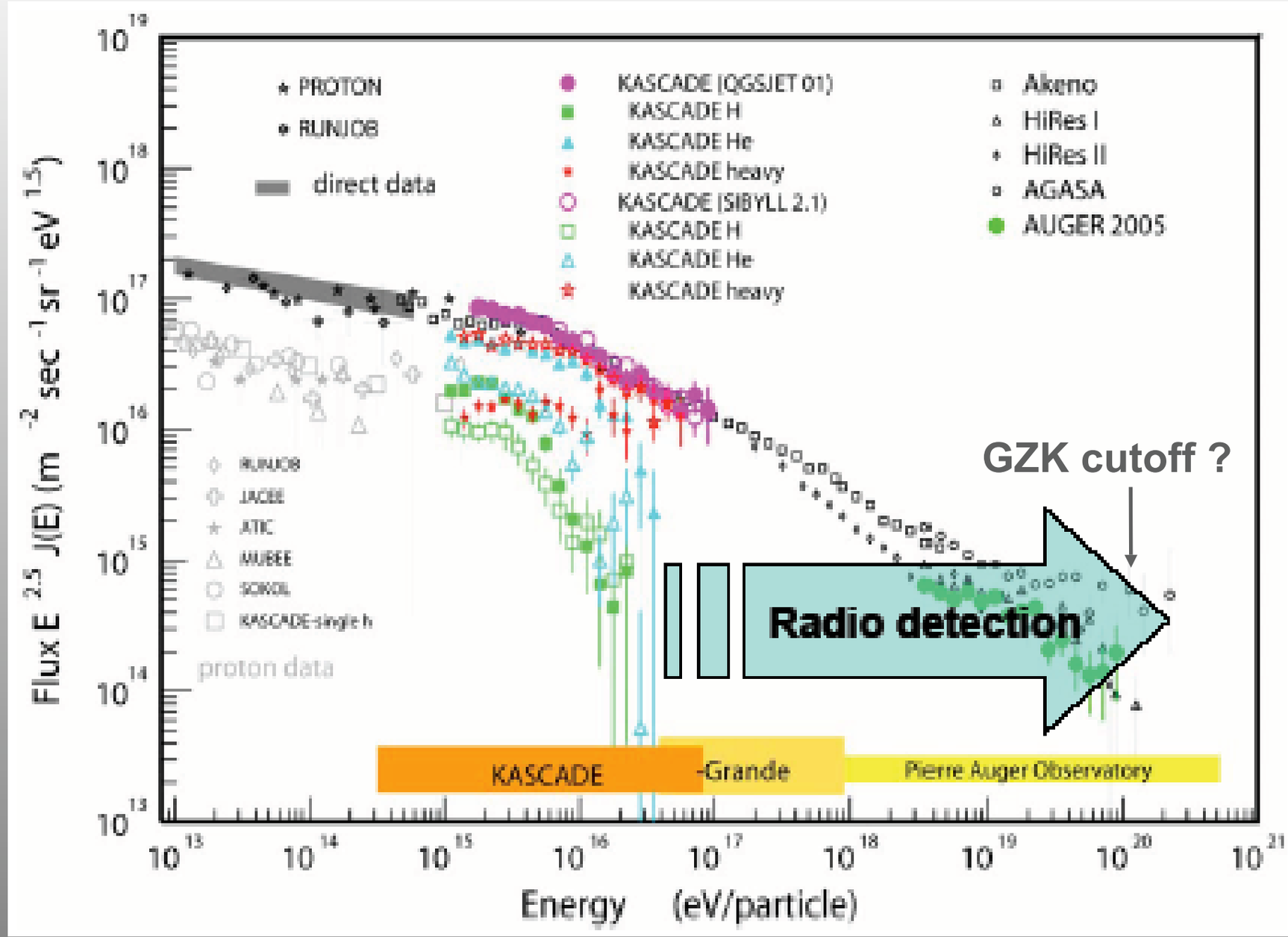
Problematic of ORIGINE & NATURE of the cosmic rays

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-

Origin of the electric field

Recombination of positrons in the atmosphere

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

+ Cerenkov emission (on axis)

Separation of charges due to the geomagnetic field

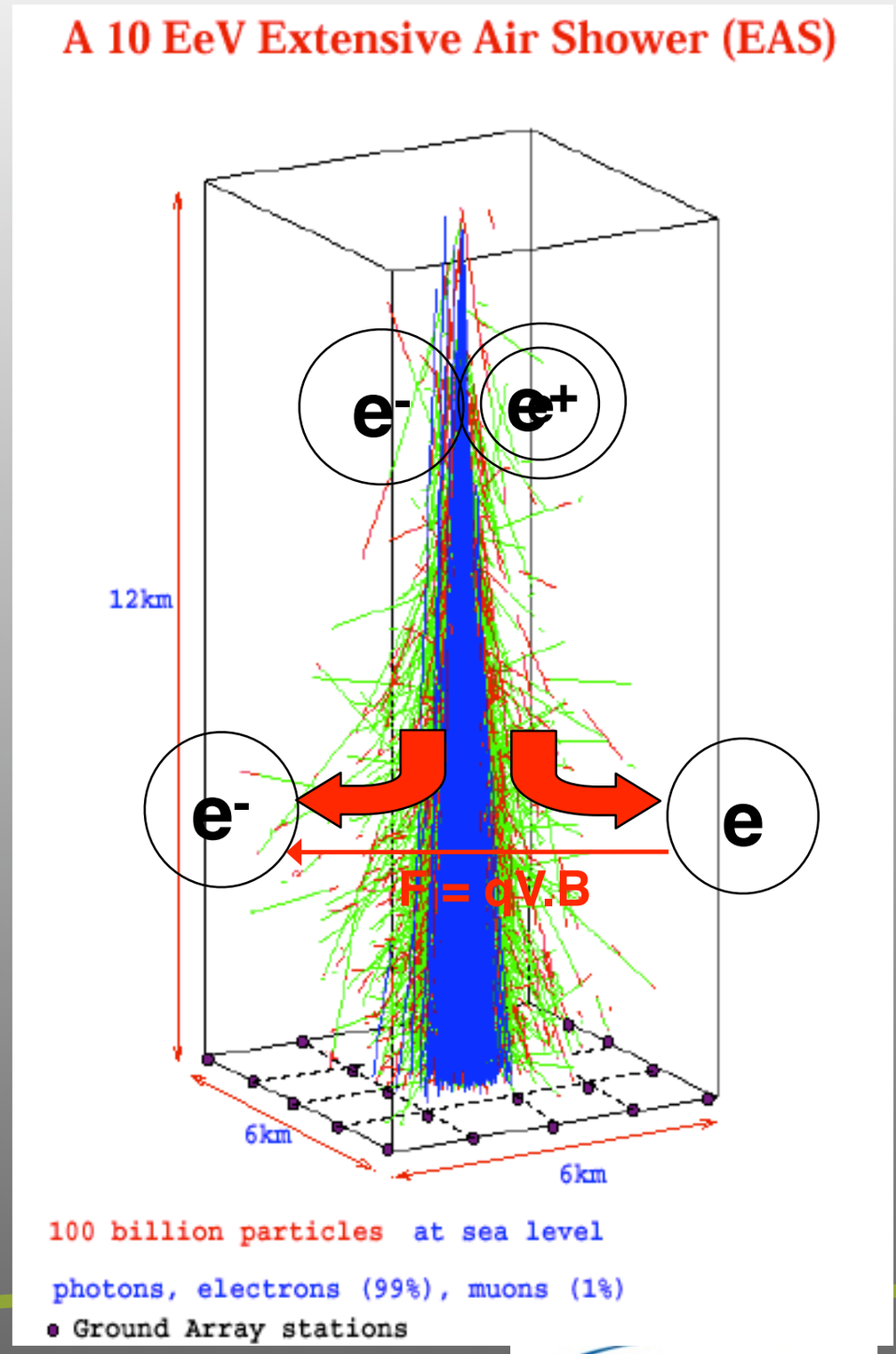
Dipolar emission

Creation of charges along the shower path

Dipolar current

Deflection of charges in the geomagnetic field

Synchrotron emission



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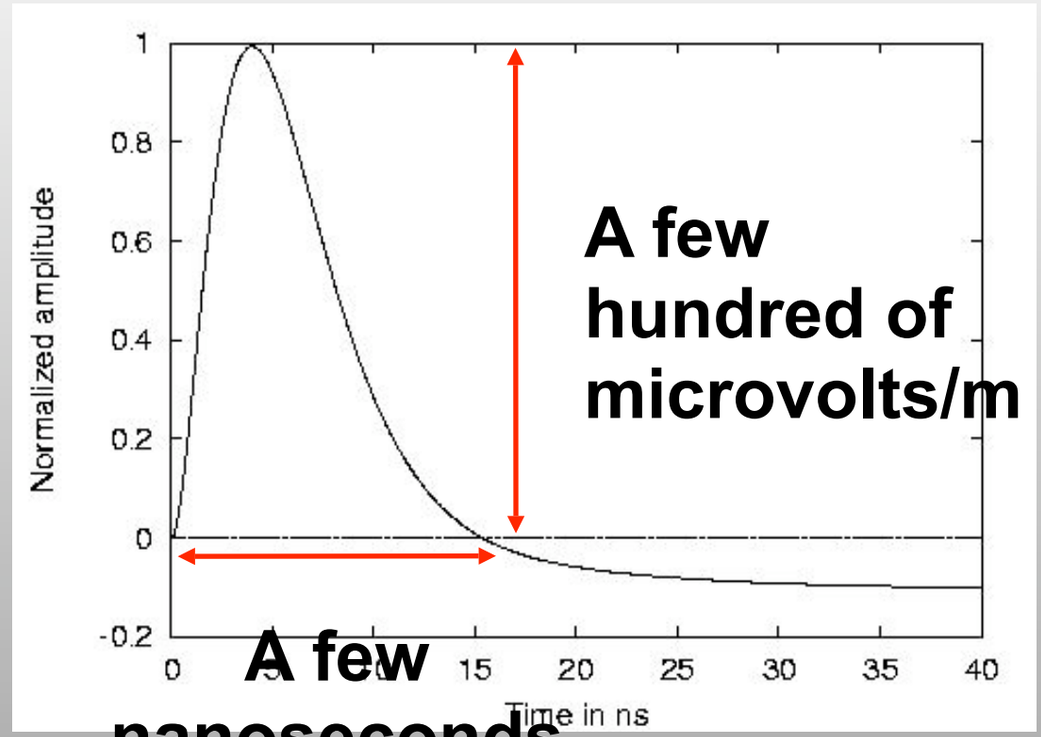
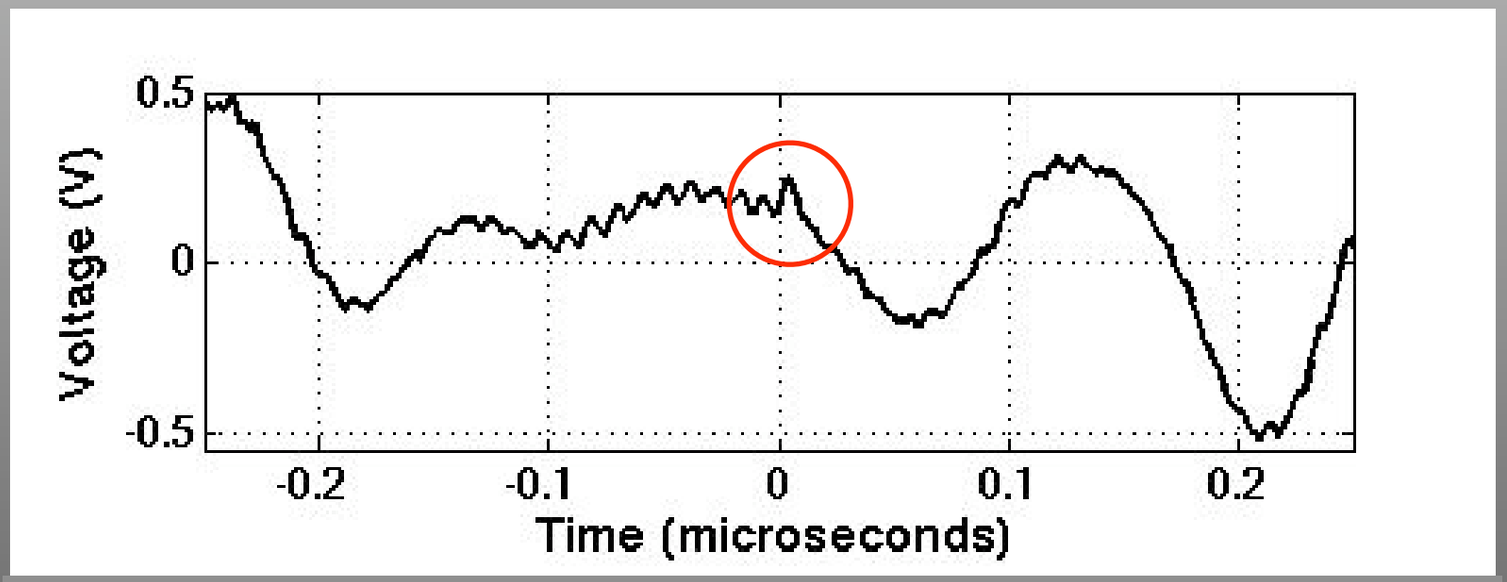
The signal to detect

- To get the shower direction
- To find the energy of the incident particle
- To know its nature





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

200
- **Primary particle energy : ∝ total charge ∝ electric field**

(amplitude of the signal)

- **Nature : longitudinal profile, X_{max}**

(shape of the signal)

To demonstrate

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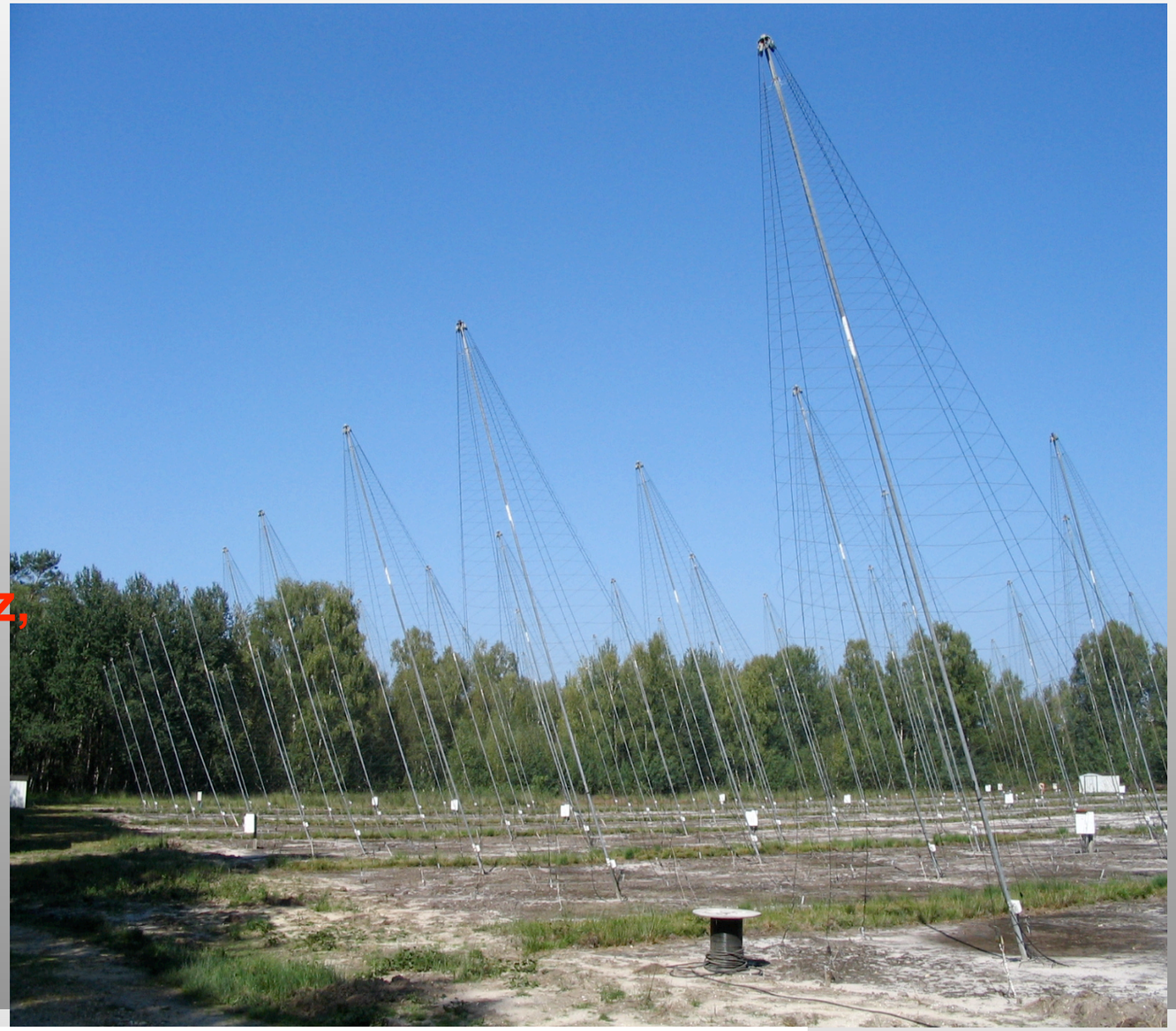
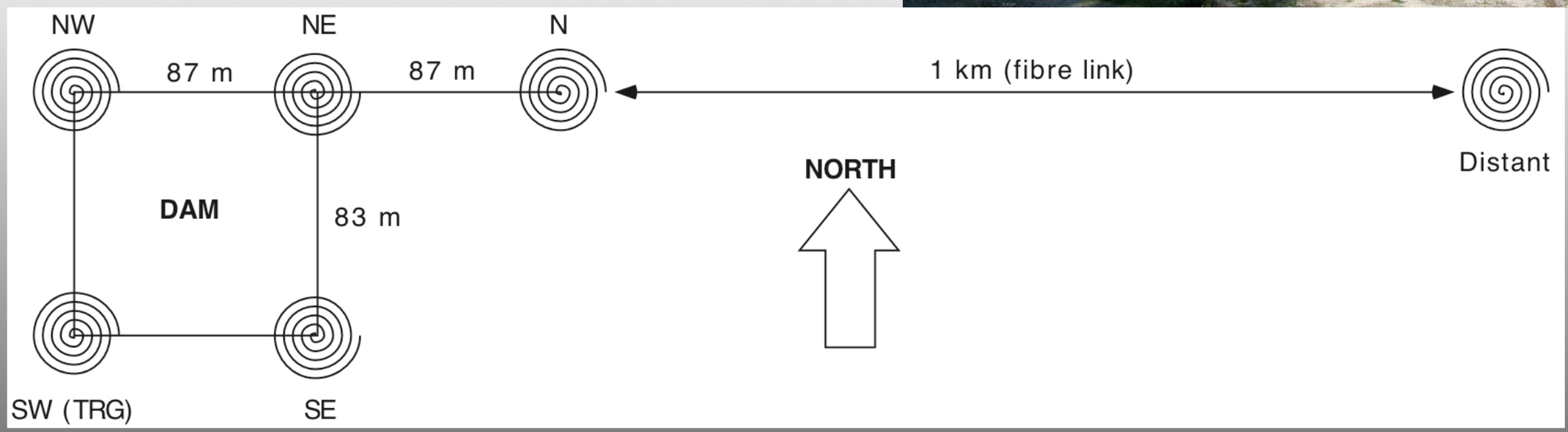
For the CODALEMA collaboration

Radio triggered system: 2003 – 2004

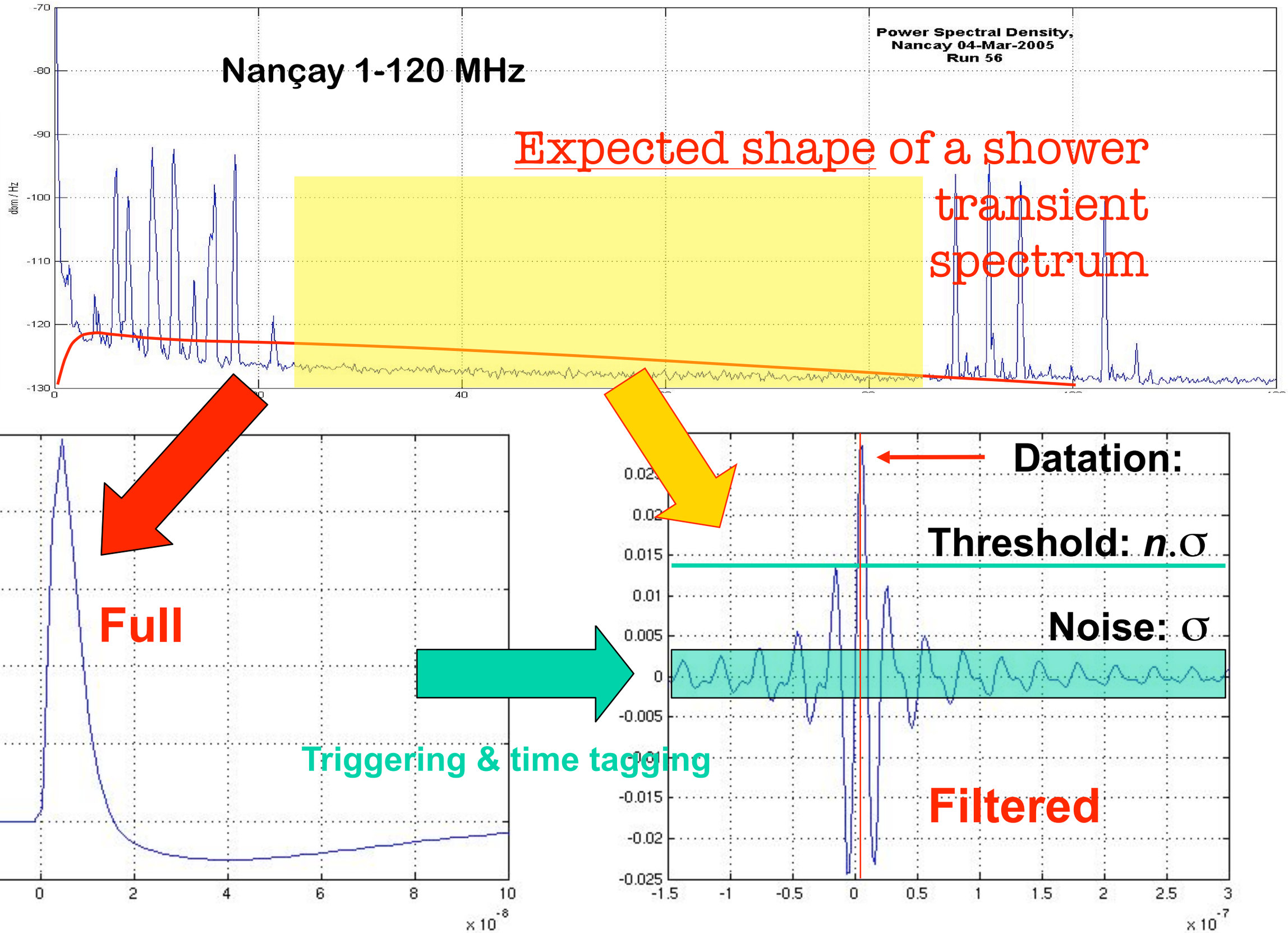
DAM: (Decametric Array) of the Radio Observatory of Nançay

- Spiral log-periodic ant., 1(10)-120 MHz (6dB), 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

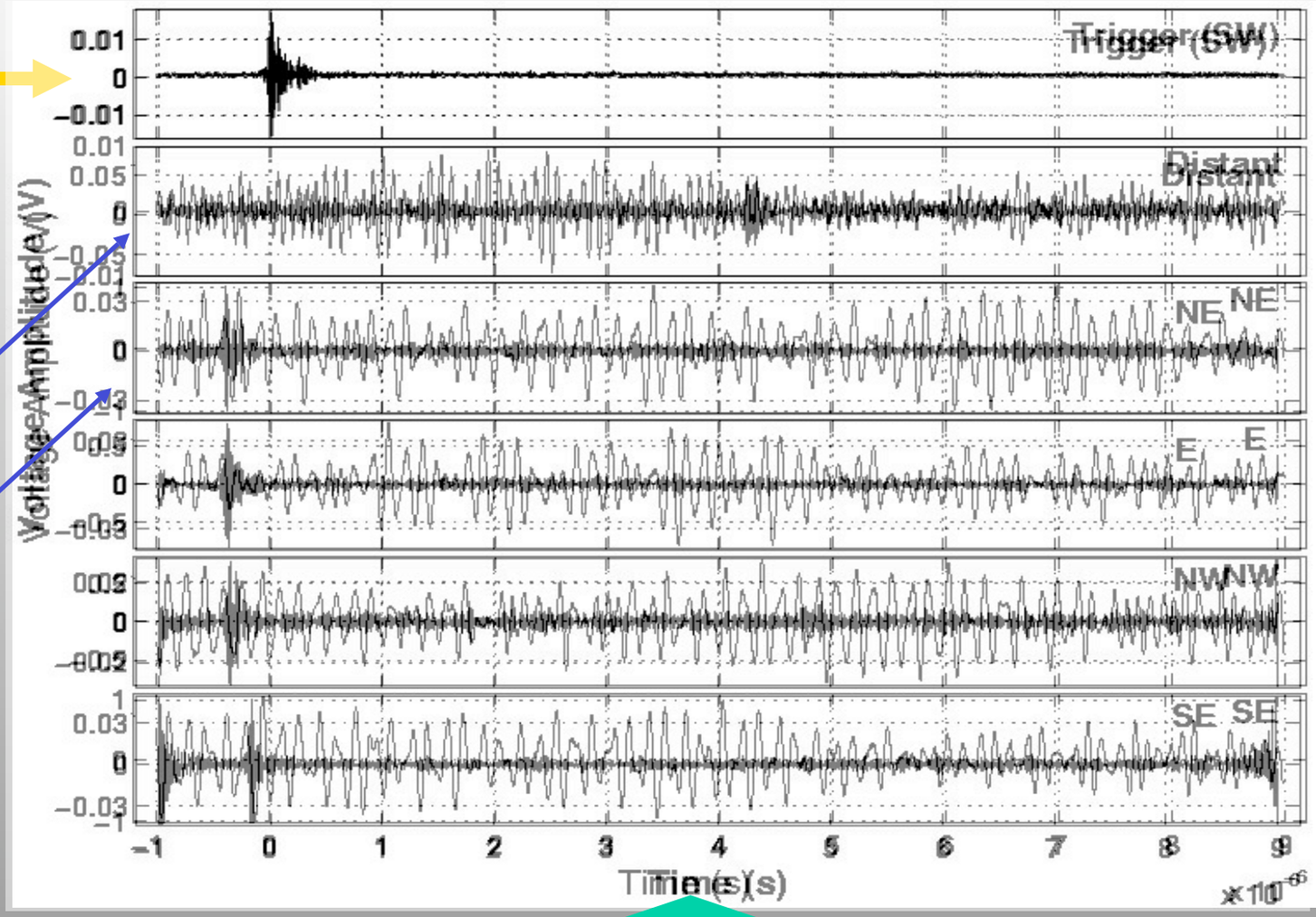


Transient recognition

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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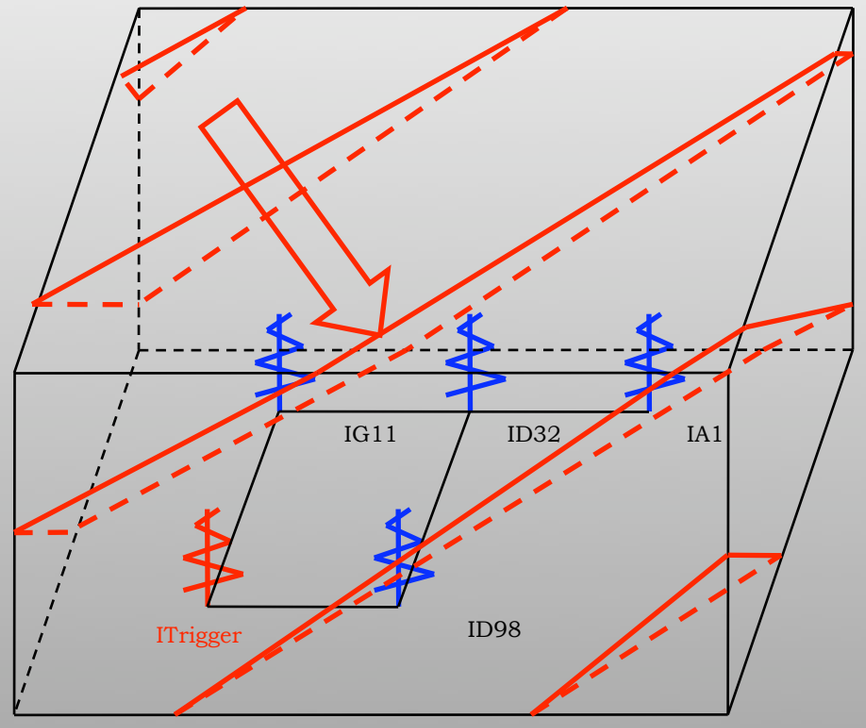
Triangulation



Principle of the triangulation

- **At least 3 tagged antennas**
- **Using the time difference between the peaks**
- **On a plane wavefront hypothesis**

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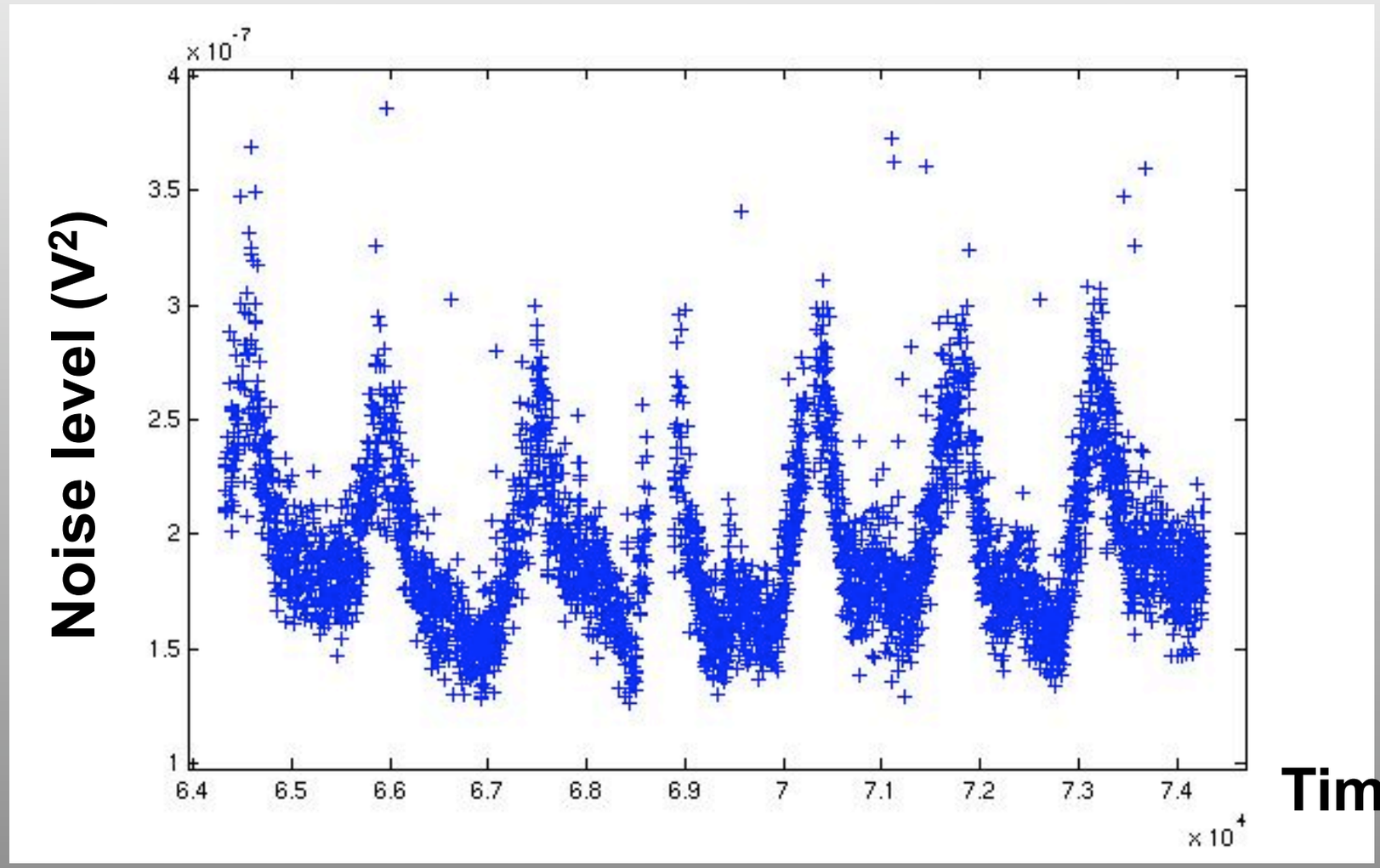
Triangulation performances (1)

(using Solar bursts)



- Correlated with day/night alternation (but not human activity)
- Ionospheric variations ?
- Typical feature

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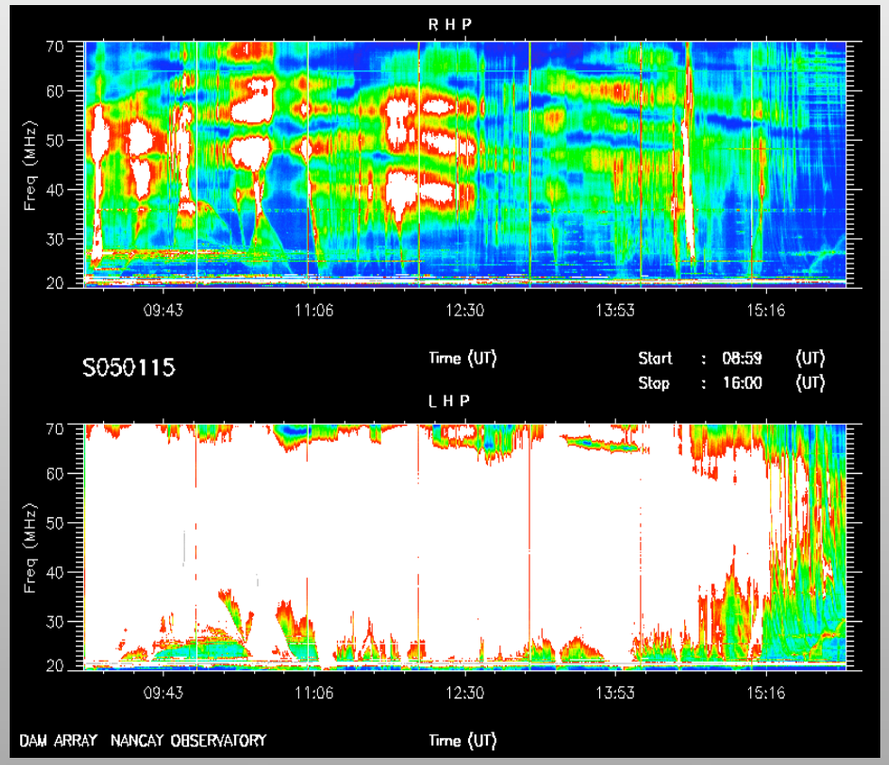
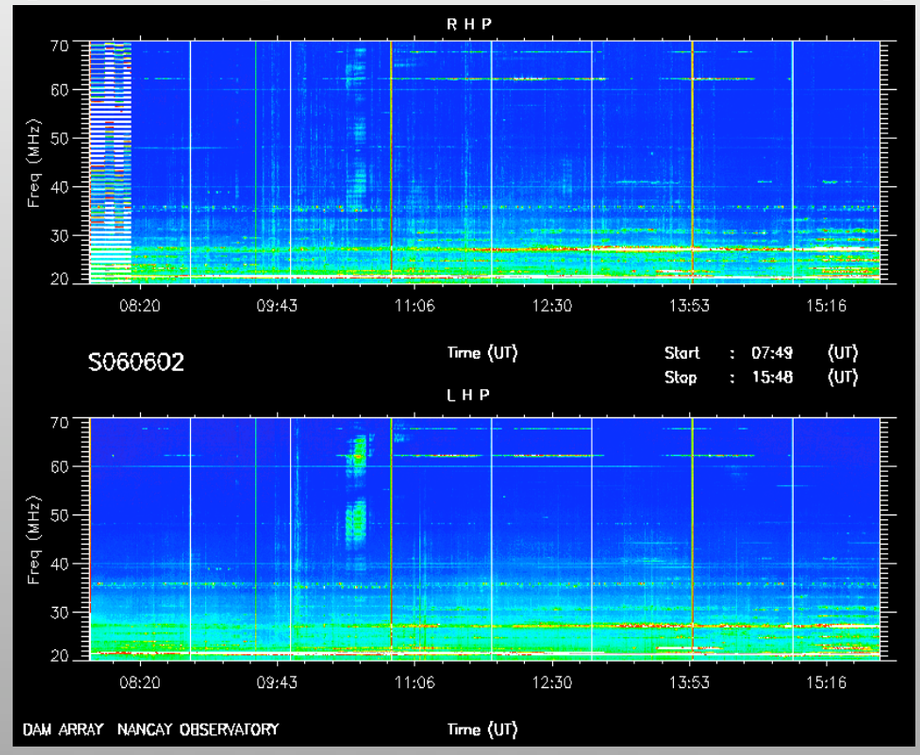
Triangulation performances (2)

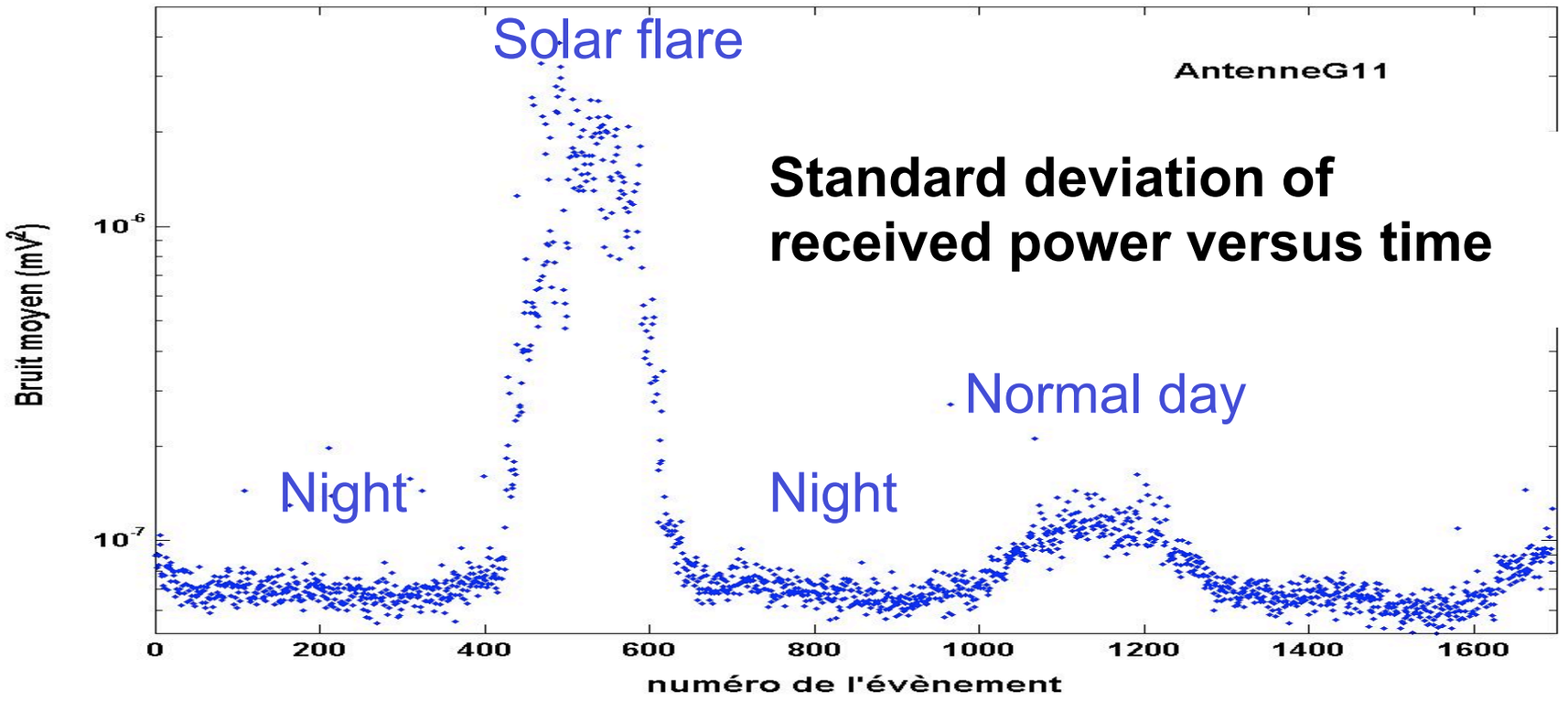
(using Solar bursts)

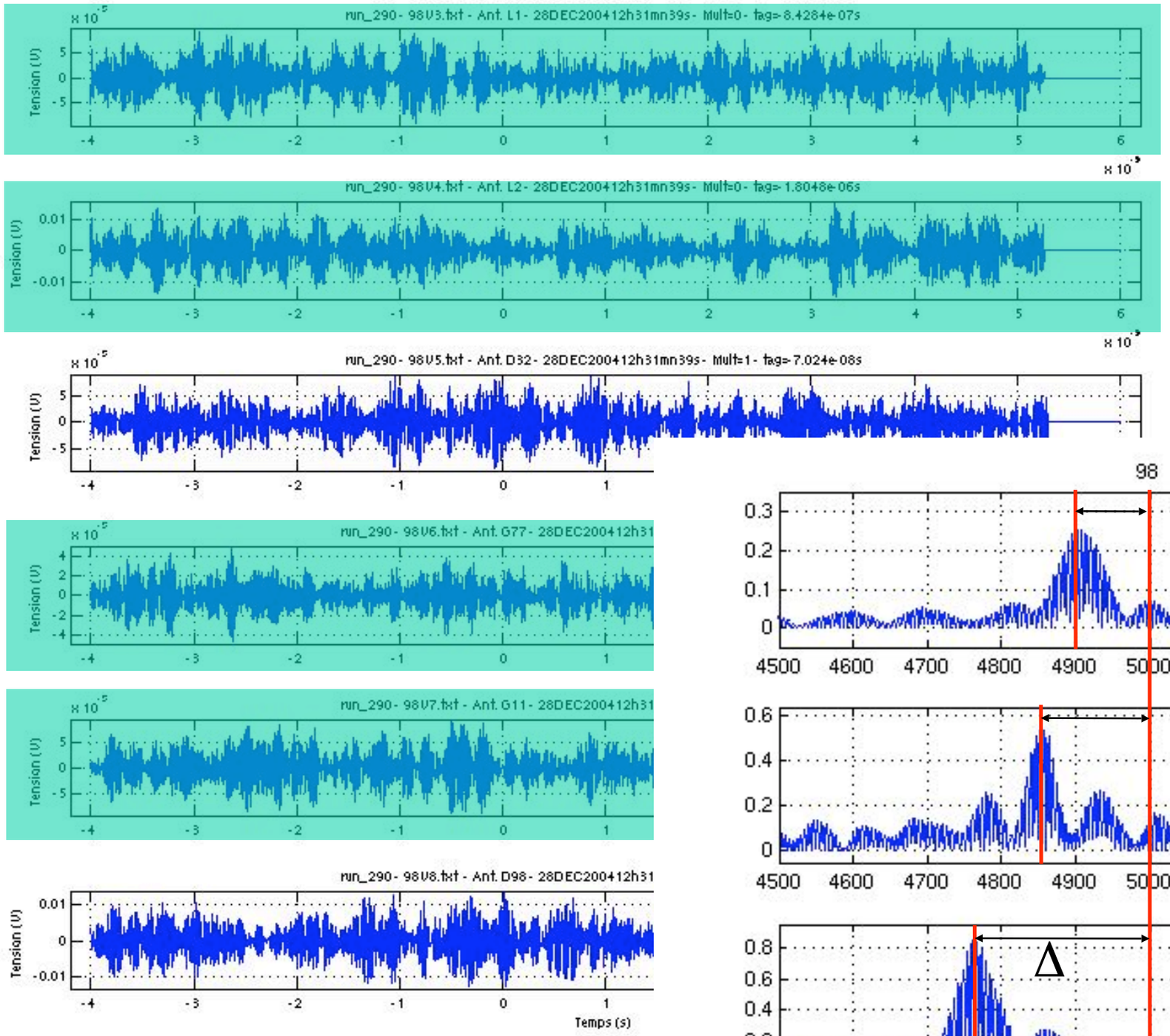
DAM sun survey
15/01/05
&
02/06/06

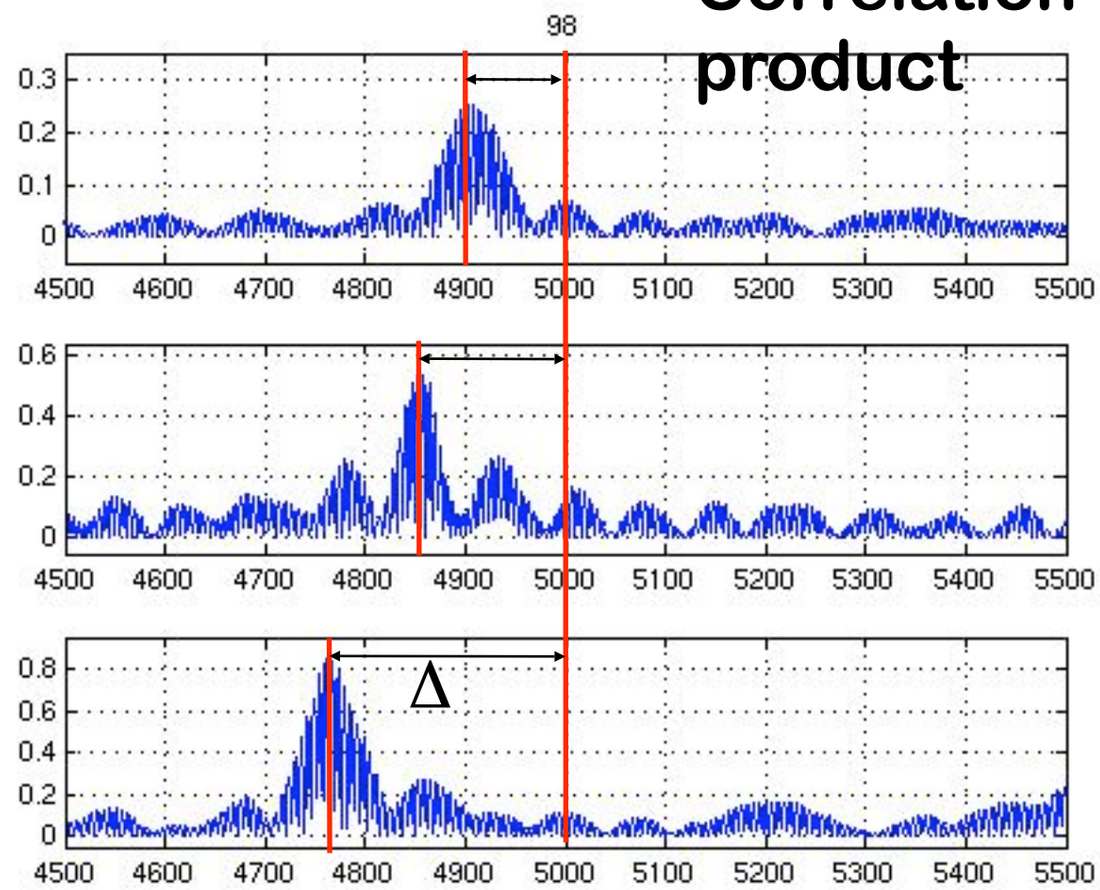




solar flare in active region AR10720 on 2005 Jan. 15







Correlation product

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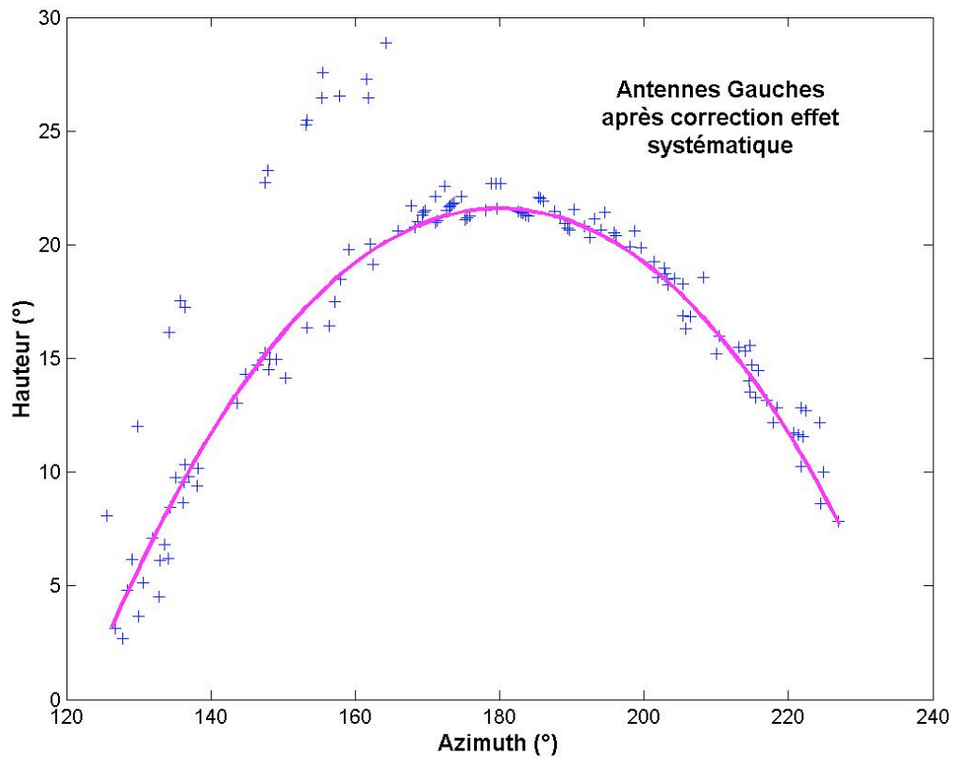
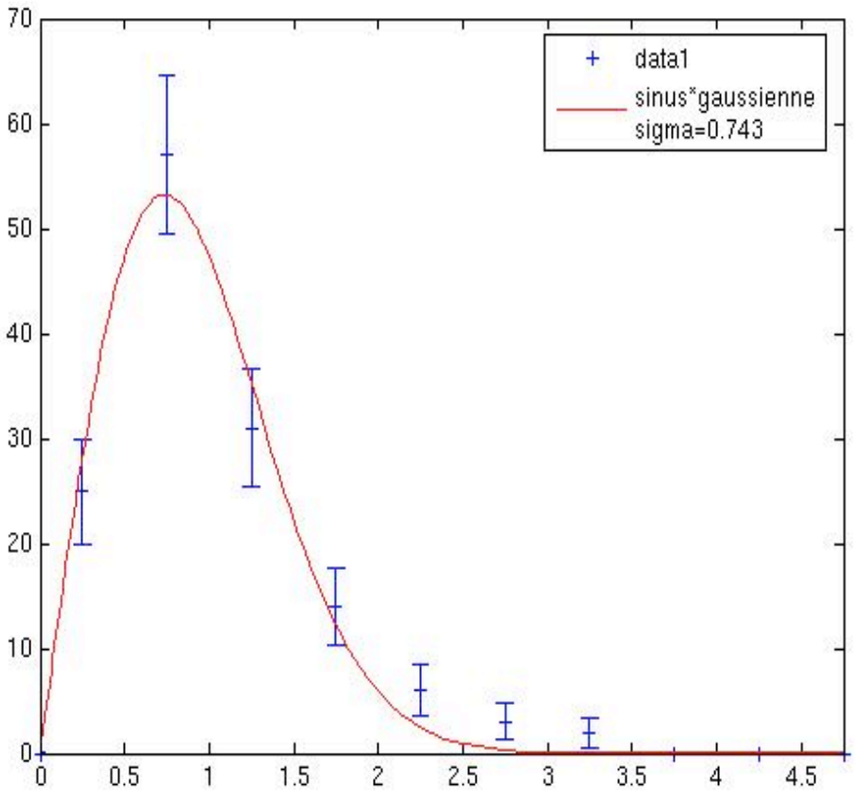
Triangulation performances (3)
(using Solar bursts)

Reconstructed directions versus sun ephemerids





Distribution of the residuals

Direction accuracy

σ = 0.74 °

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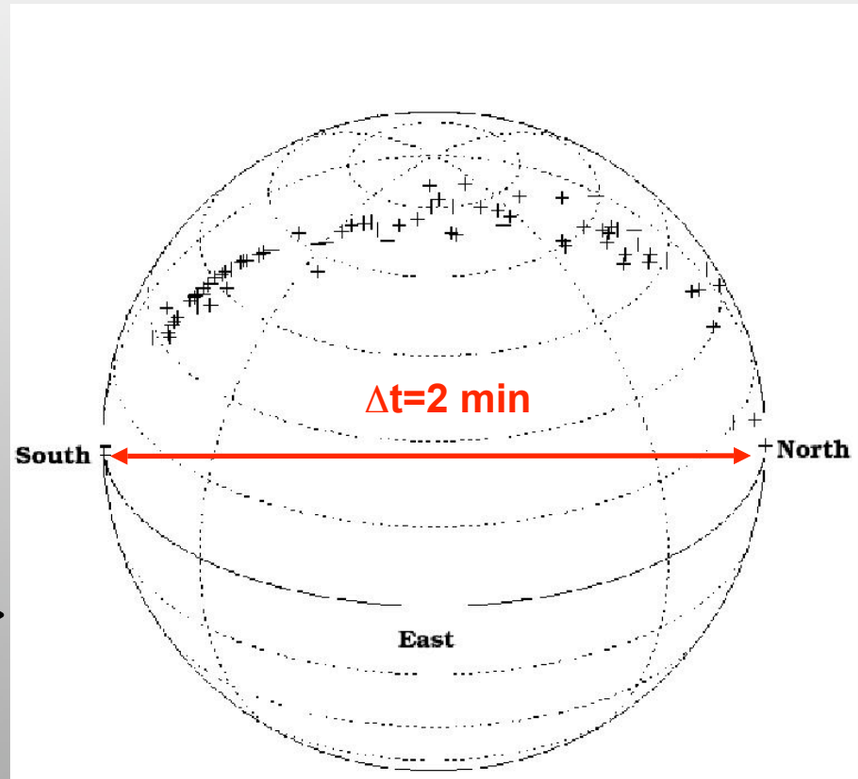
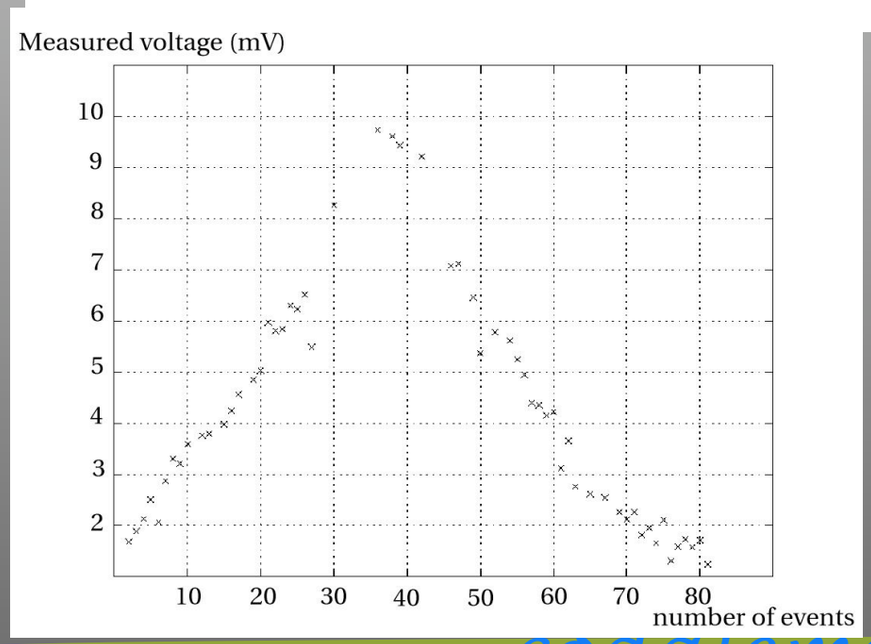
Triangulation performances (4)

Test on the trajectory of a flying object



Field sensitivity

Amplitude rises when distance between source and antenna decreases



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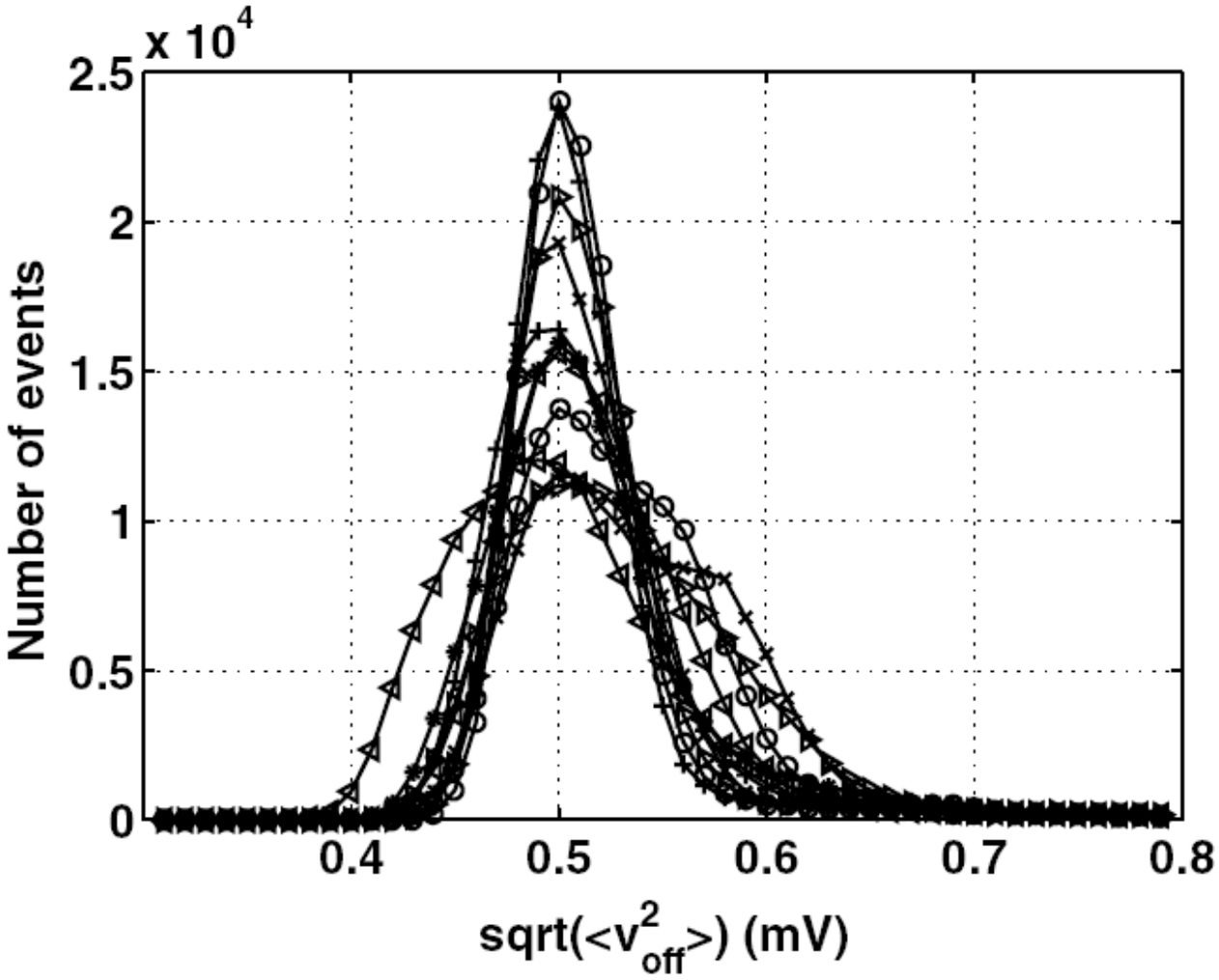
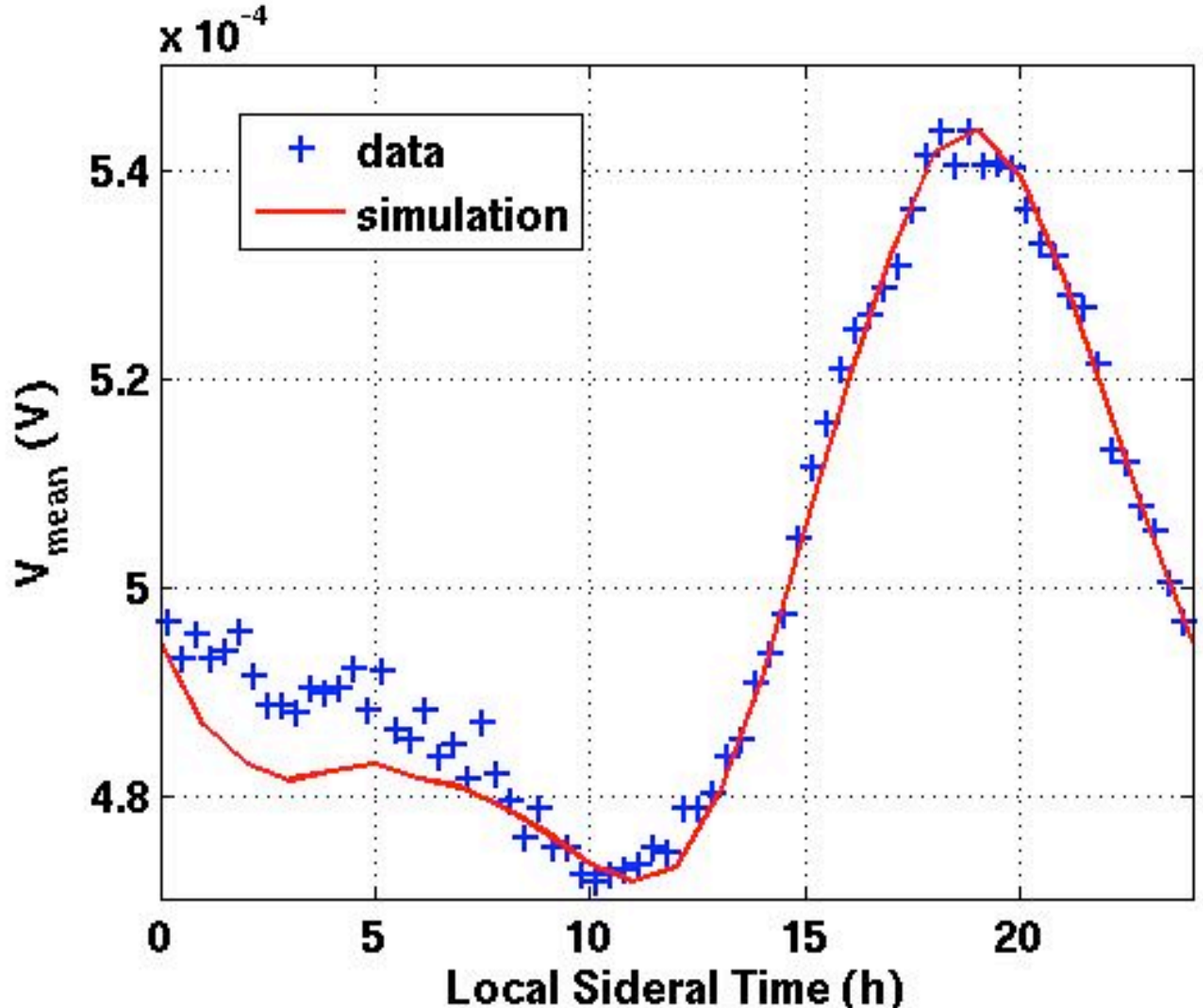
Signal sensitivity



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



Richard D
For the CODALEM

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(shape of the signal)

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For the CODALEMA collaboration

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

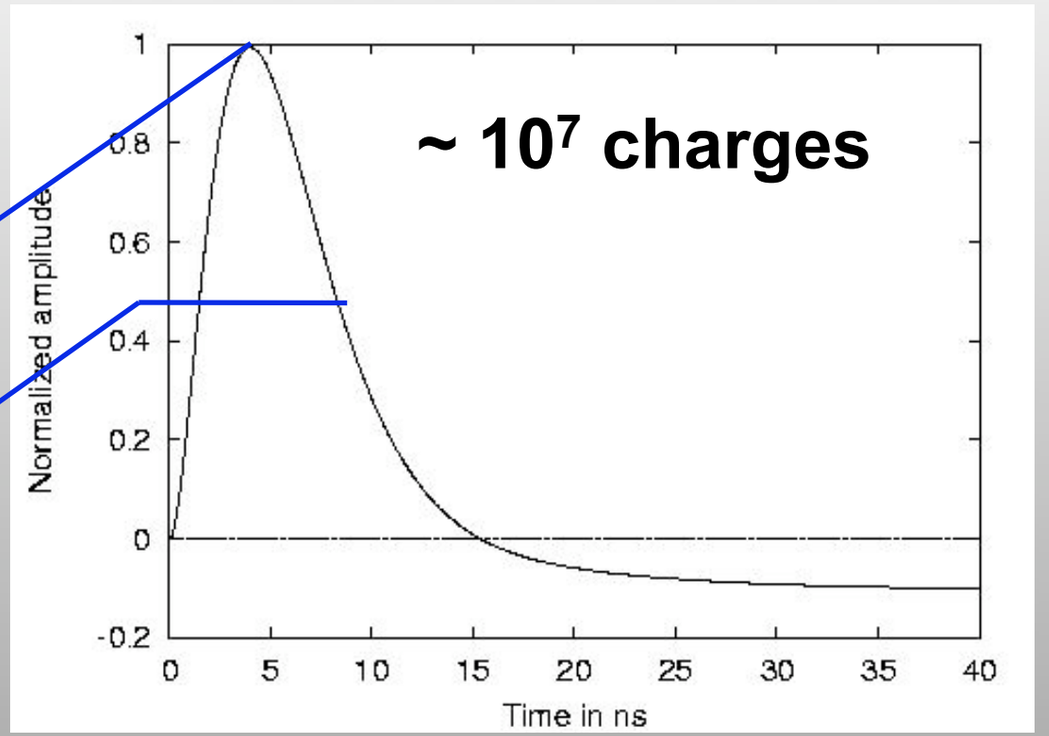
Vertical shower @ *small impact parameter*

Following H. R. Allan (1971)

Signal simulation:

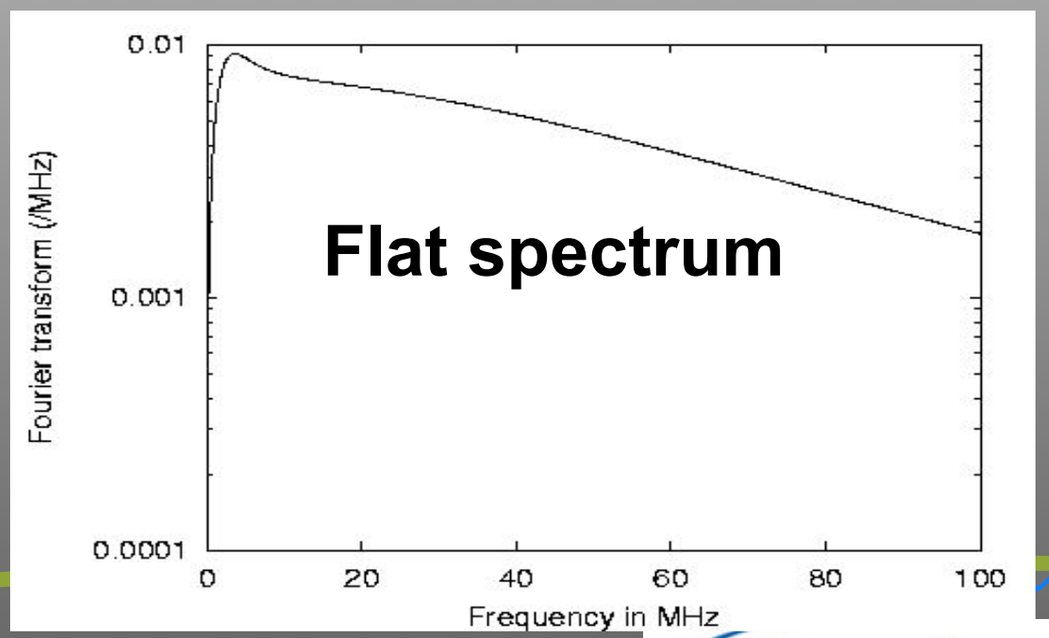
e_{pk}~150 µV/m

FWHM duration ~ 8 ns



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

2004-2005 setting @ Nançay



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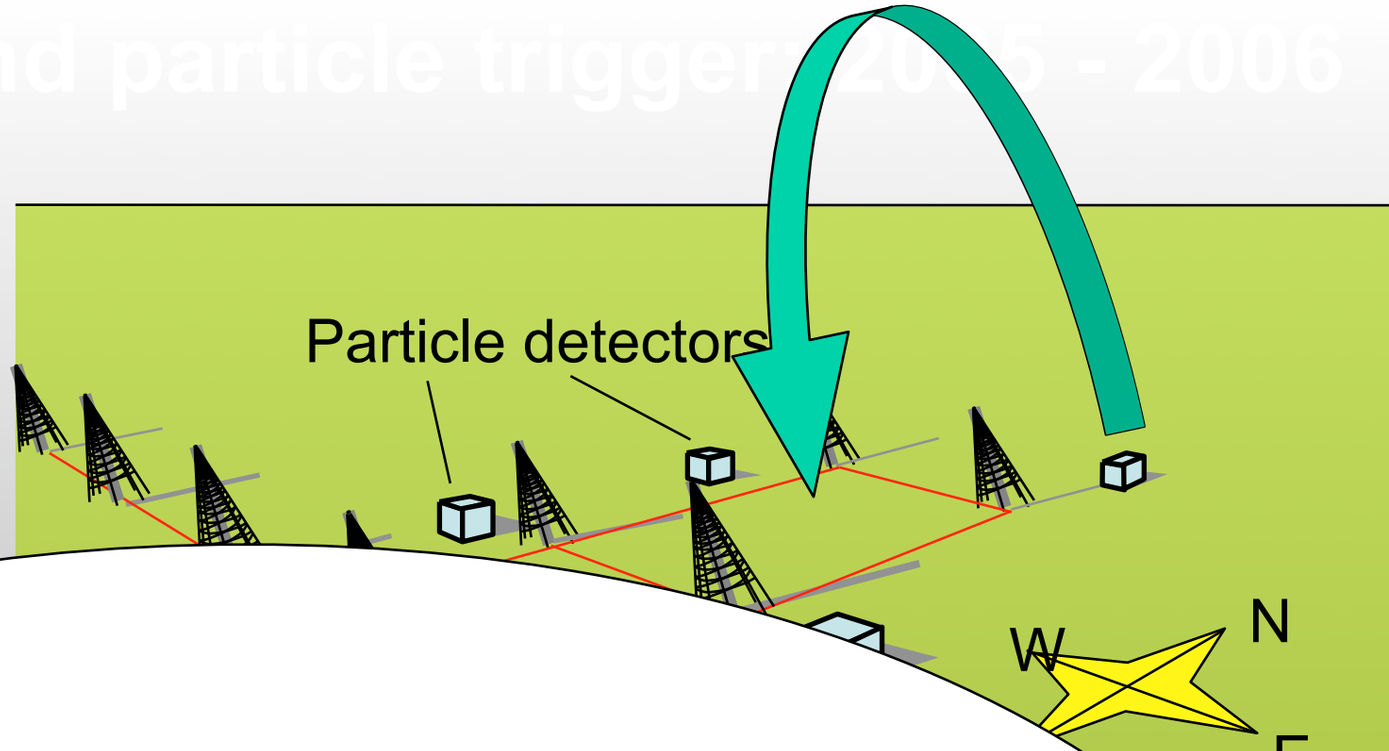
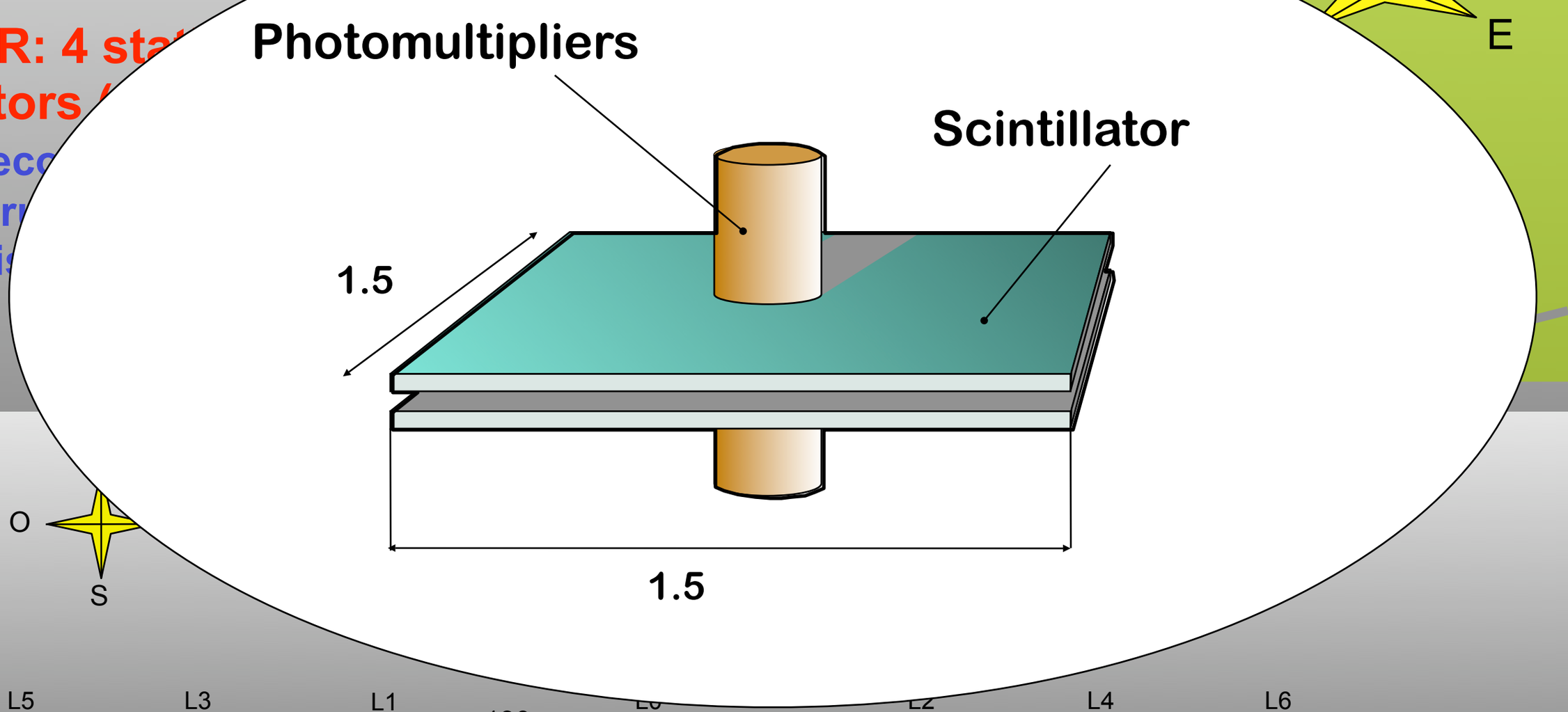
DAM: (Decametric Array) of the Radio Observatory of Nançay

- **FILTERED IN 24-82 MHz**
- **Waveform 8 bits, 500 MS/s, 10 μs**



TRIGGER: 4 sta
scintillators (

- **Signal recc**
- **Reconstr**
- **Compari**



Scintillators events

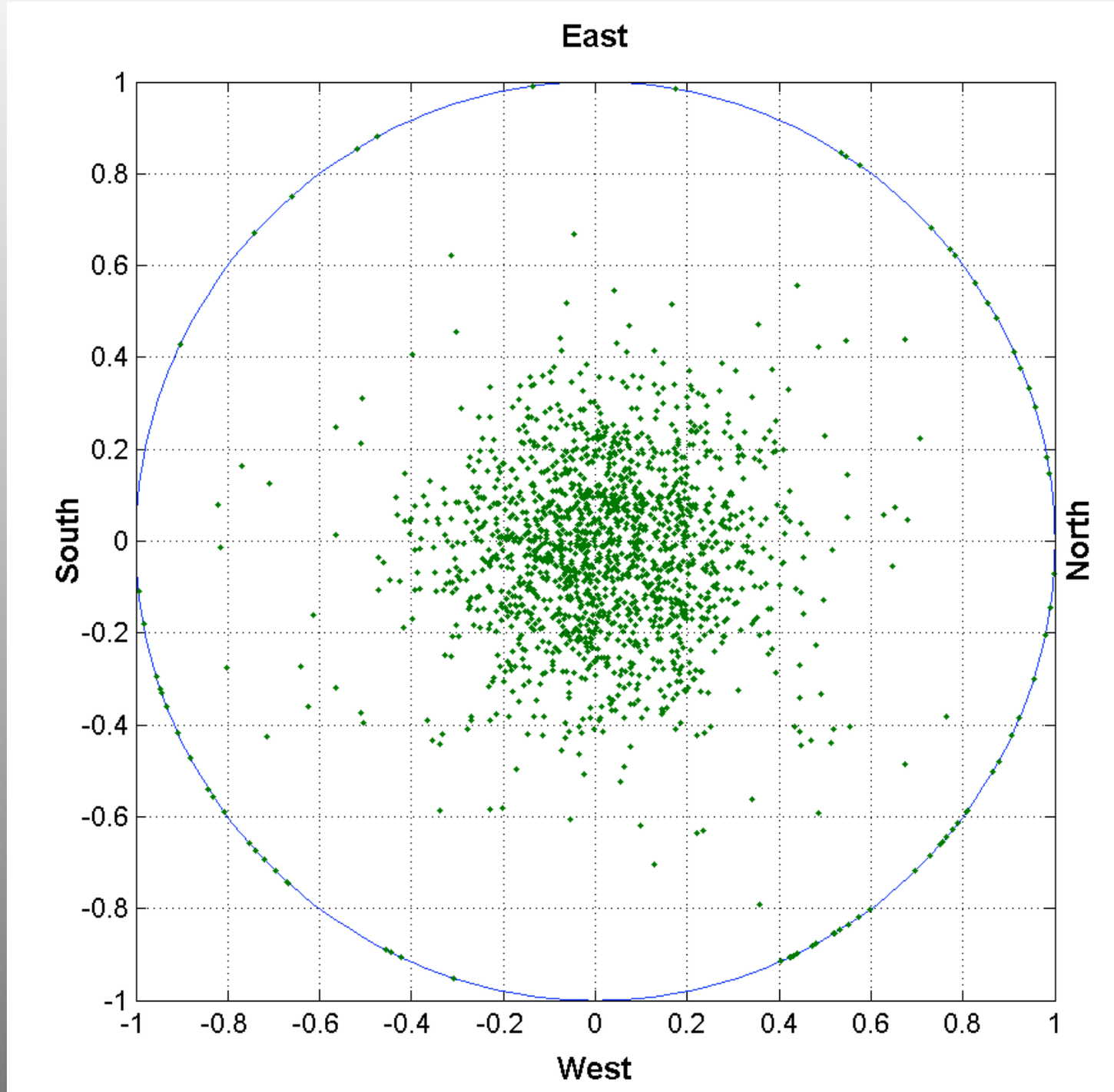
Reconstruction of the particle pancake arrival direction

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

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Time distribution for antenna events

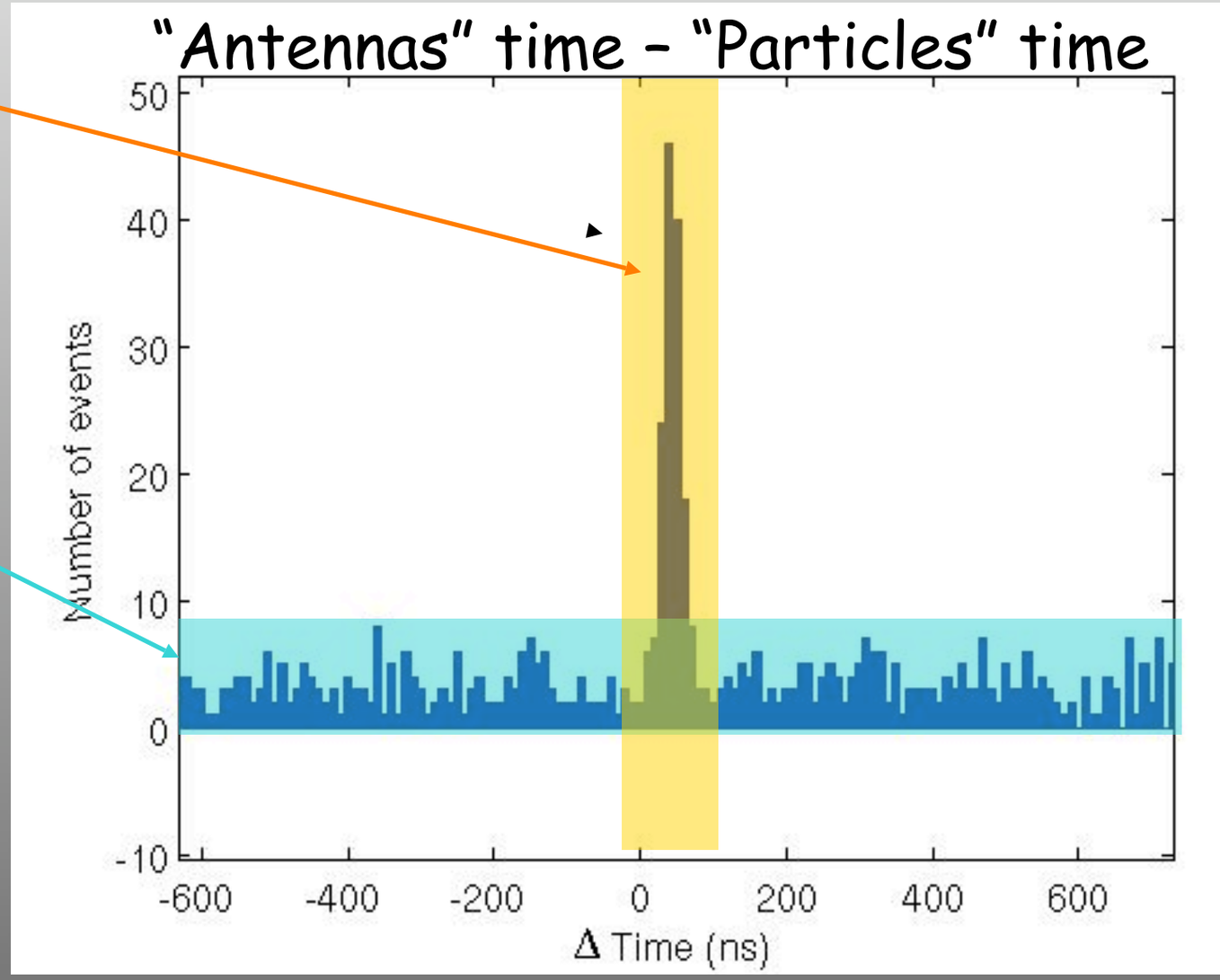
Coincidence rate: 1 Antenna + Trigger = 1 event / 1 h

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

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

Flat distribution
= Fortuitous

Using scintillators acceptance ⇒ Energy threshold ~ 5.10^{16} eV



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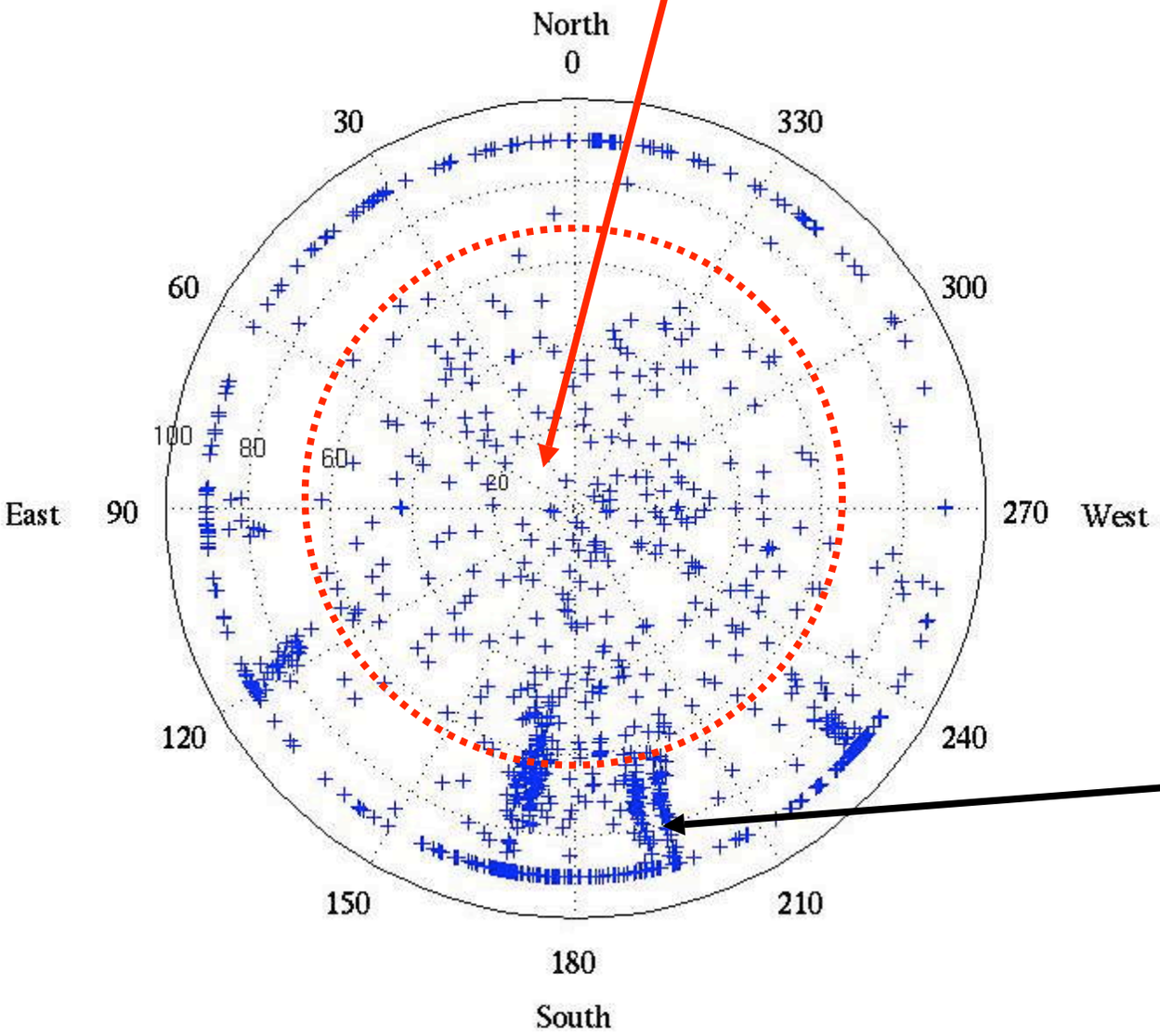
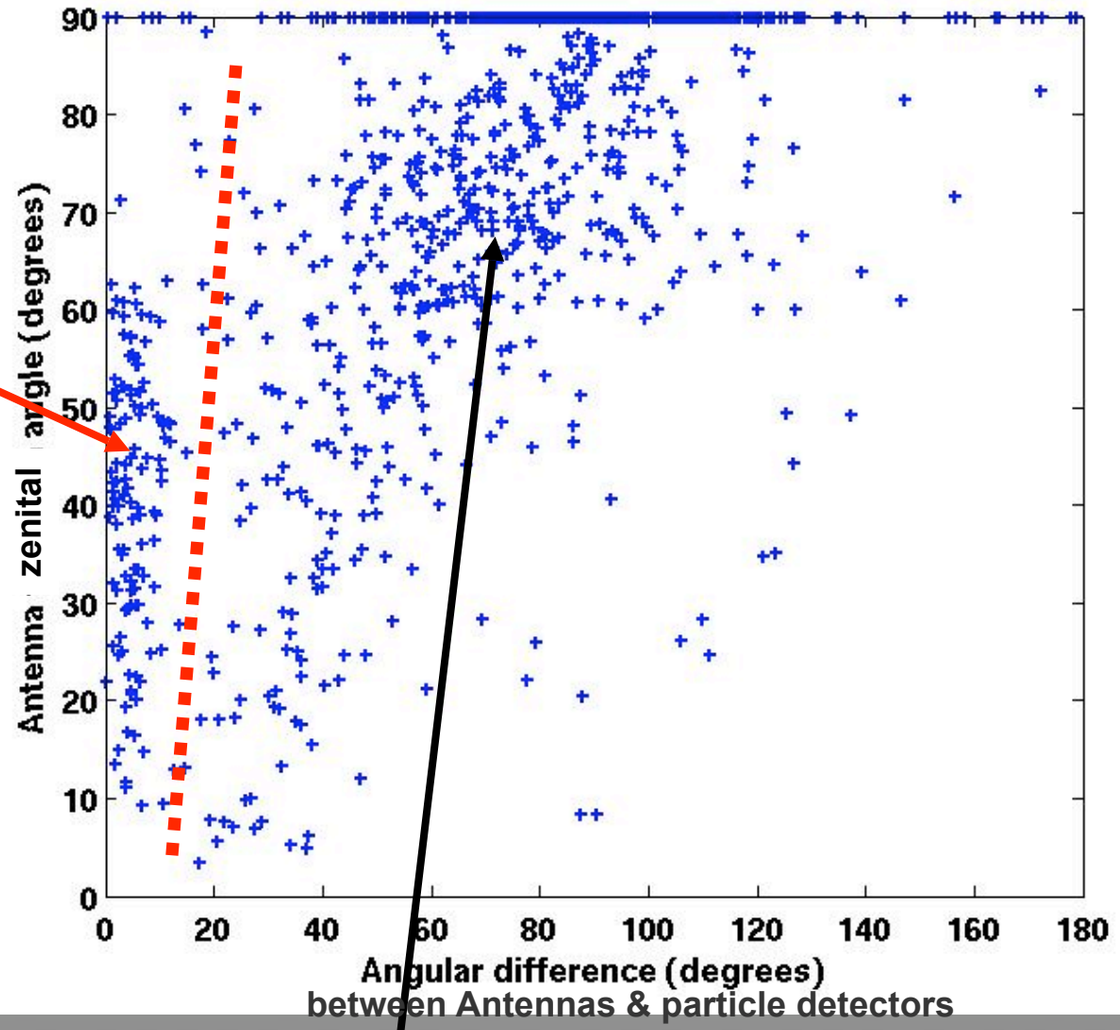
Coincidence characteristics

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)

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collaboration

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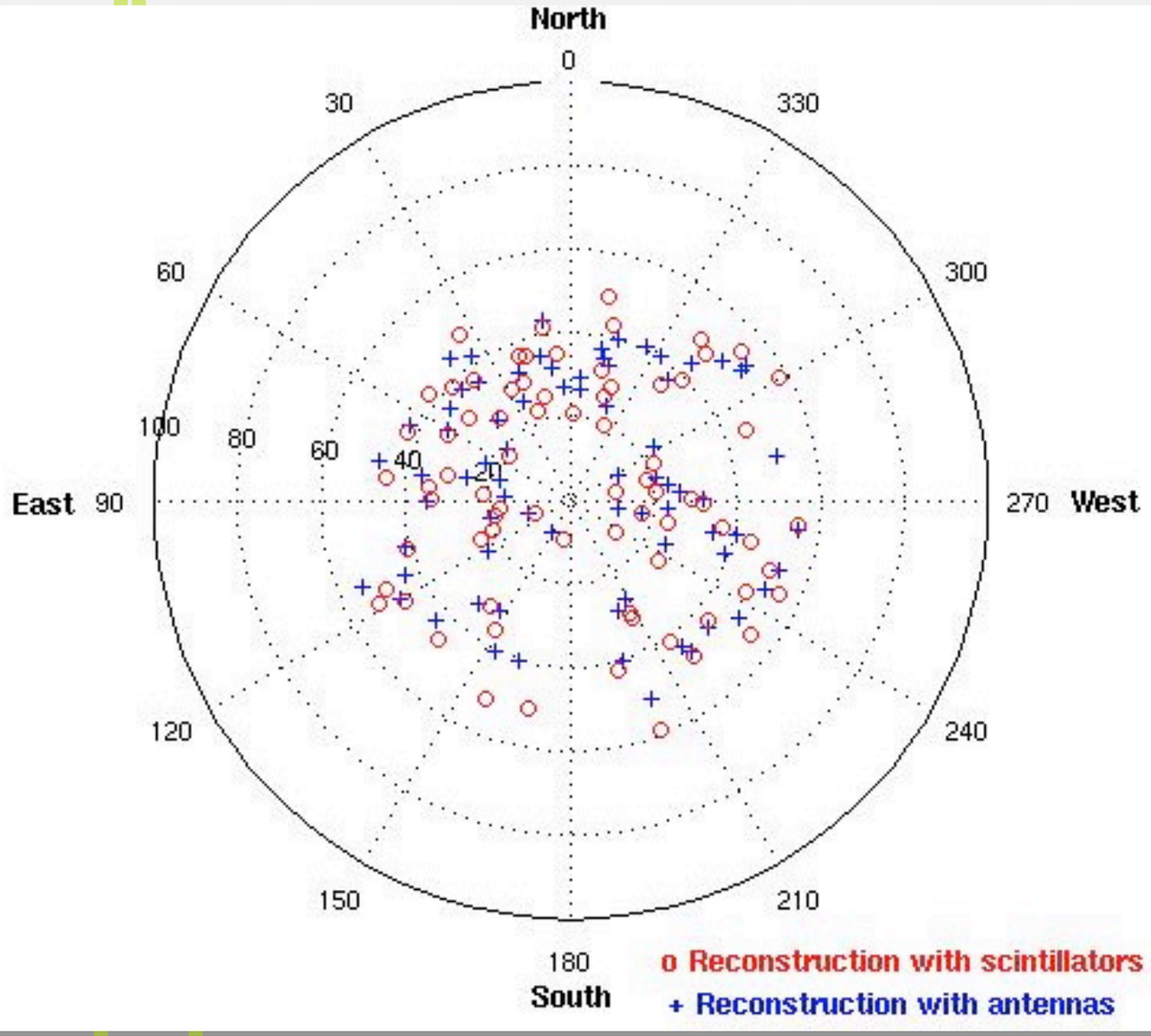
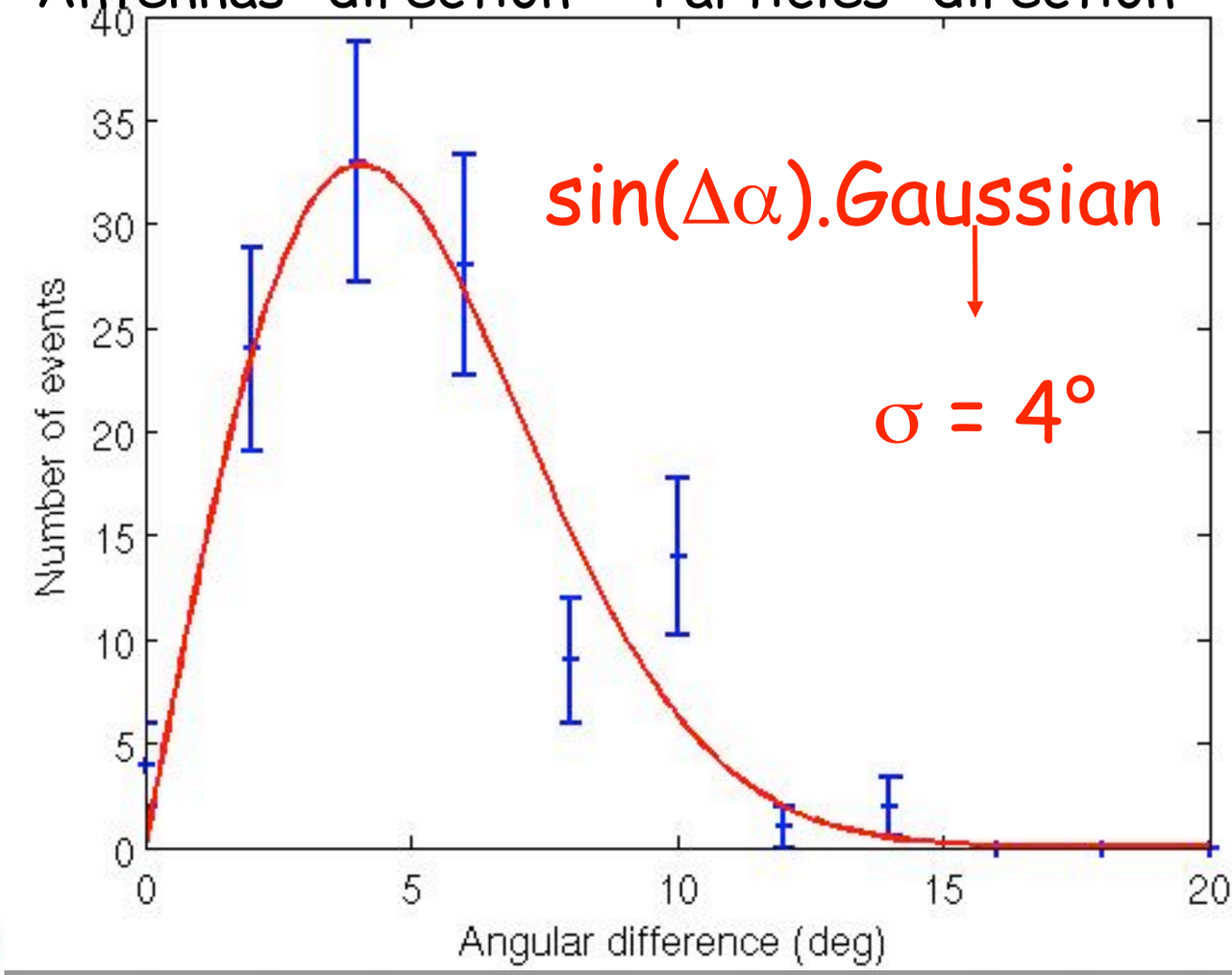
Correlation of Arrival directions





Reconstruction of EAS arrival direction is confirmed via Radio-Detection

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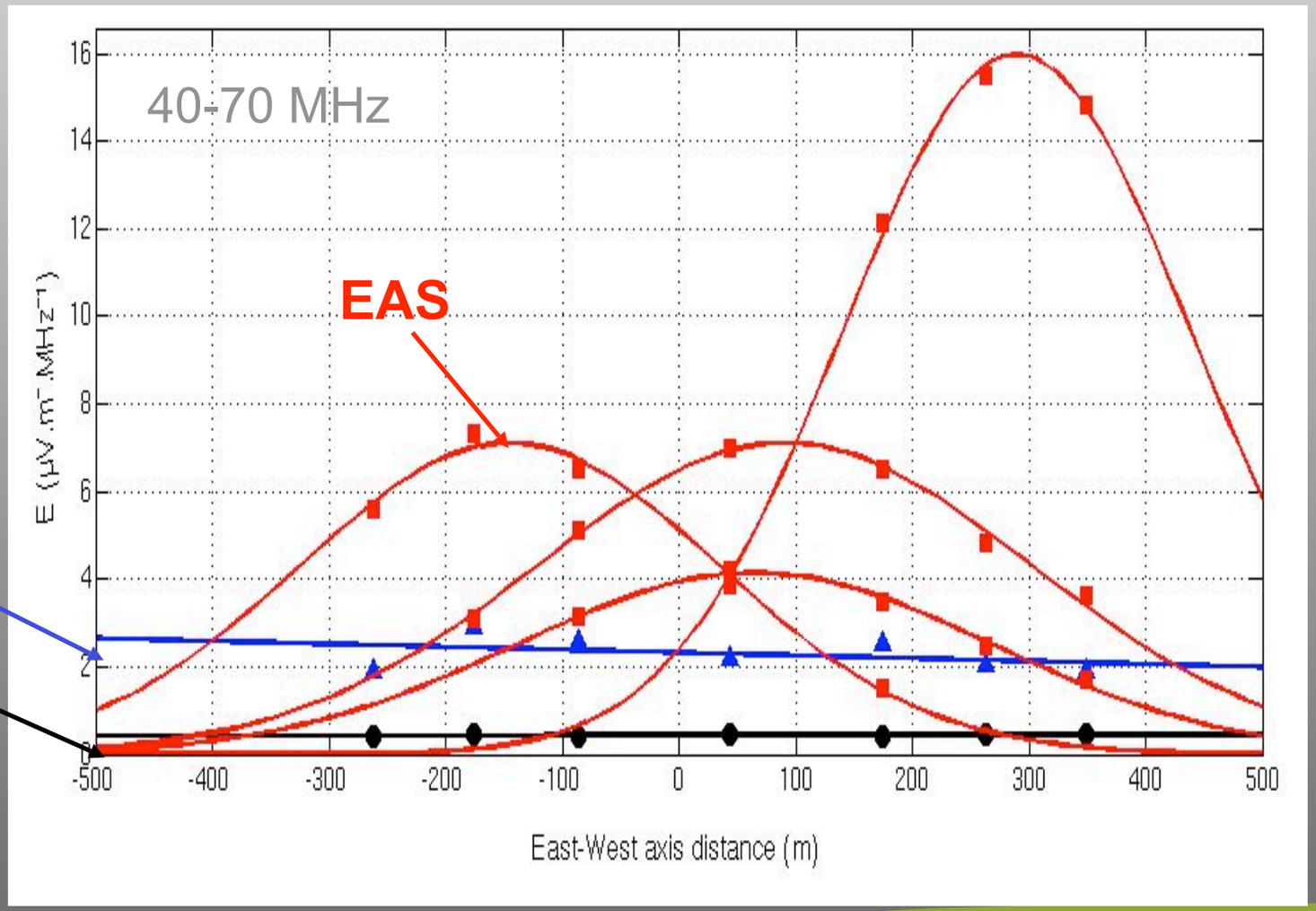
Electric Field topologies

Variable antenna multiplicity (limited array)

Field amplitudes from 250 μV/m to 1.2 mV/m in 40 - 70 MHz

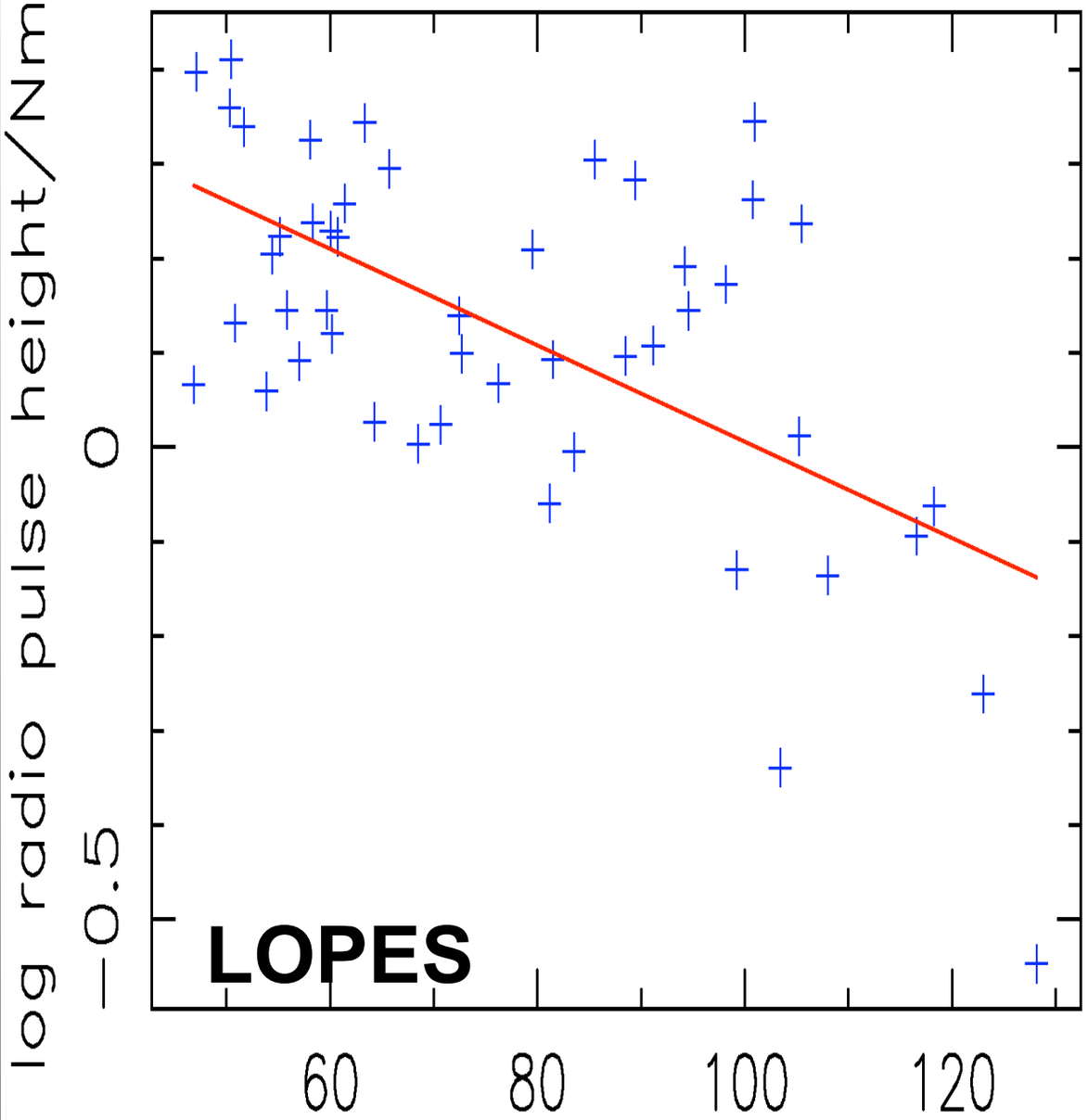
The entire shower development is seen by every antenna



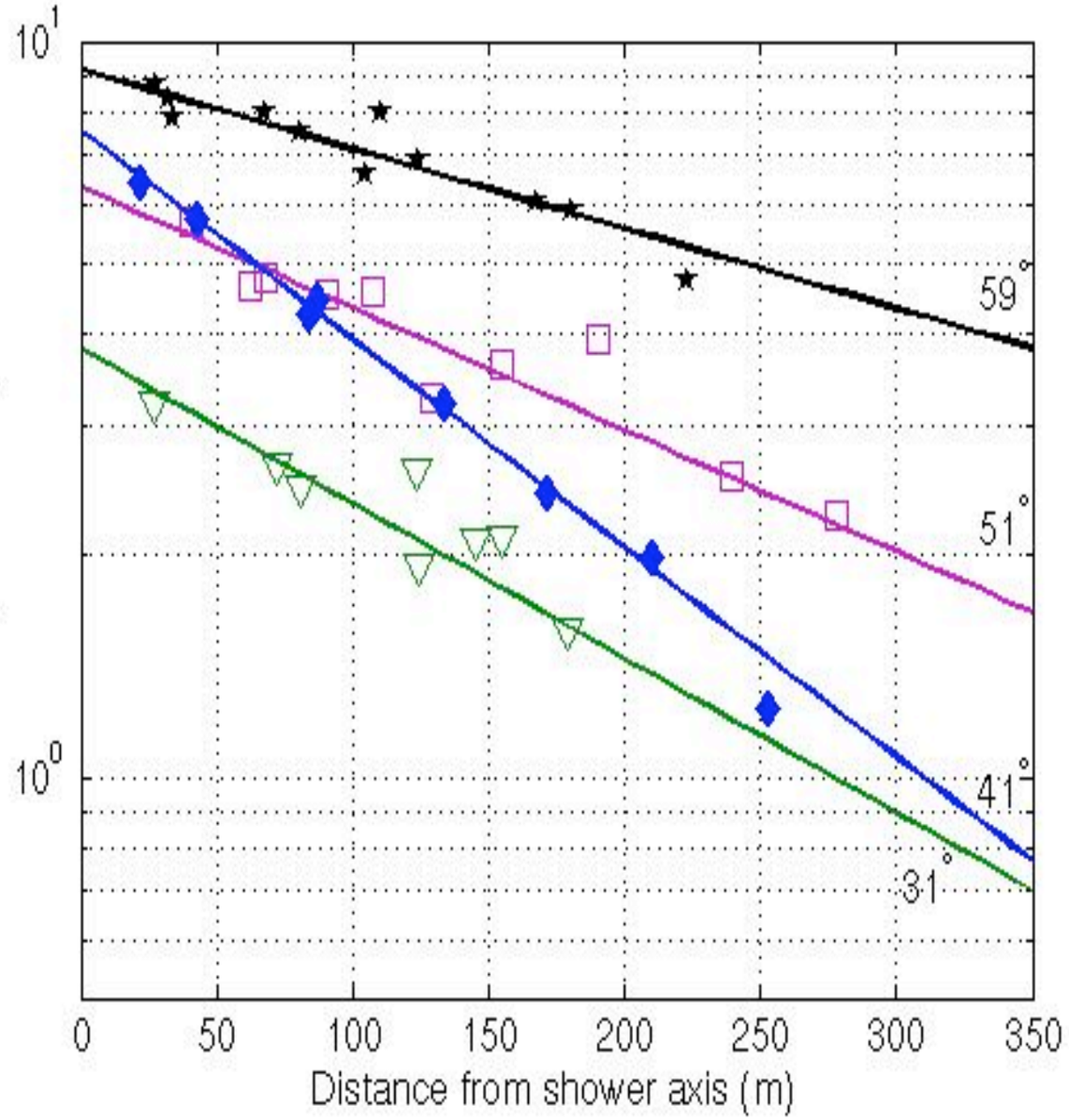
Free of particle ground density fluctuations

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

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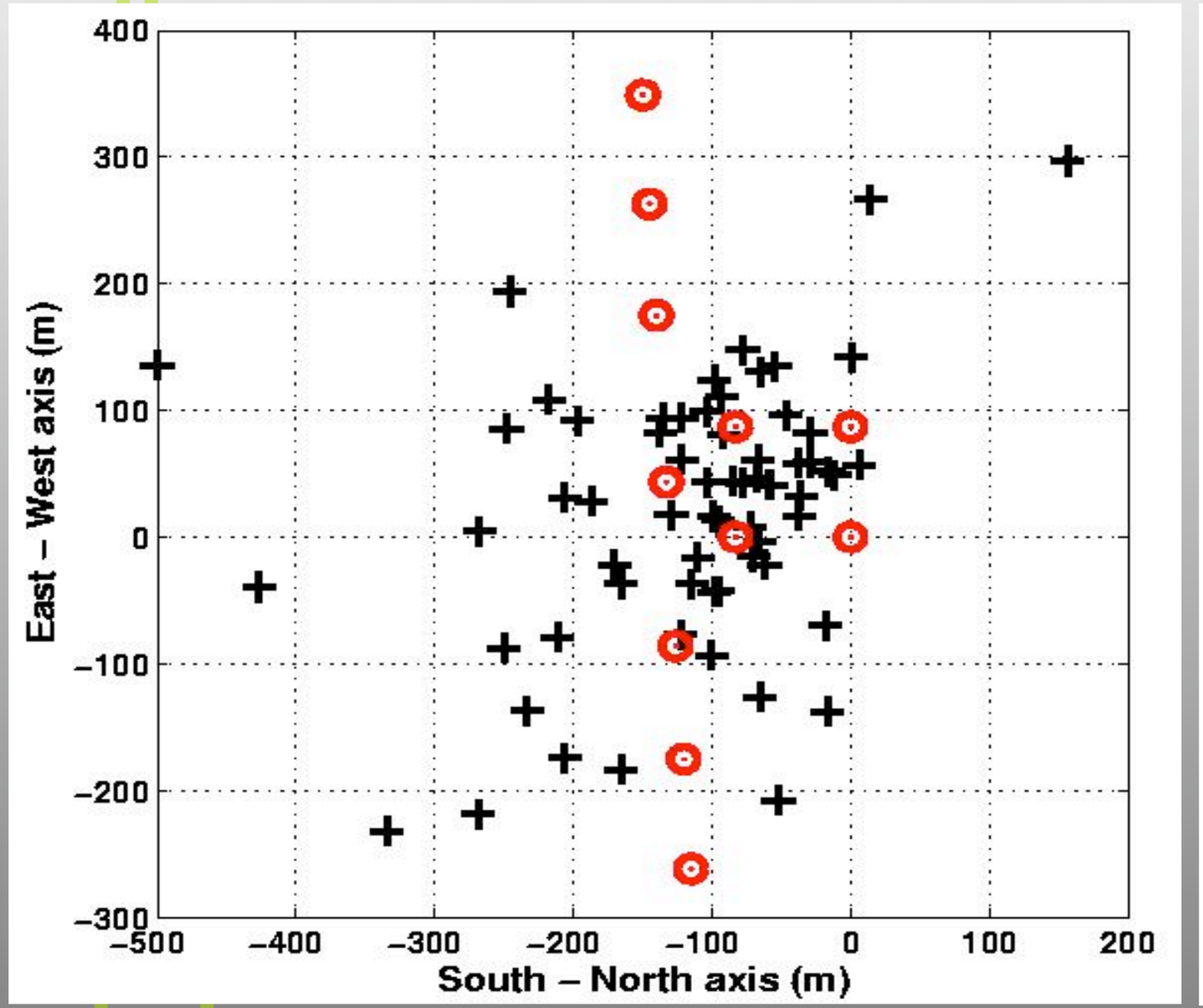
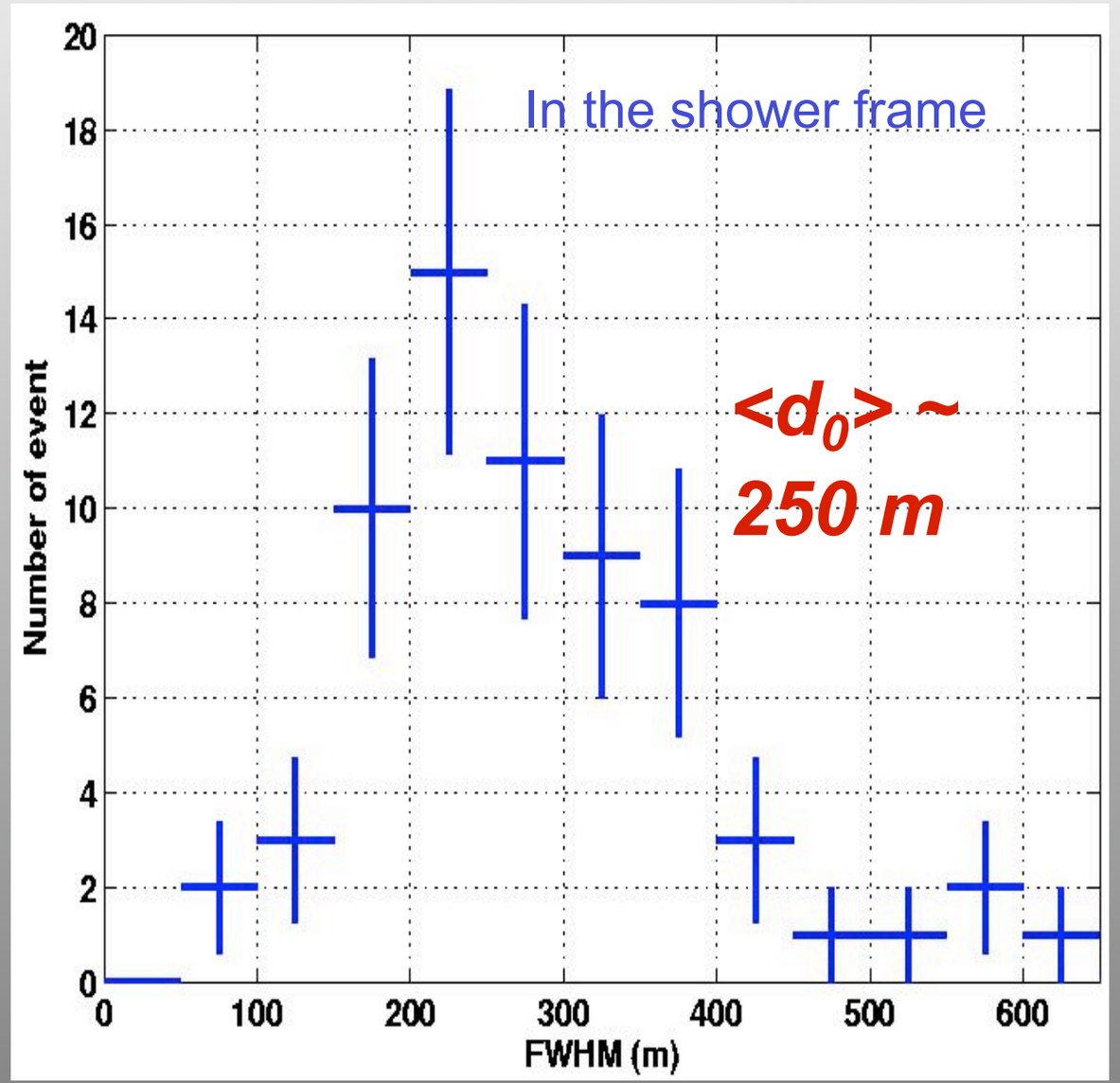
Extraction of the Parameters

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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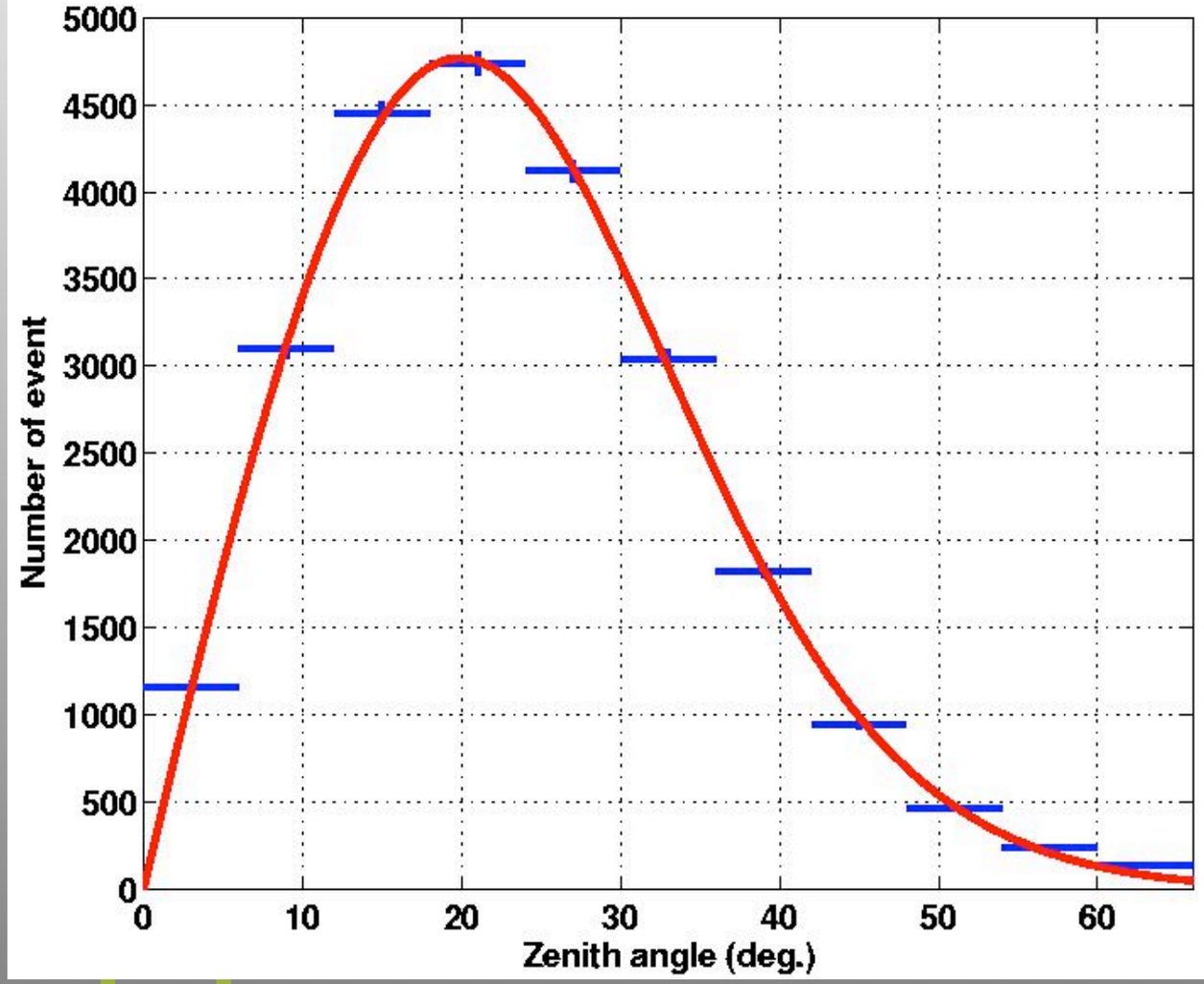
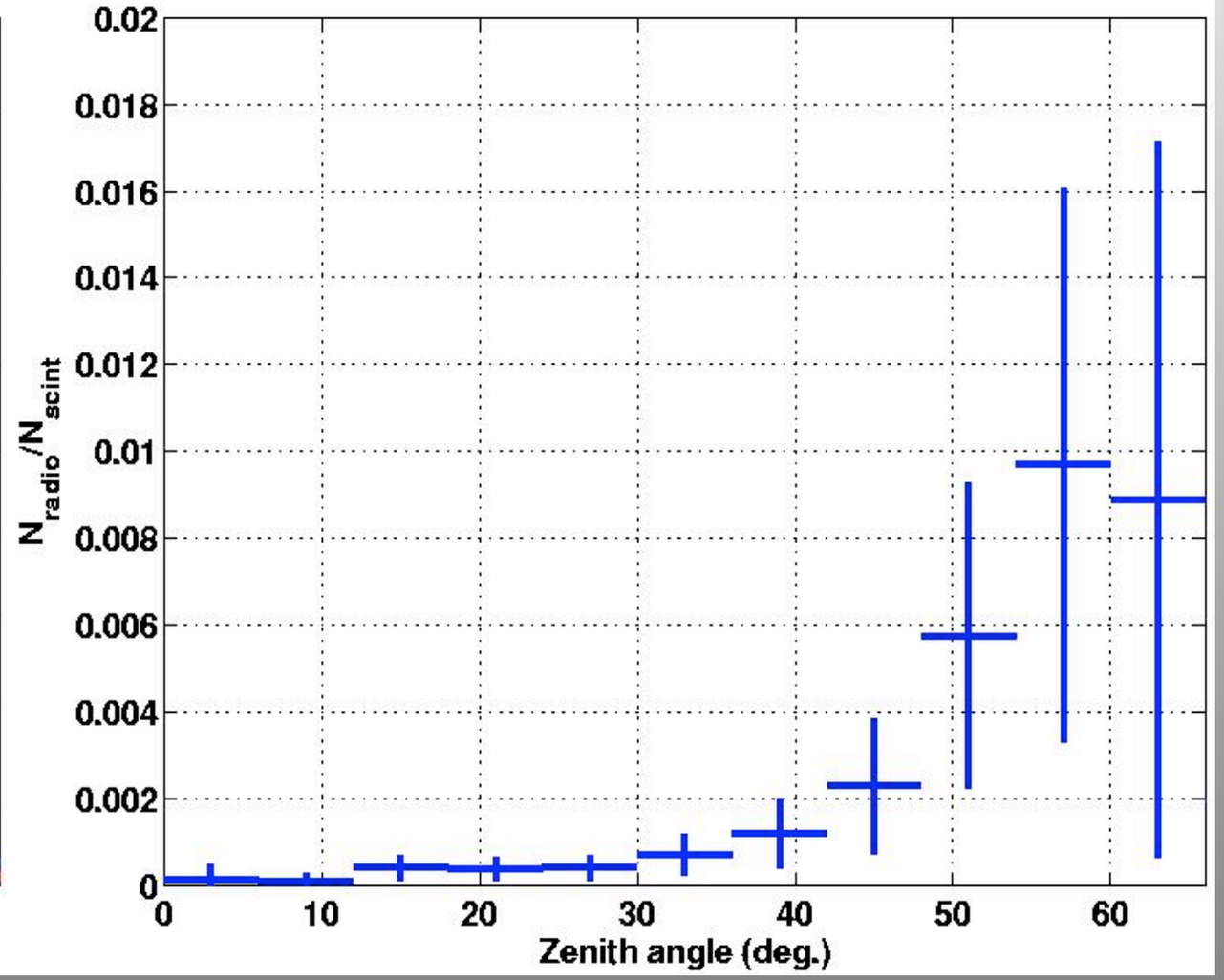
Trigger Counting (not corrected from solid angles)



Radio / Trigger Acceptance



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

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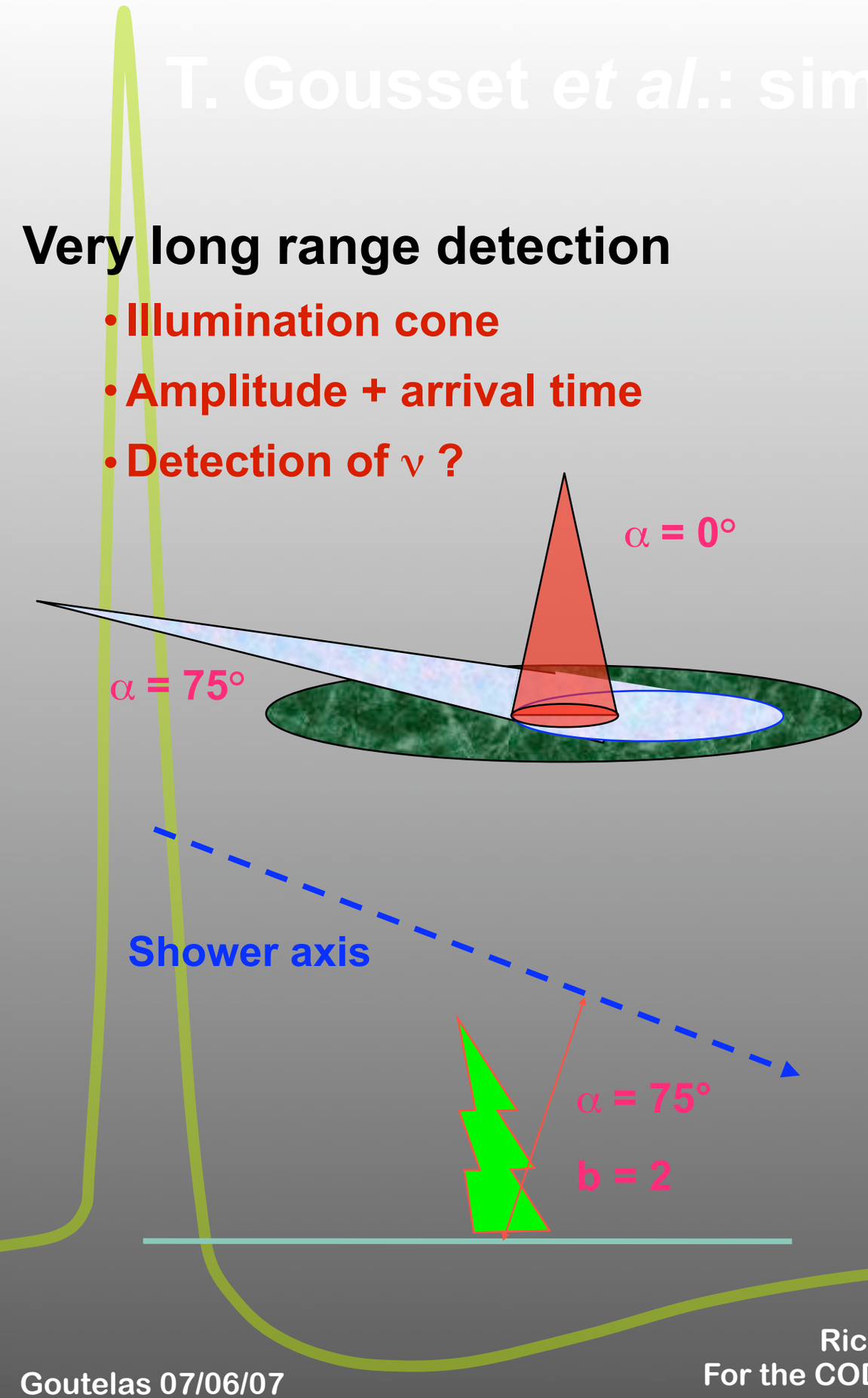
For the CODALEMA collaboration

Subatech

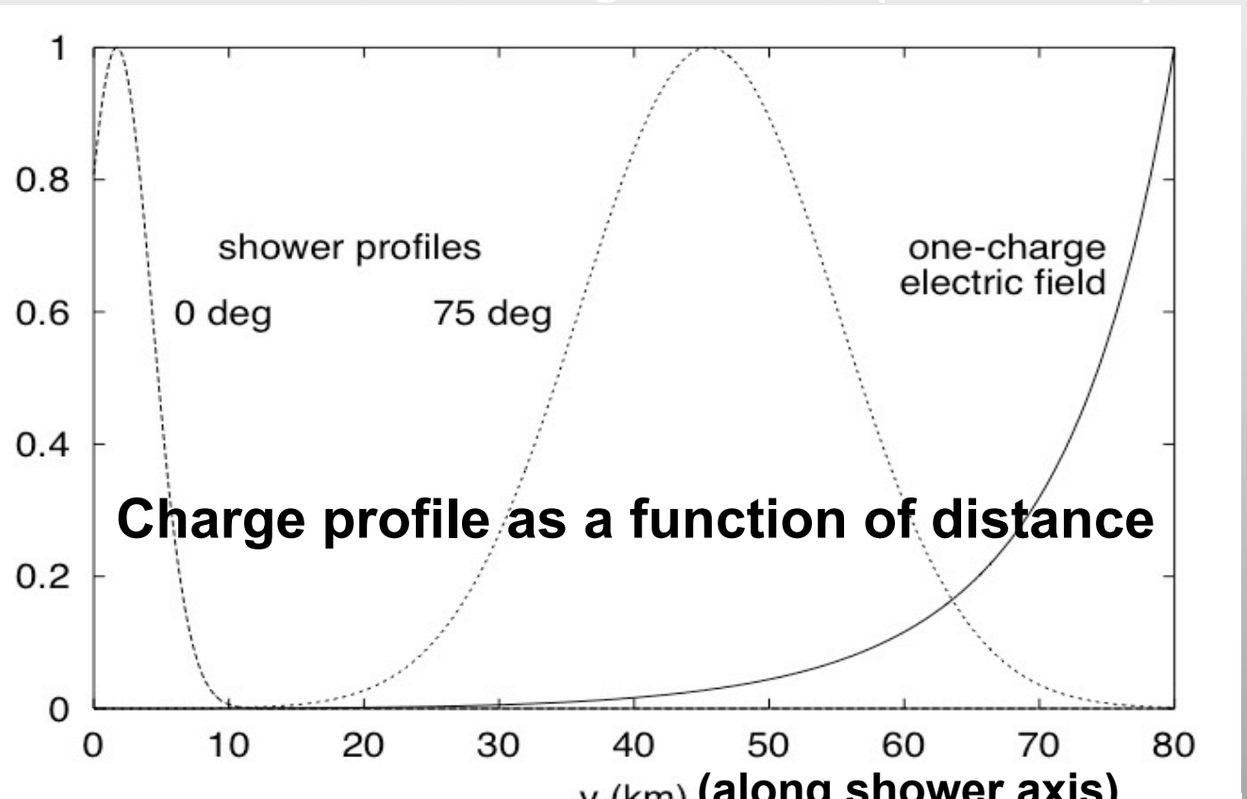
T. Gousset *et al.*: simulations of horizontal showers

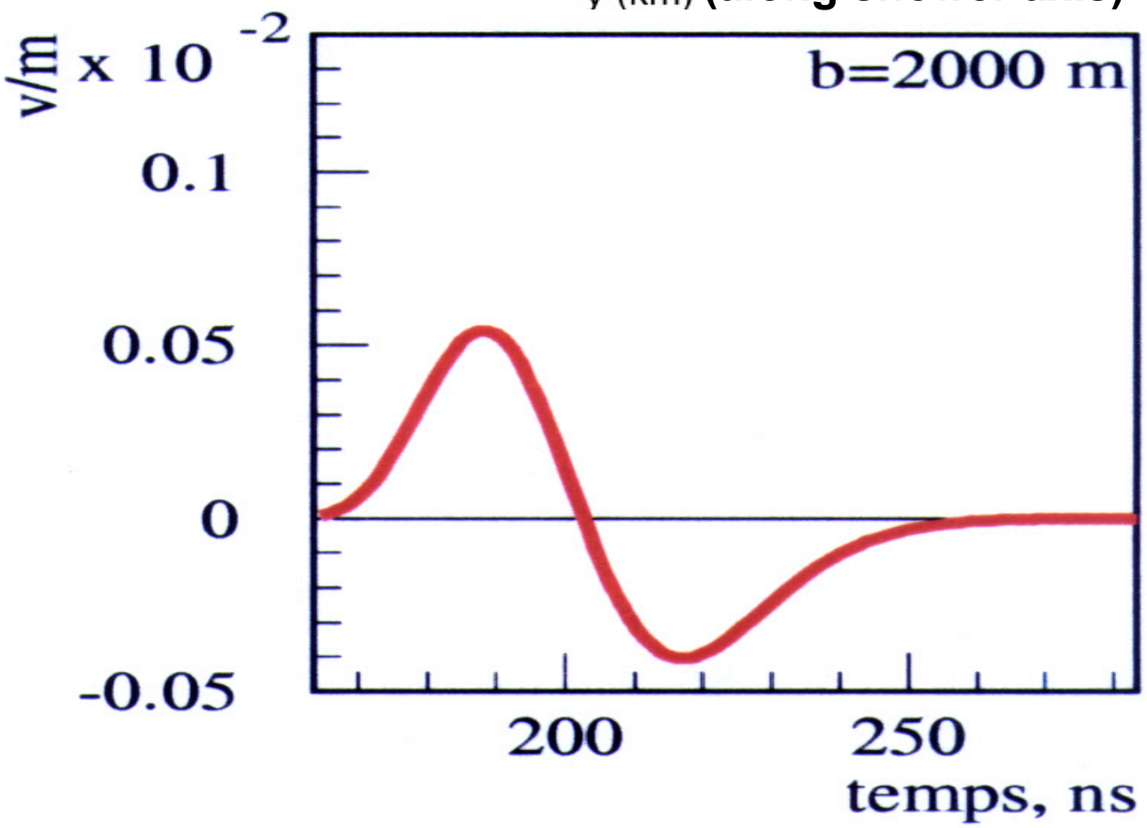
Very long range detection

- **Illumination cone**
- **Amplitude + arrival time**
- **Detection of ν ?**



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





Richa
For the CODA

Goutelas 07/06/07

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The CODALEMA active dipole

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

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Signal simulation @ 10^{20} eV

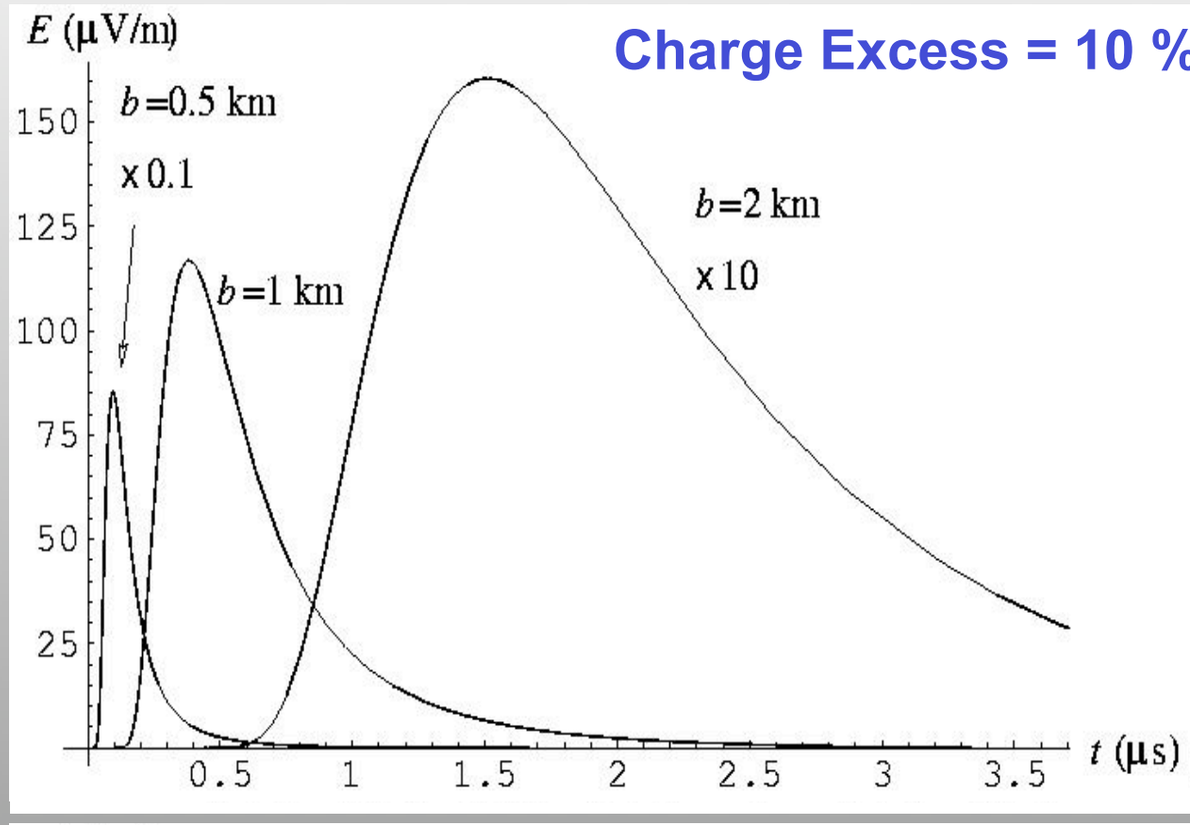
Vertical shower (charge excess only)

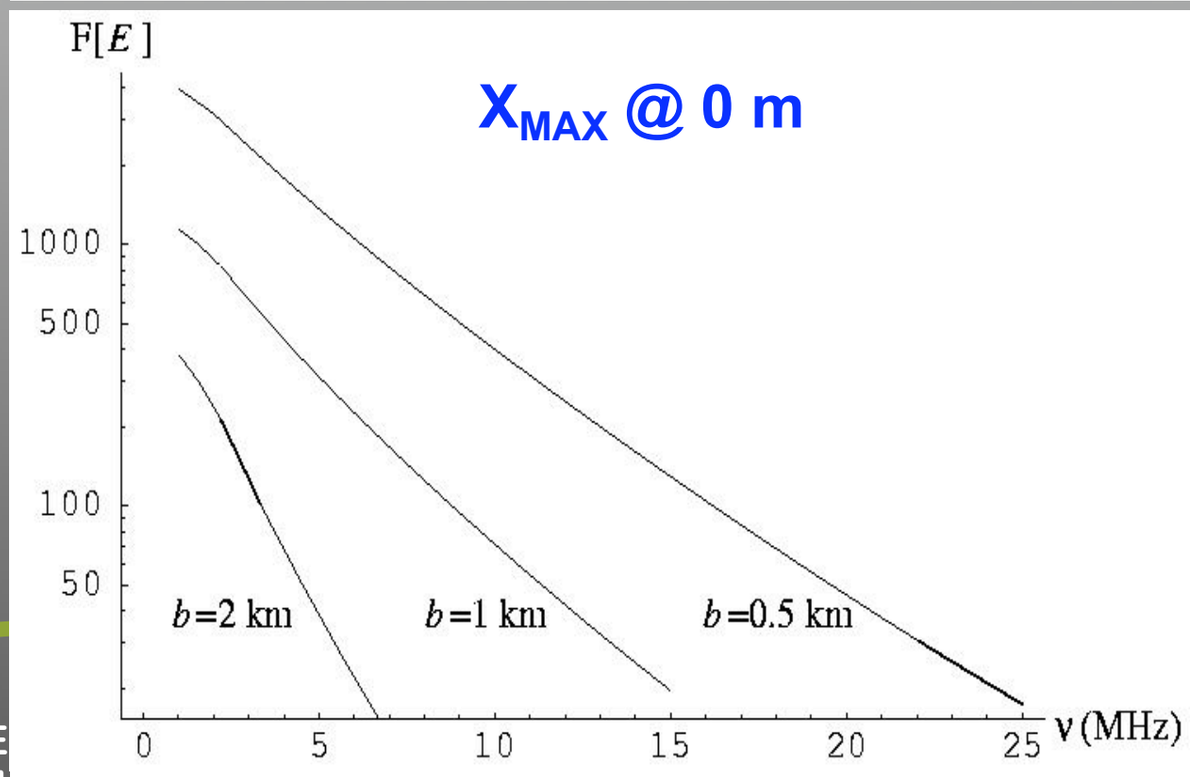
amplitude ⇒ energy
duration ⇒ impact parameter
shape ⇒ primary nature

SENSITIVE to

For detection at large distance

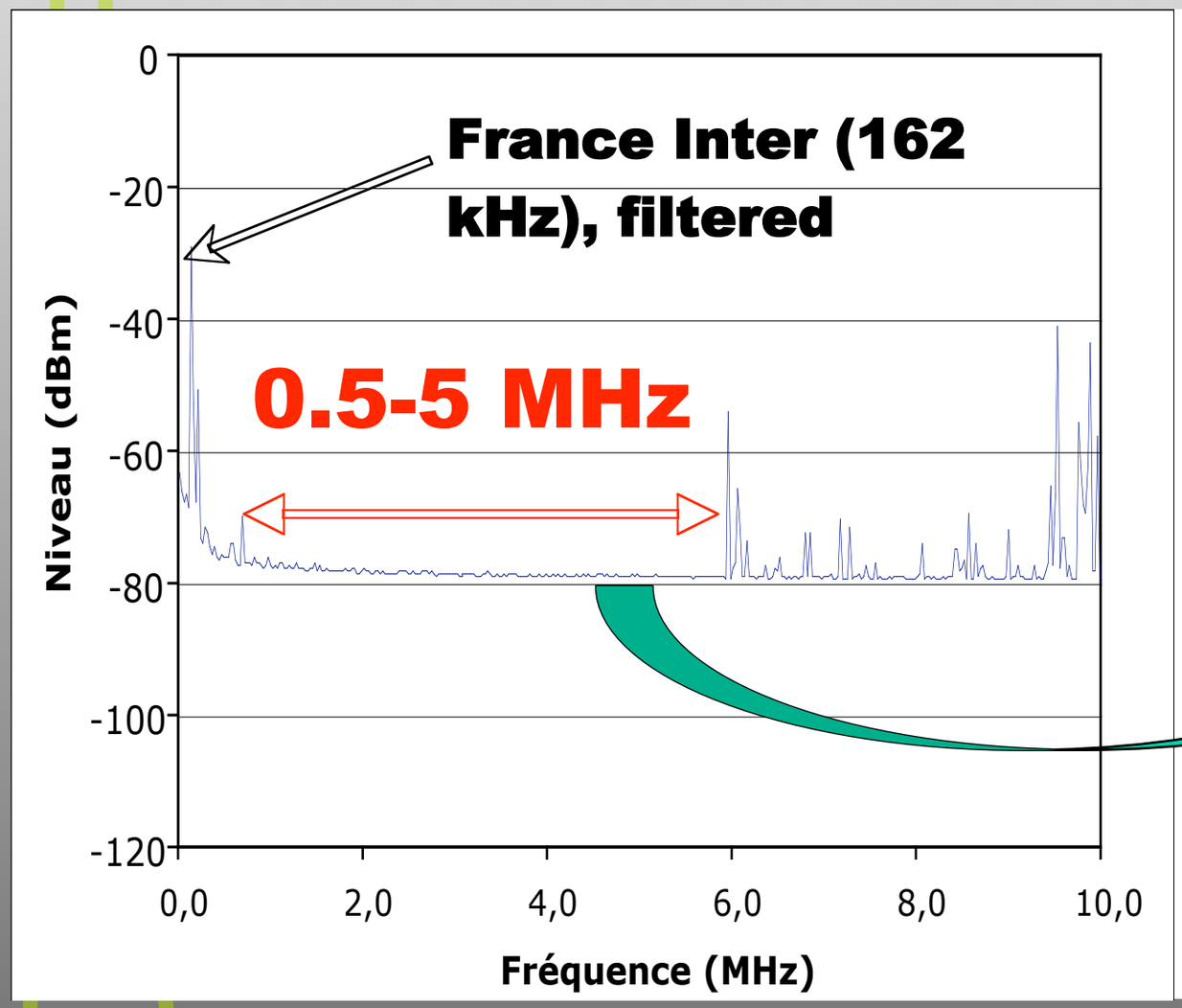
Broad-band dipoles

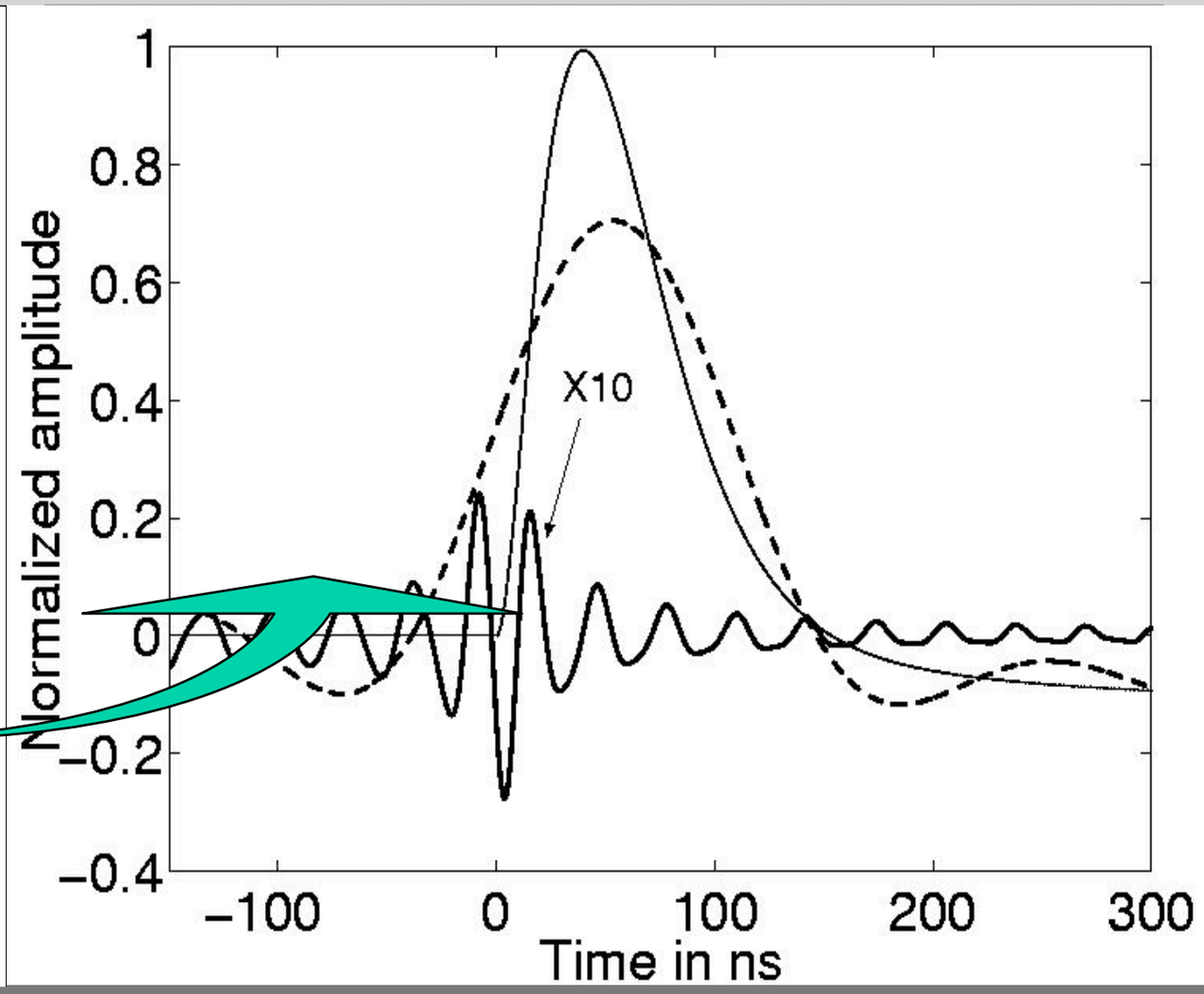




Constraint on the signal shape at low frequencies

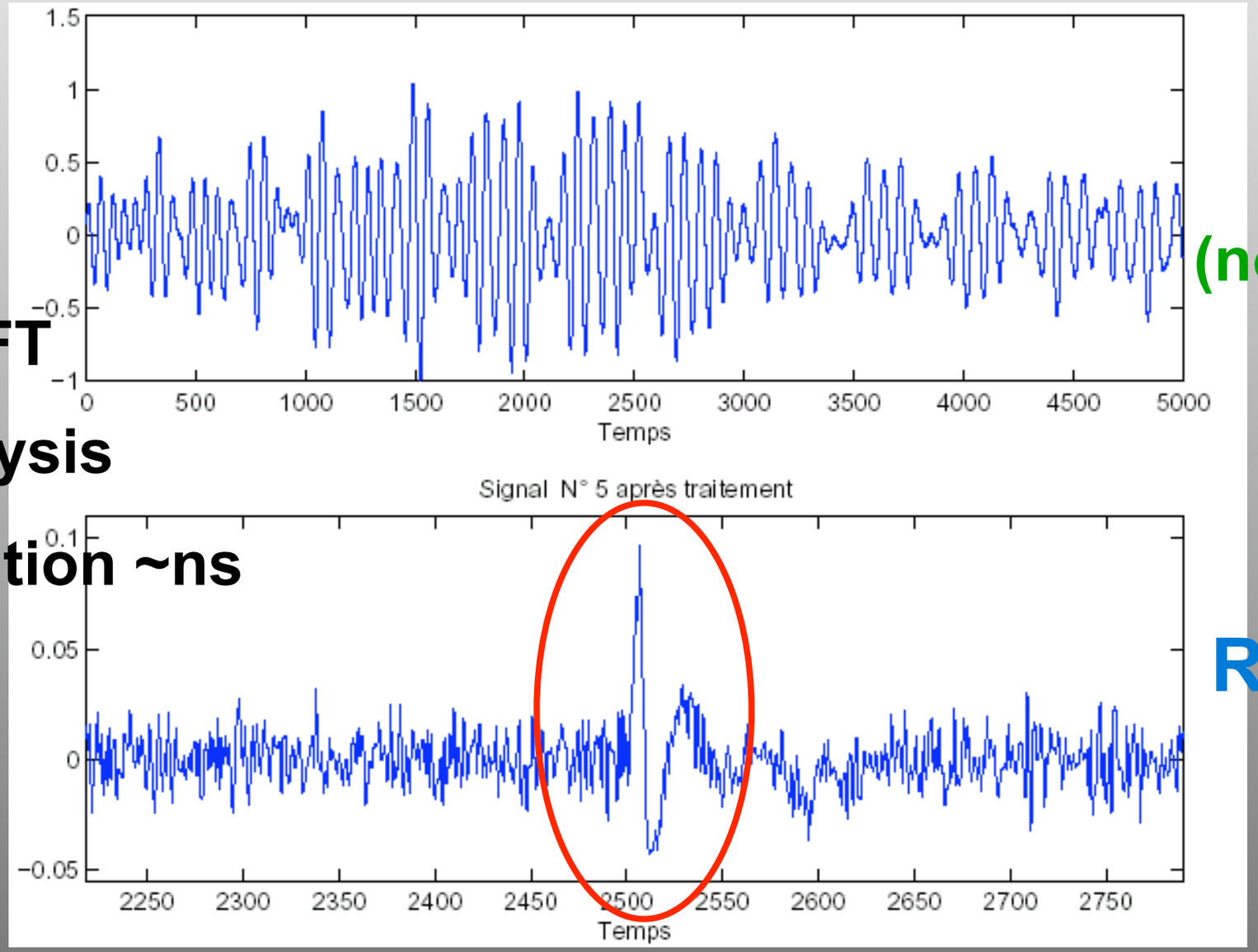
Enlarge Frequency Band: from filtered Log-Periodic(24-82 MHz)
⇒ Broad Band Dipoles (0.2-100 MHz)





Required @ Nançay for $10^{17} \Rightarrow 10^{18}$ eV
and also for Auger tests @ 10^{20} eV

Extraction via Linear Predictive Coeficients
(Adaptative optimal filtering)



Signal (noise+ pulse)

Remaining signal

Better than FFT

⇒ shape analysis

⇒ time resolution ~ns

+ Wavelet analysis for time tagging

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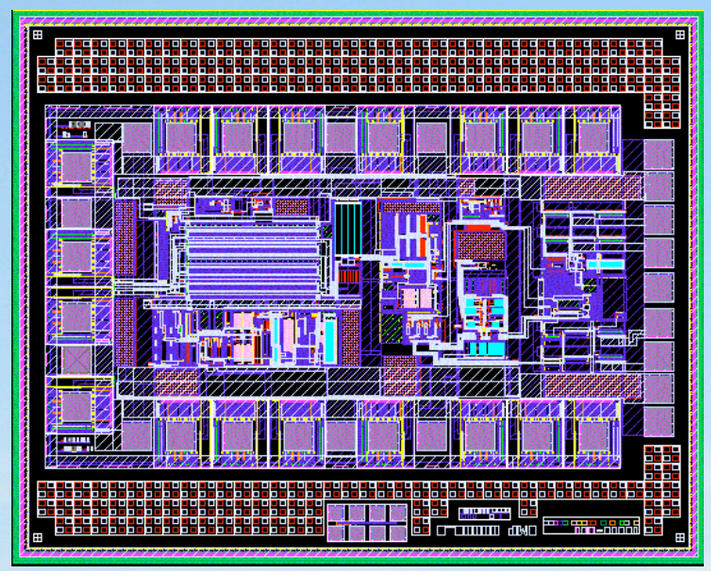
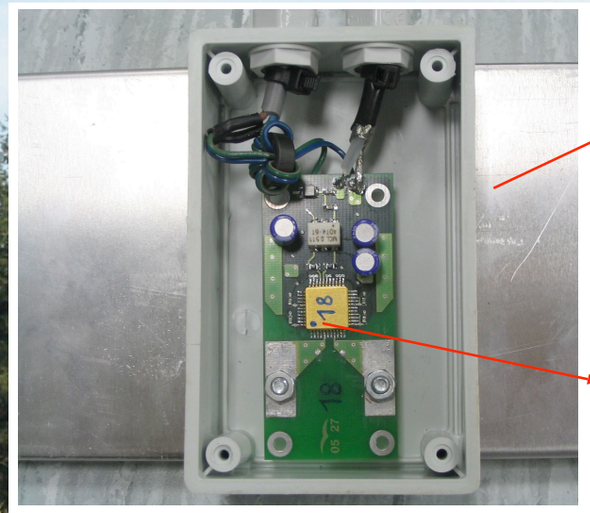
The CODALEMA short active dipole (1)

A dedicated LNA(ASIC)

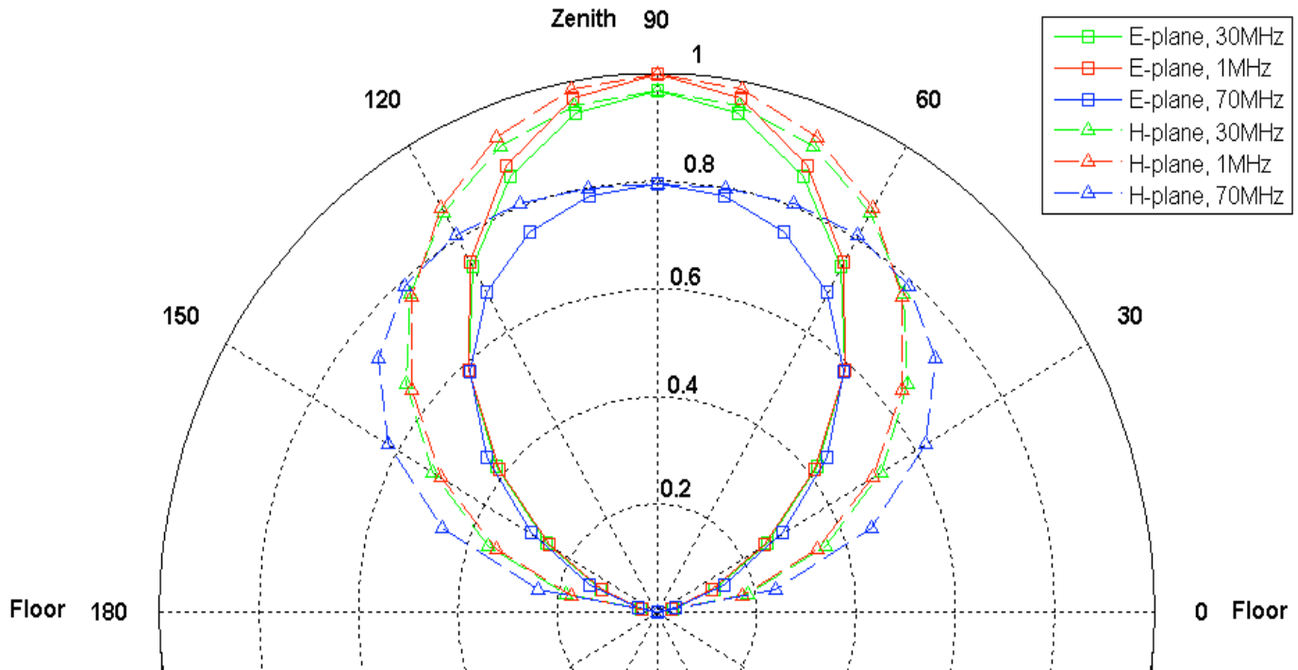




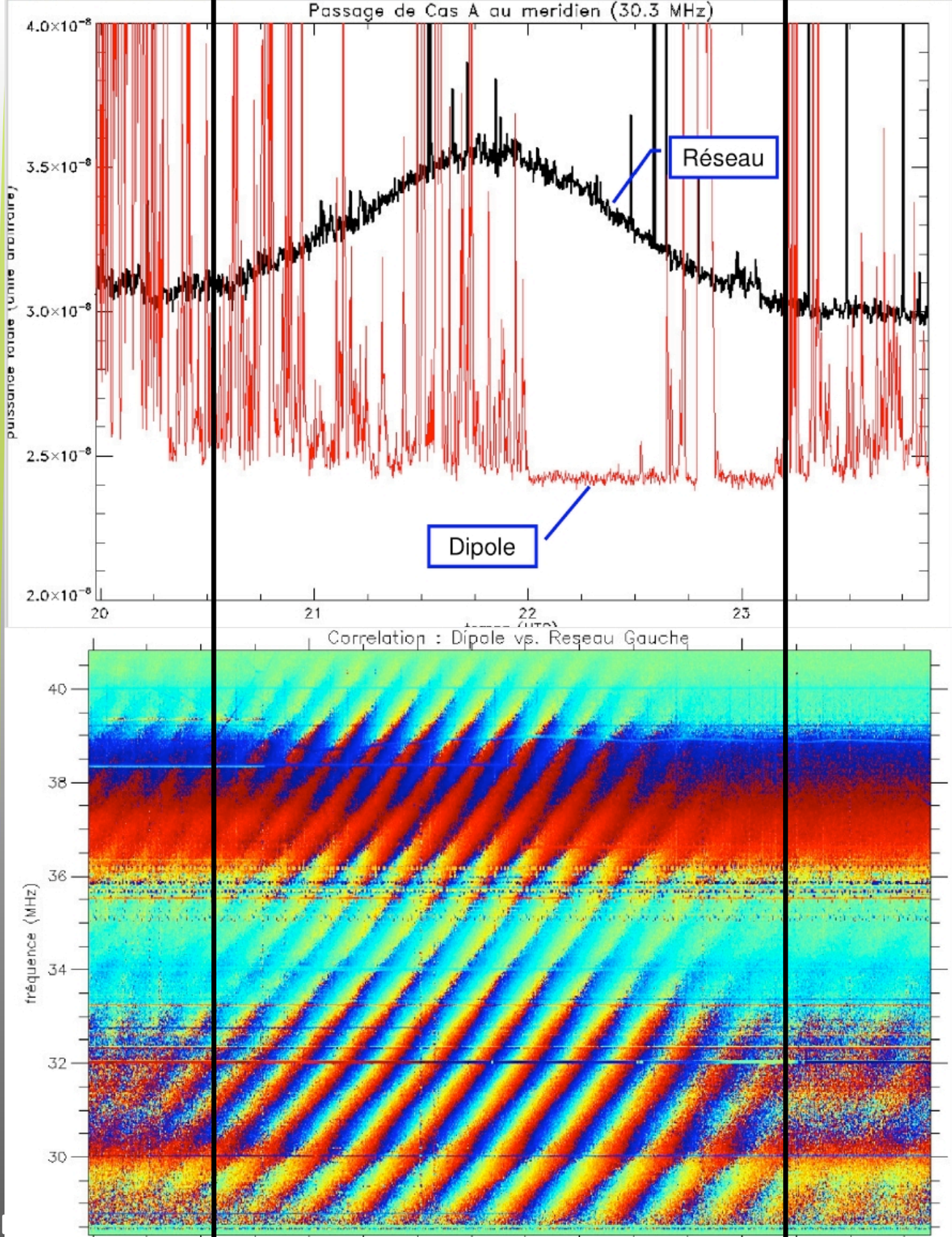
+ ADC MATACQ (12 bits, up to 1 GS/s, 2500 Samples)
+ Full Bandwidth (0-250 MHz)

Constant directivity

Normalised gain in E and H plane versus the Elevation angle



The CODALEMA Short active Dipole (2)



Good astronomical performances on a wide band

“Sees” the sky background

(Interferometry Dipole-DAM on Casiopea A)

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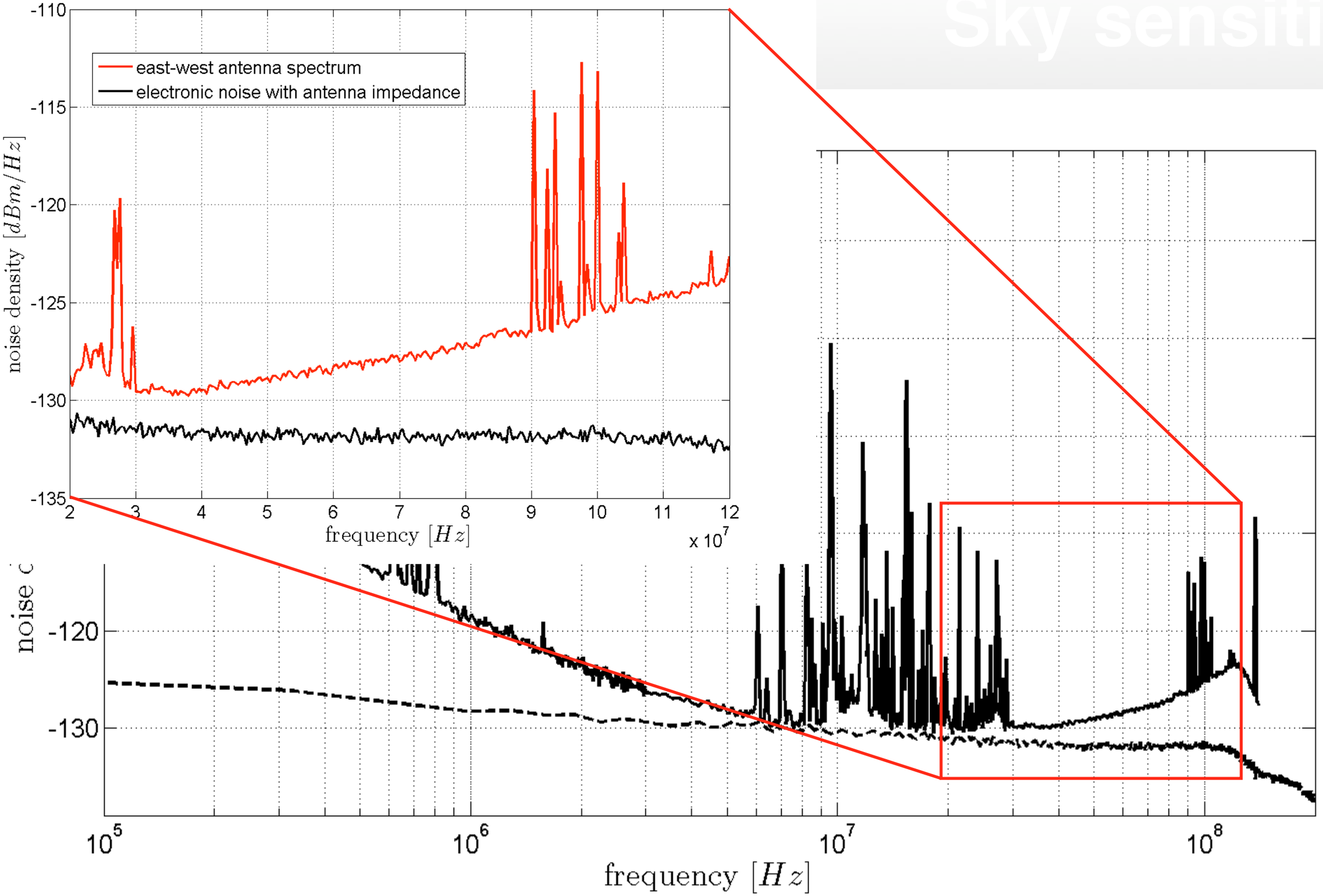
Sky sensitivity



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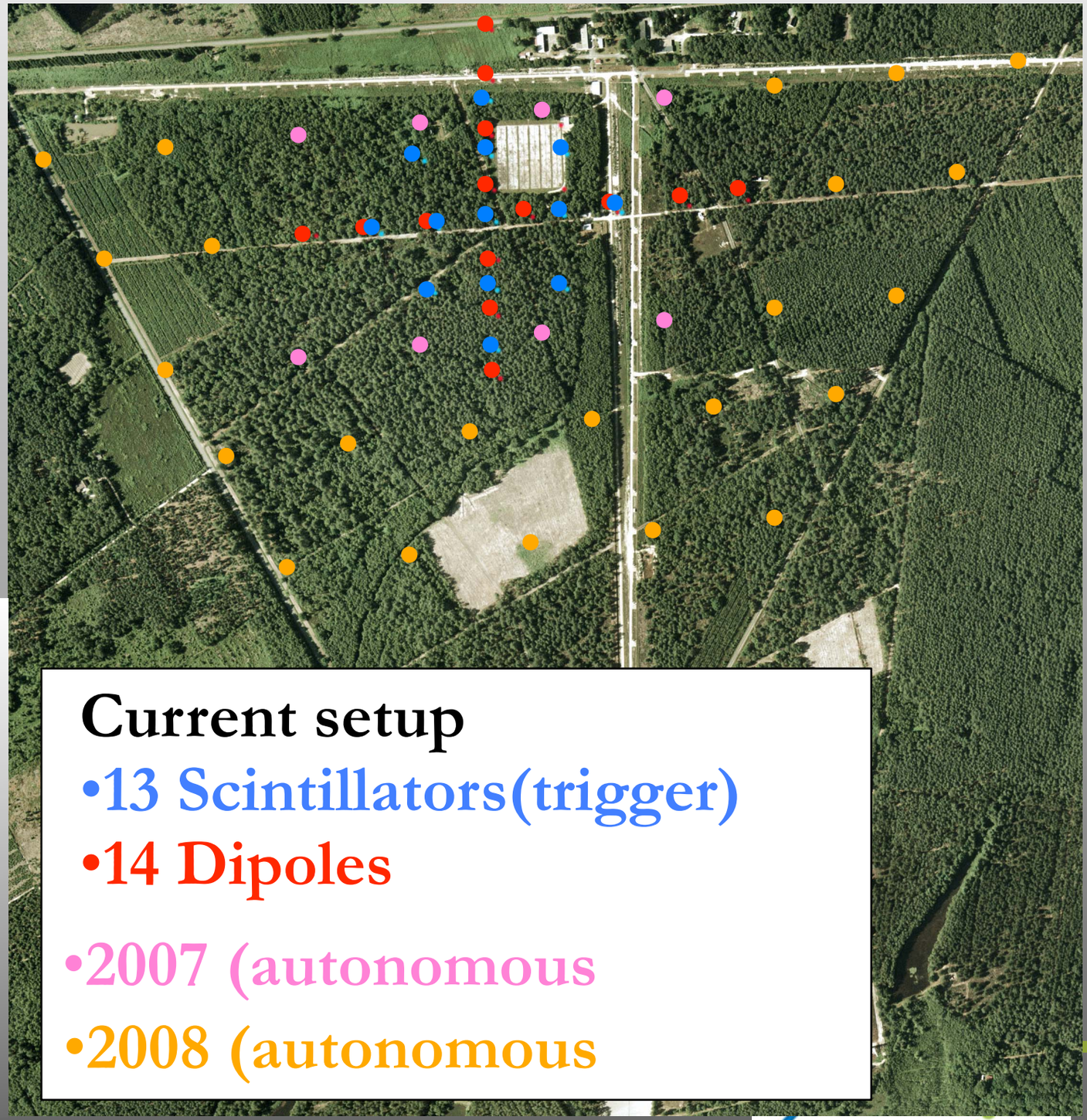
Braodband dipoles: schedule @ Nançay (2006-2008)

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

Setup of a 1 km^2 engineering array for a future giant radio-detector

Autonomous dipoles:

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



Current setup

- 13 Scintillators(trigger)
- 14 Dipoles
- 2007 (autonomous
- 2008 (autonomous

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Calibration Radio vs. Scintillators

Outer showers

Queue LDF Particules

distance

Inner shower 10^{17} eV

Outer shower 10^{18} eV

600 X 600 m

240 m X 240

Scintillateur

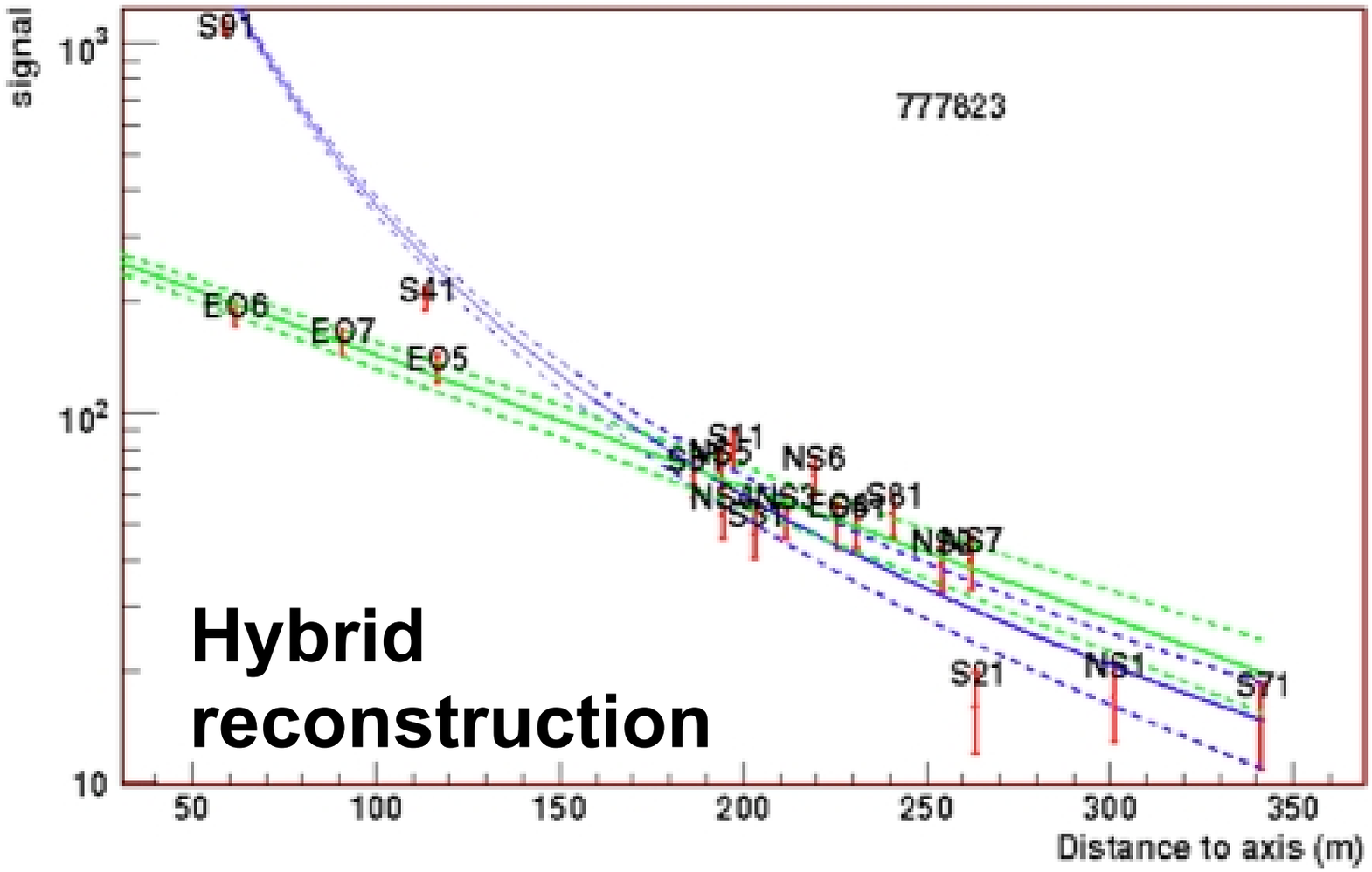
Dipole

DAM

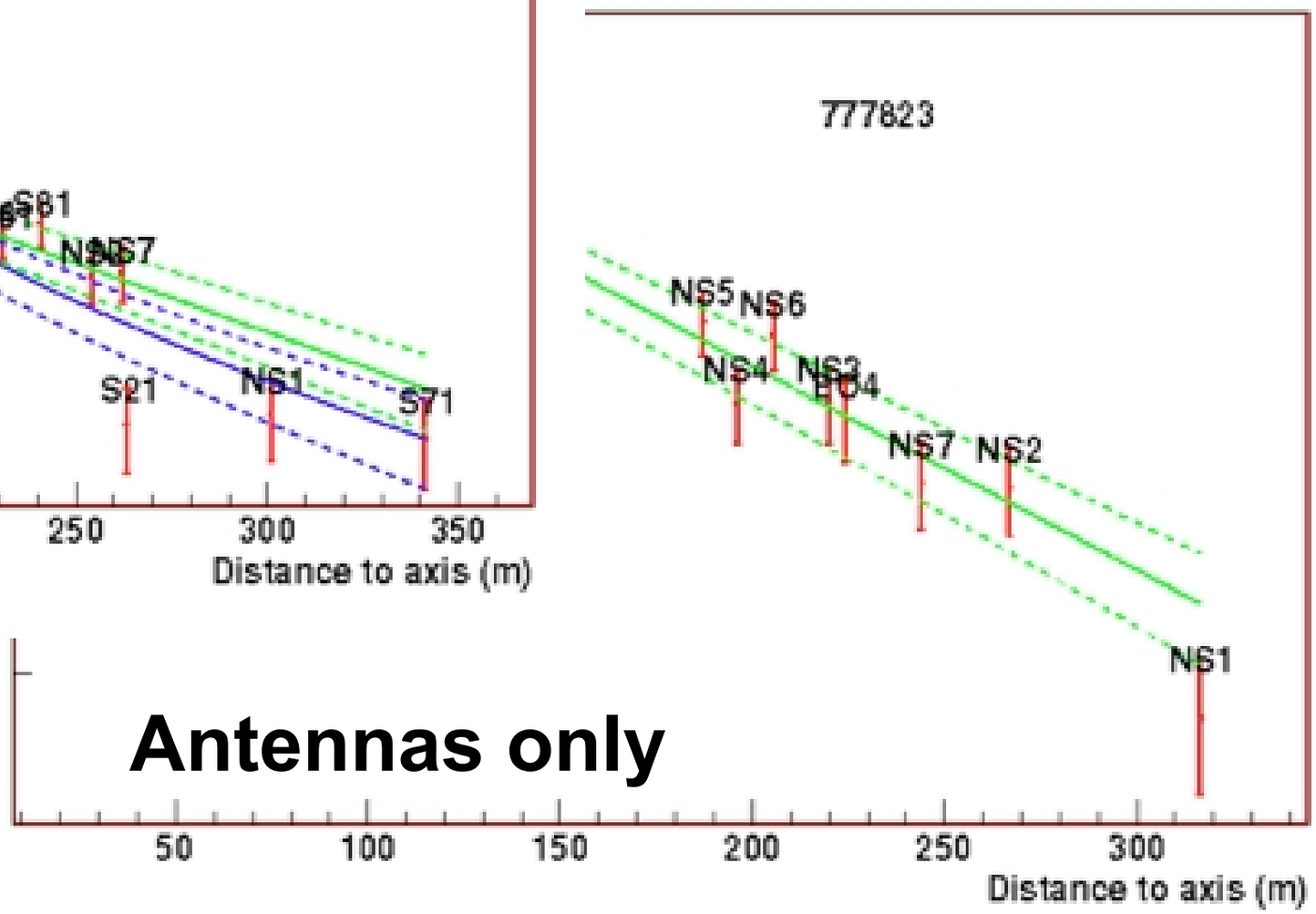
Goutelas 07/06/07

For

Single Event Analysis (1): LDF / field profiles



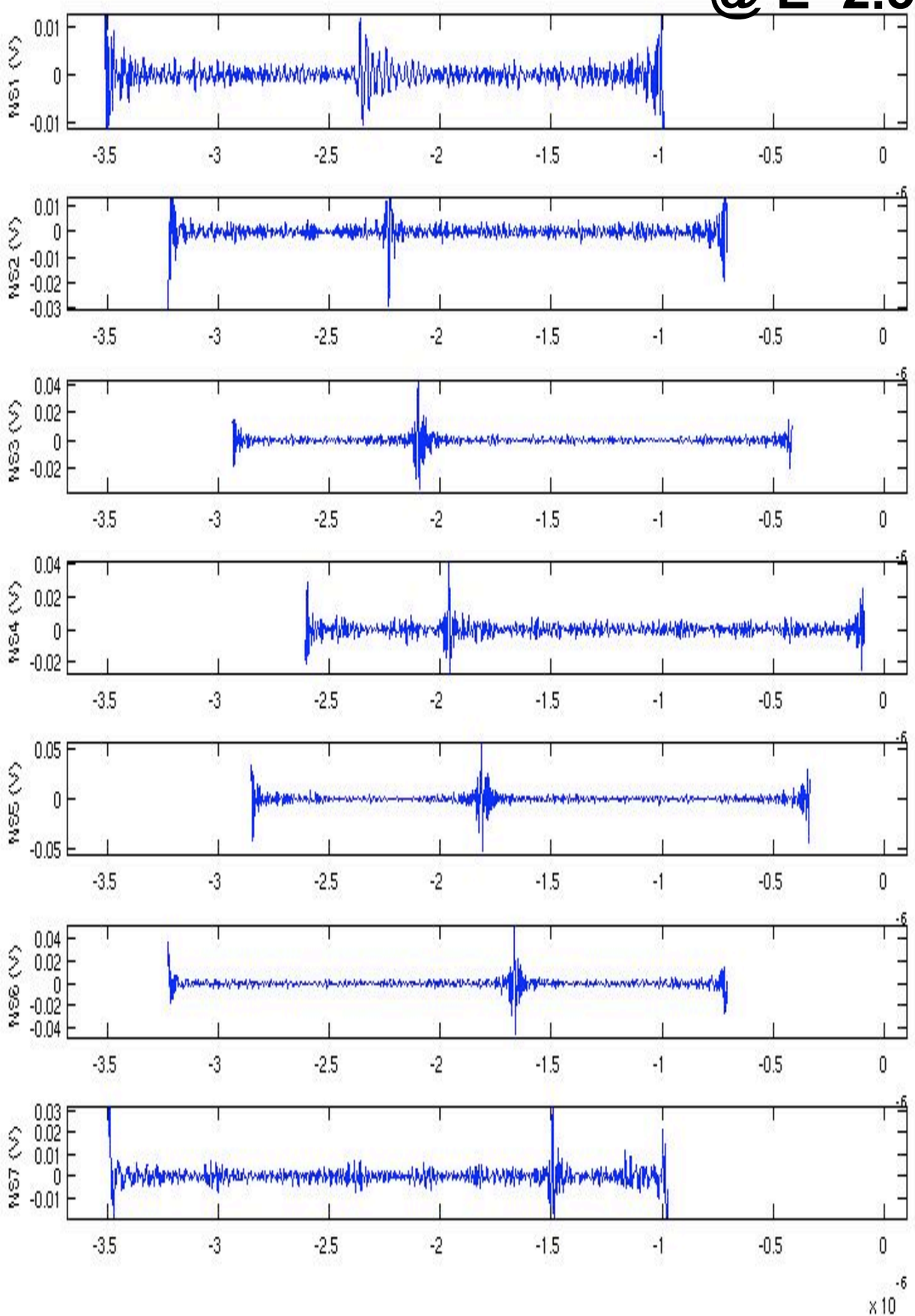
Hybrid reconstruction

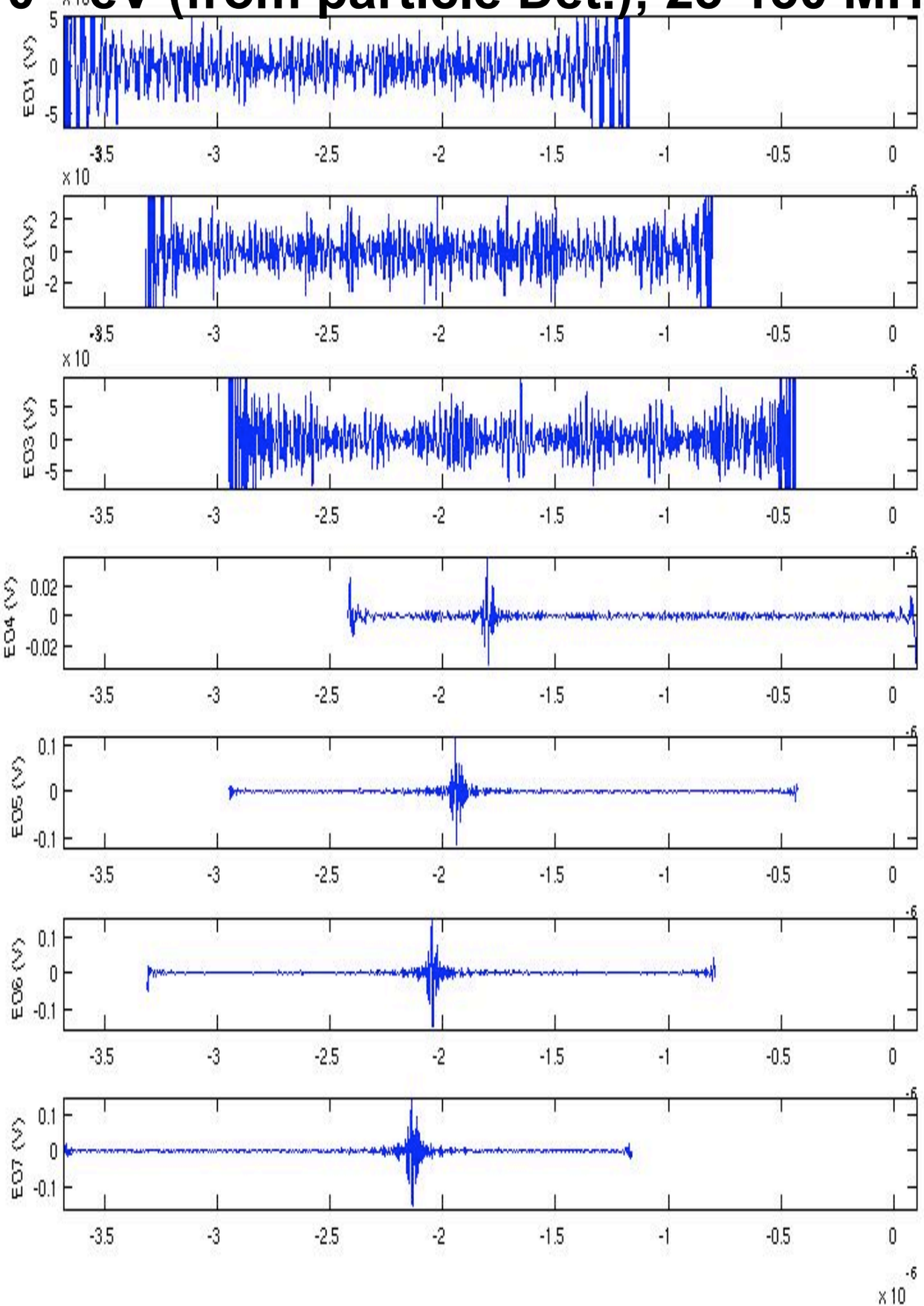


Antennas only

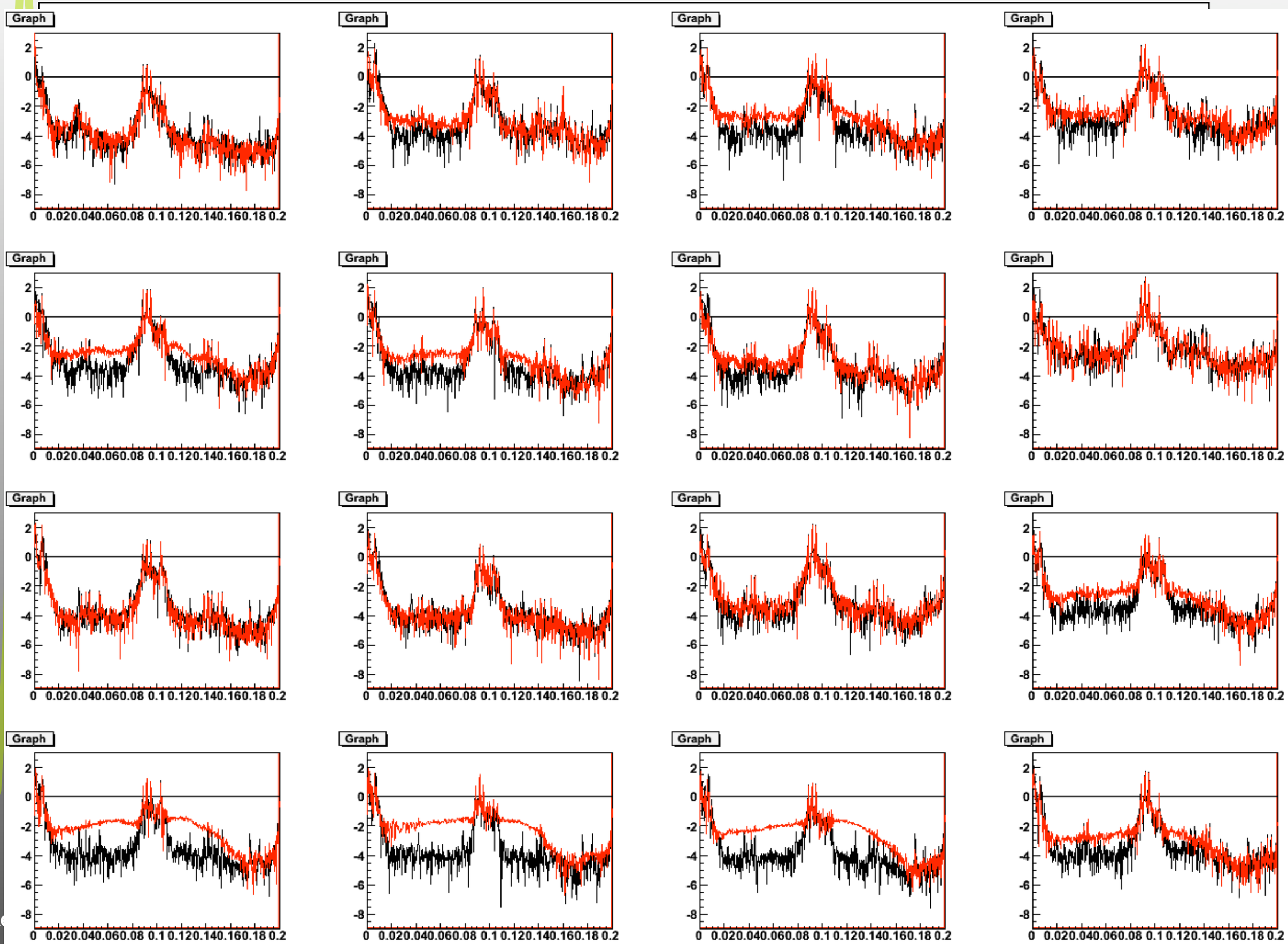
Dipoles: single event analysis (2)

@ E~2.5 10^{18} eV (from particle Det.); 23-130 MHz

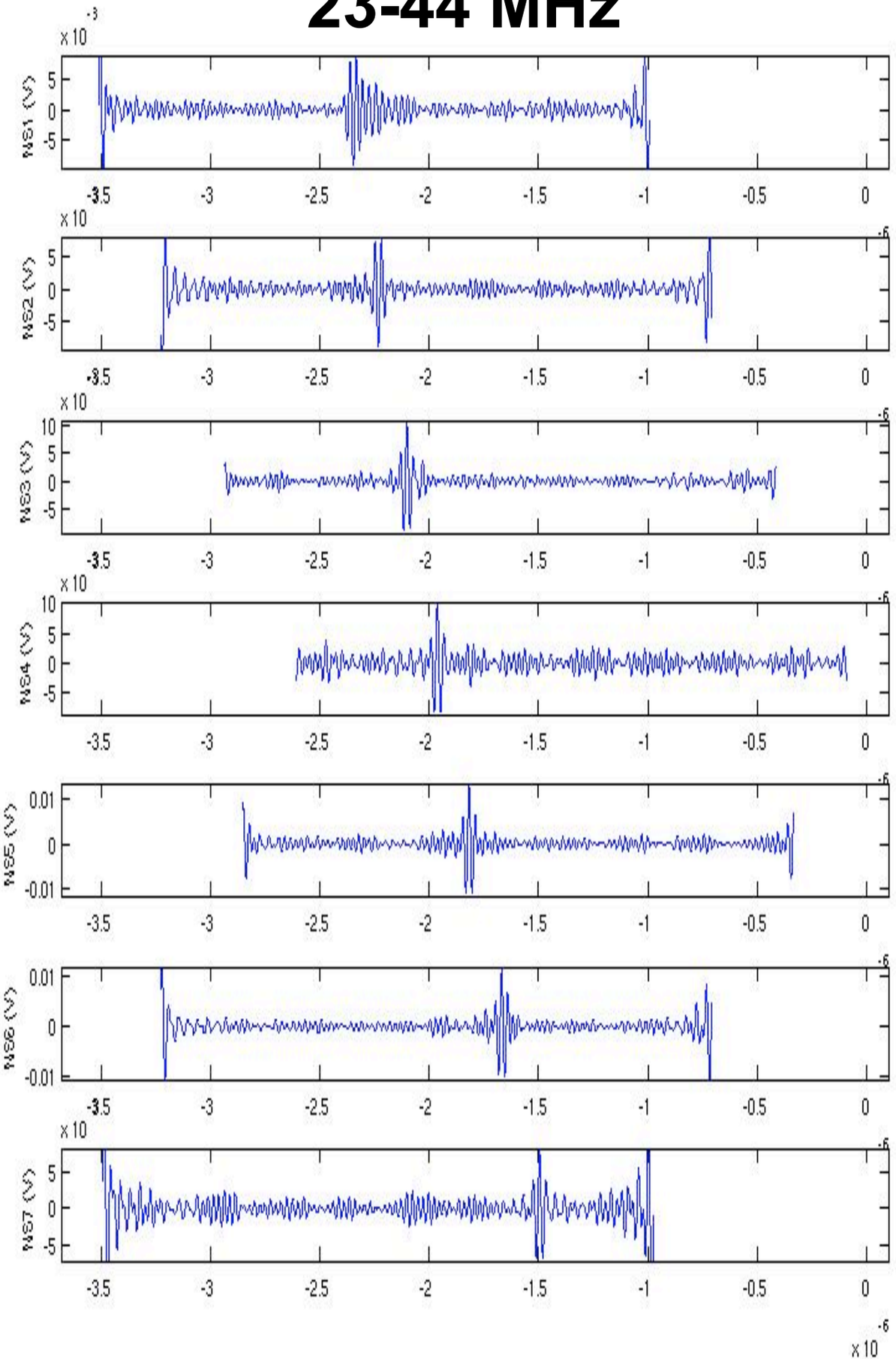




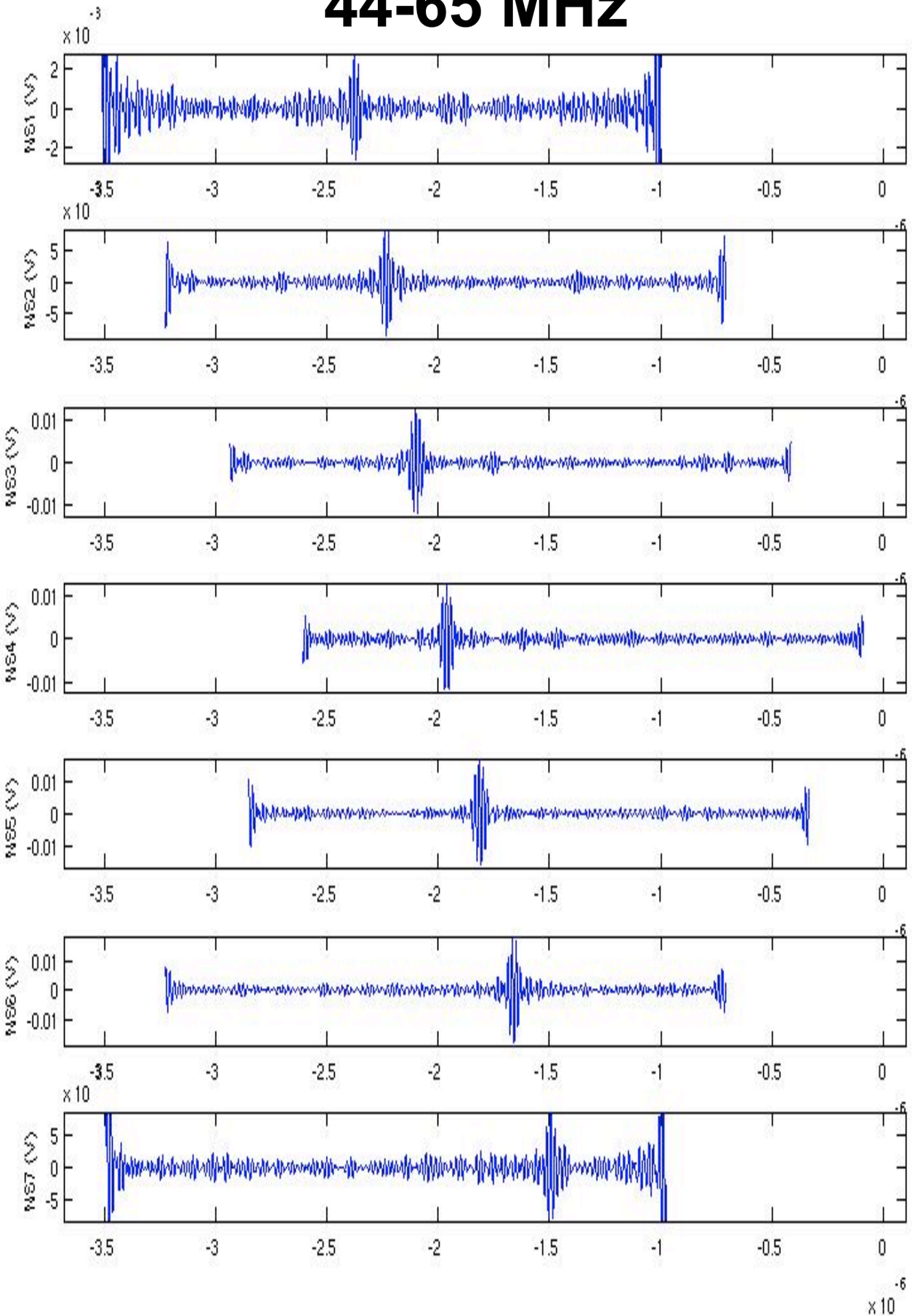
Single Event Analysis (3)



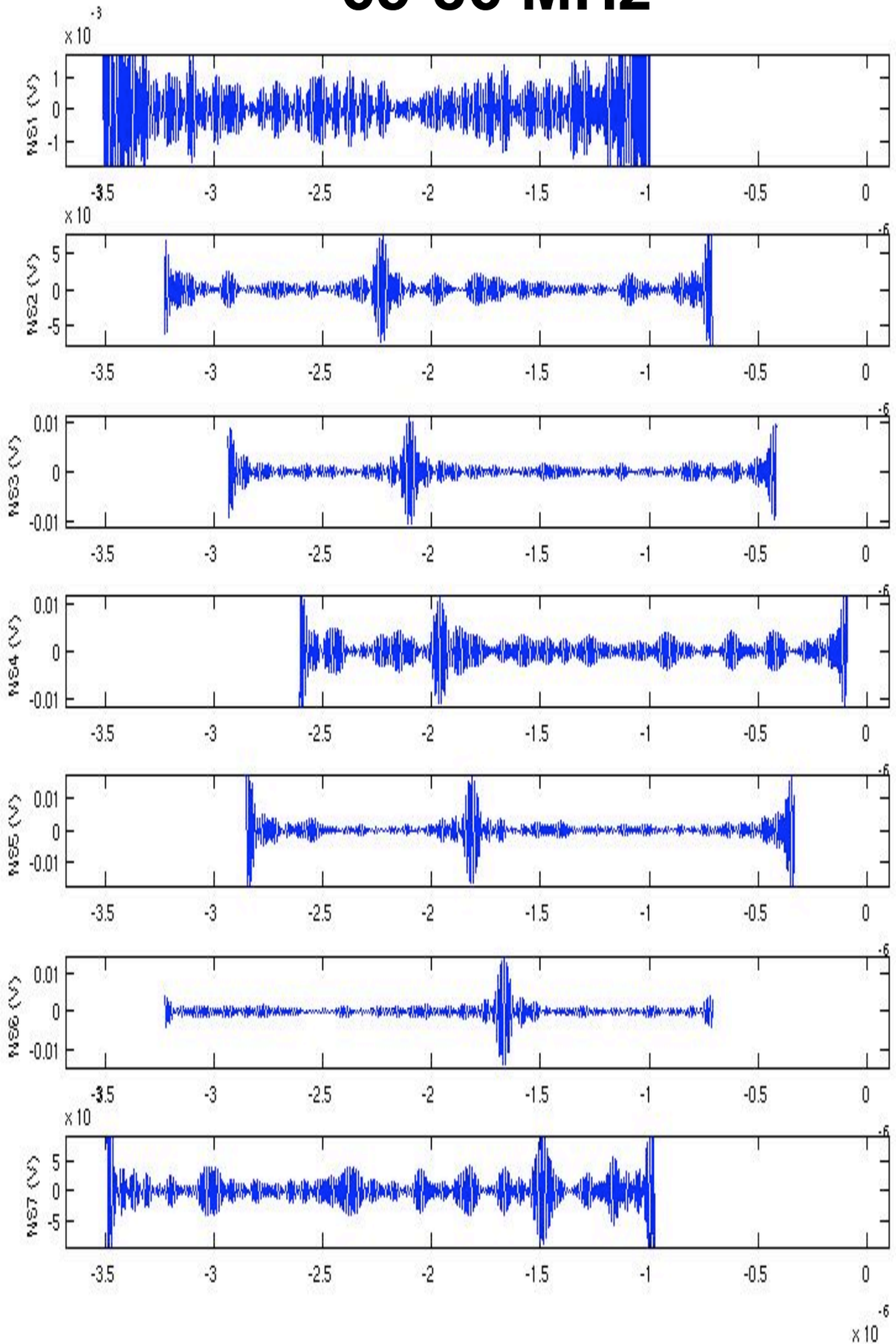
23-44 MHz



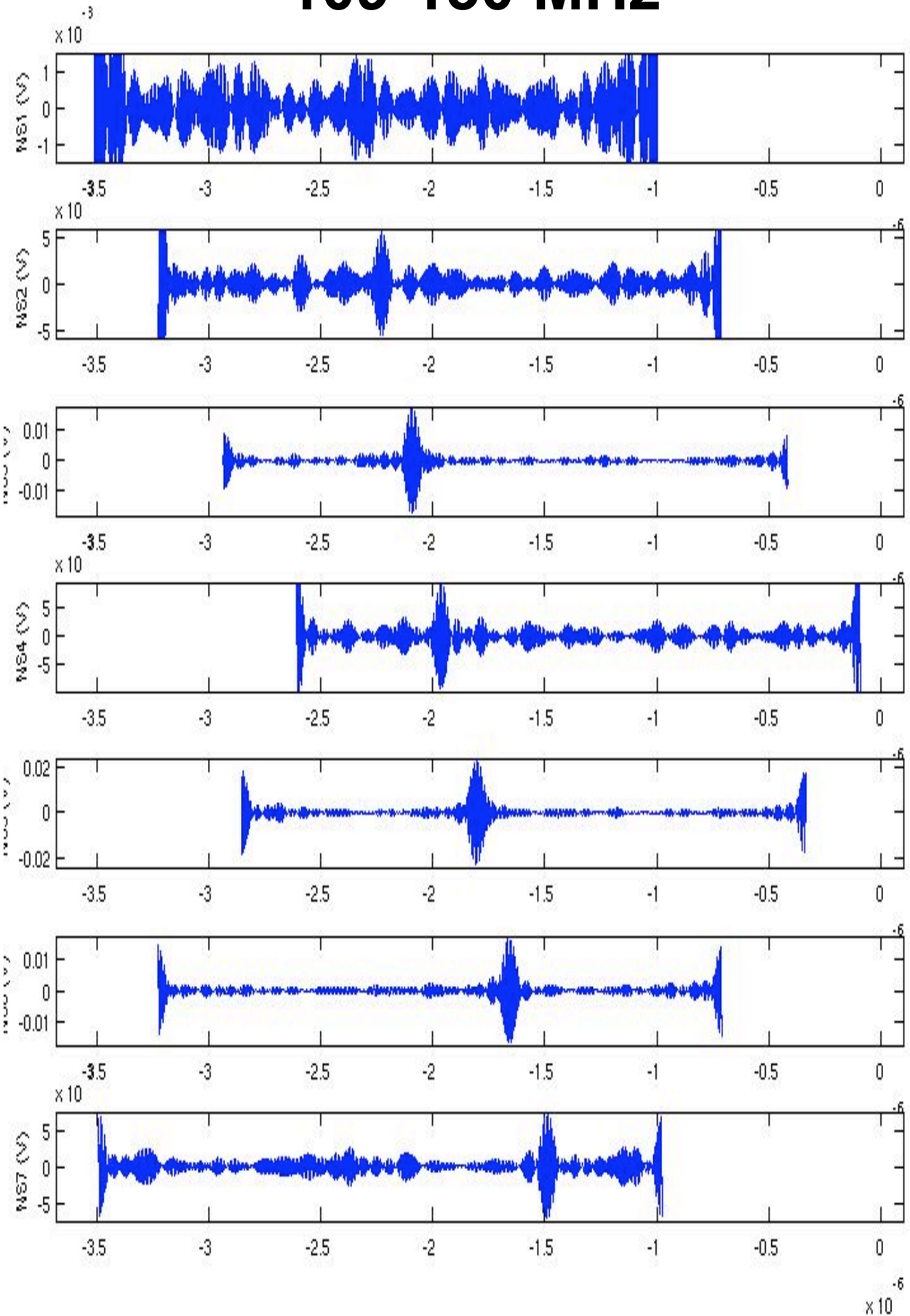
44-65 MHz



65-86 MHz



109-130 MHz



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)

200

To demonstrate

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

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For the CODALEMA collaboration

Theory: what approach ?

Geosynchrotron 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 to determine the main effect (recently implemented on CODALEMA)

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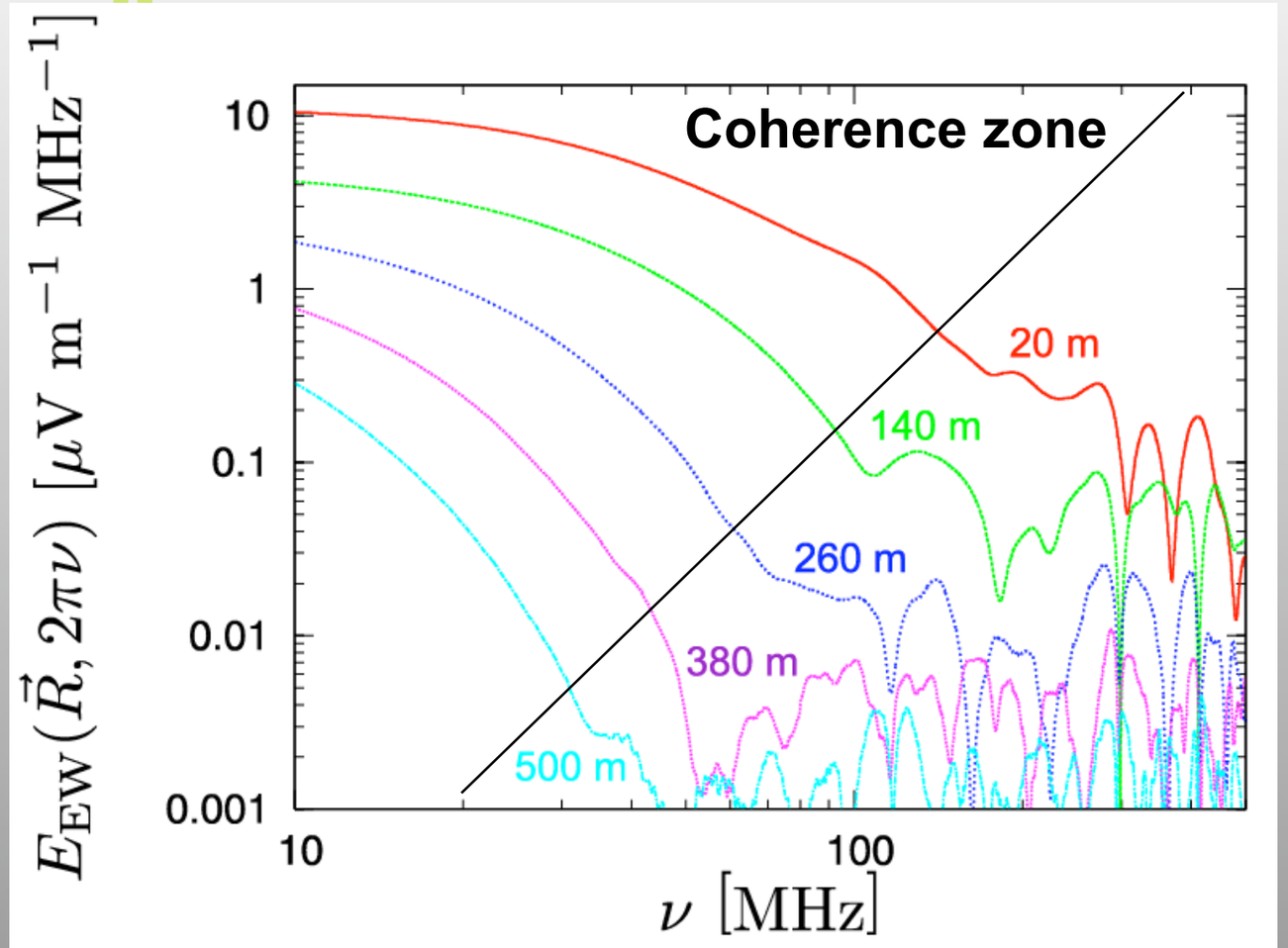
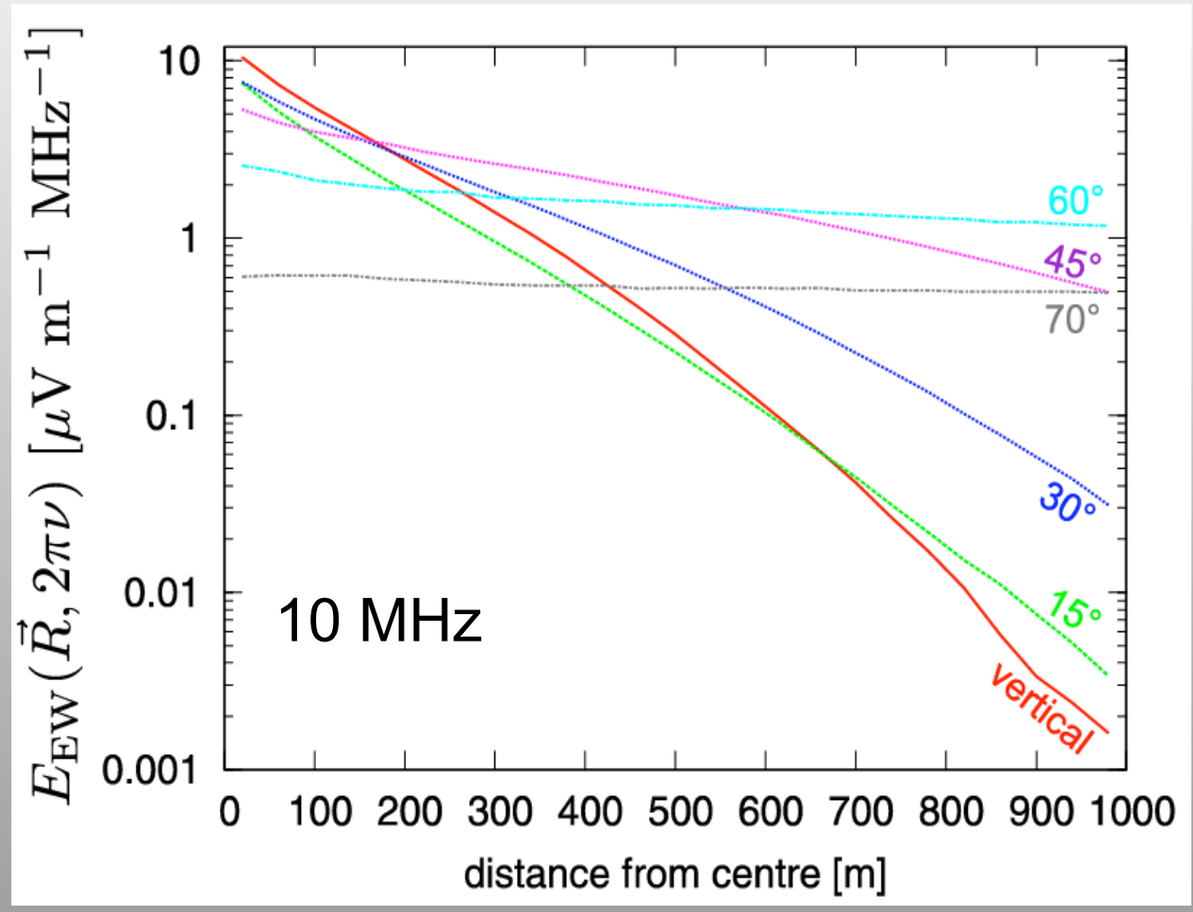
T. Huege: Frequency spectra @ 10^{17} eV





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

- Favourable for inclined showers
- Approx. Exponential scaling

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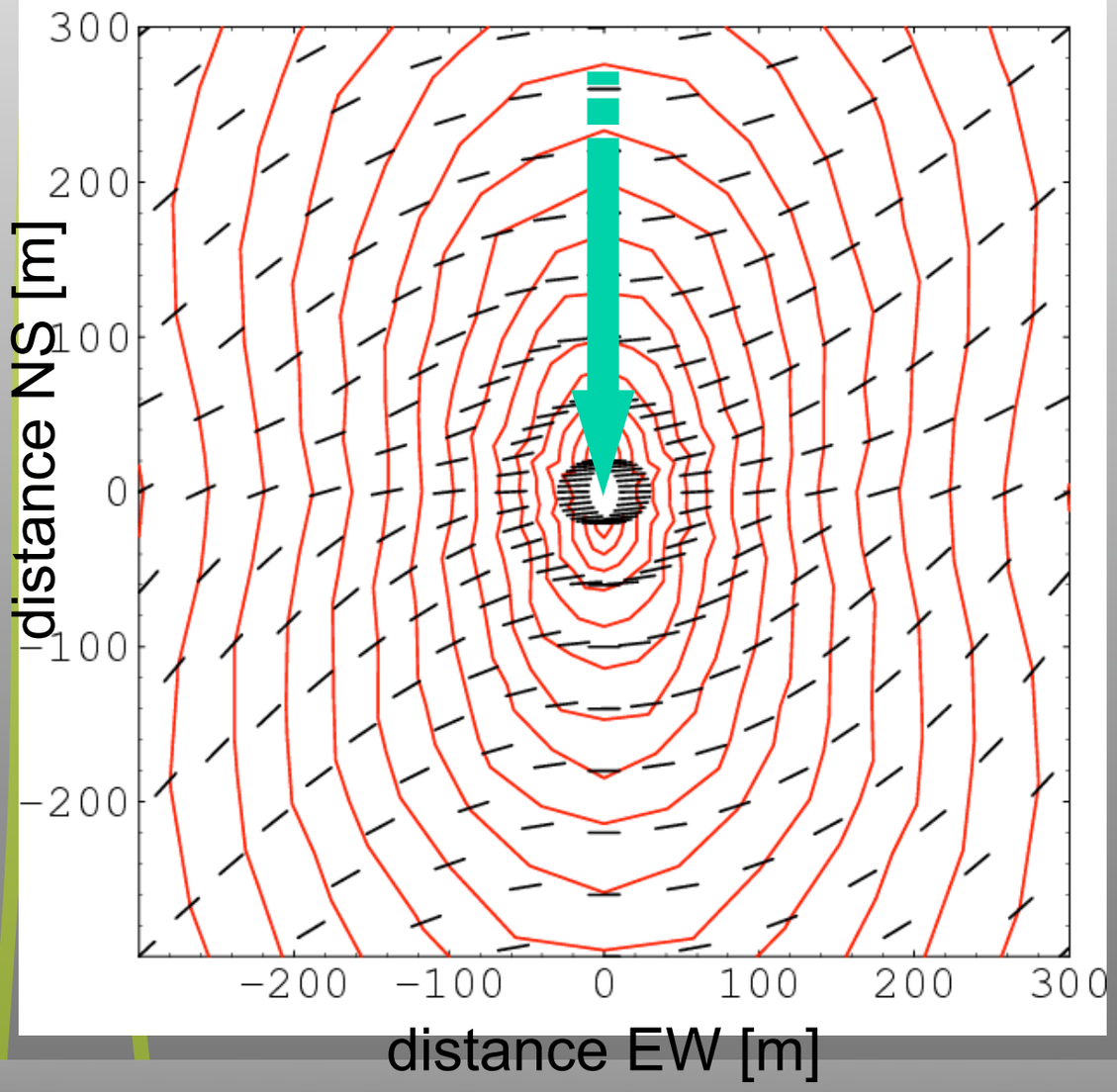
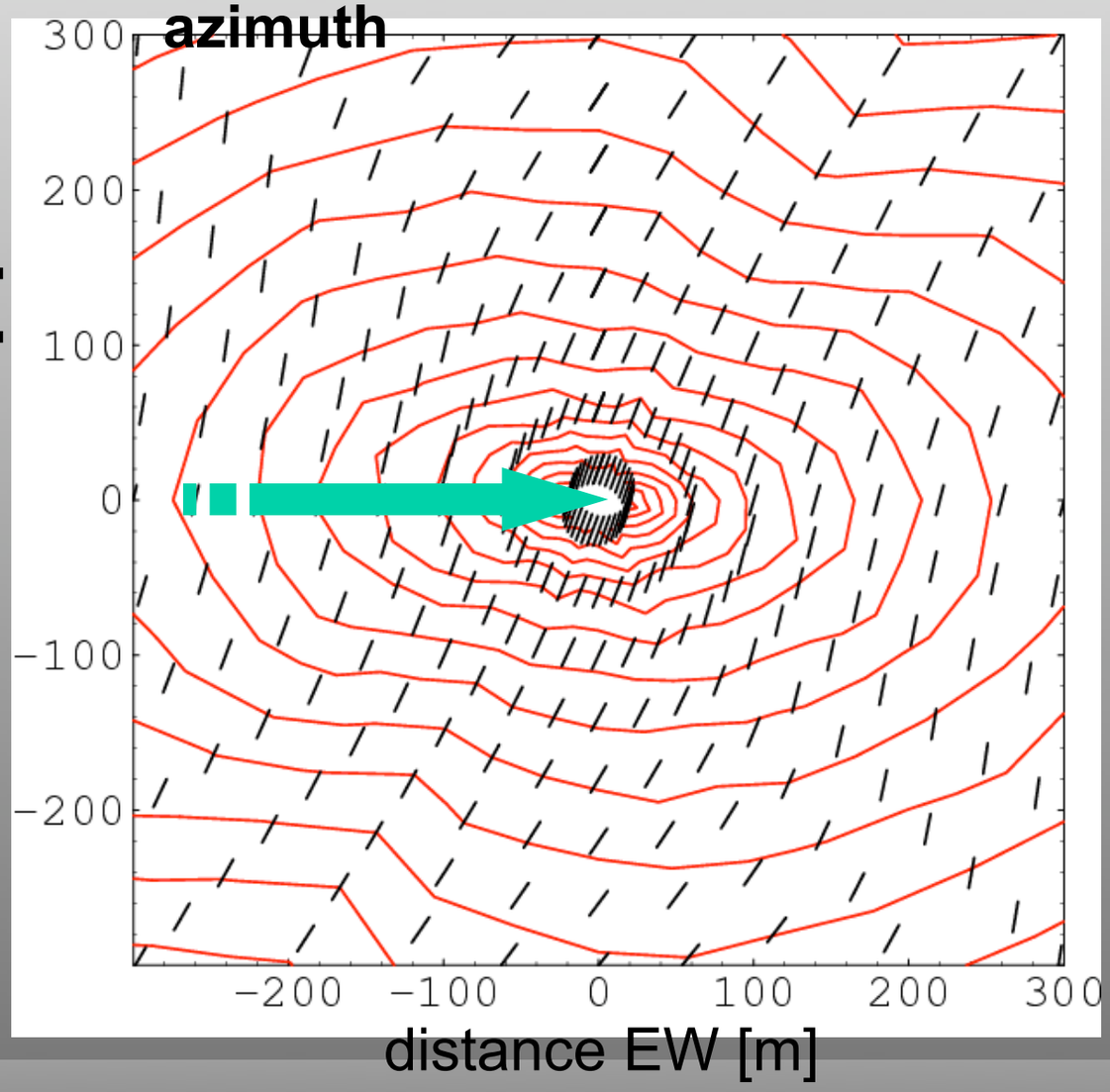
Total field strength emission pattern and ratio of east-west to north-south linear polarisation

45° zenith angle, 0° azimuth



45° zenith angle, 90° azimuth



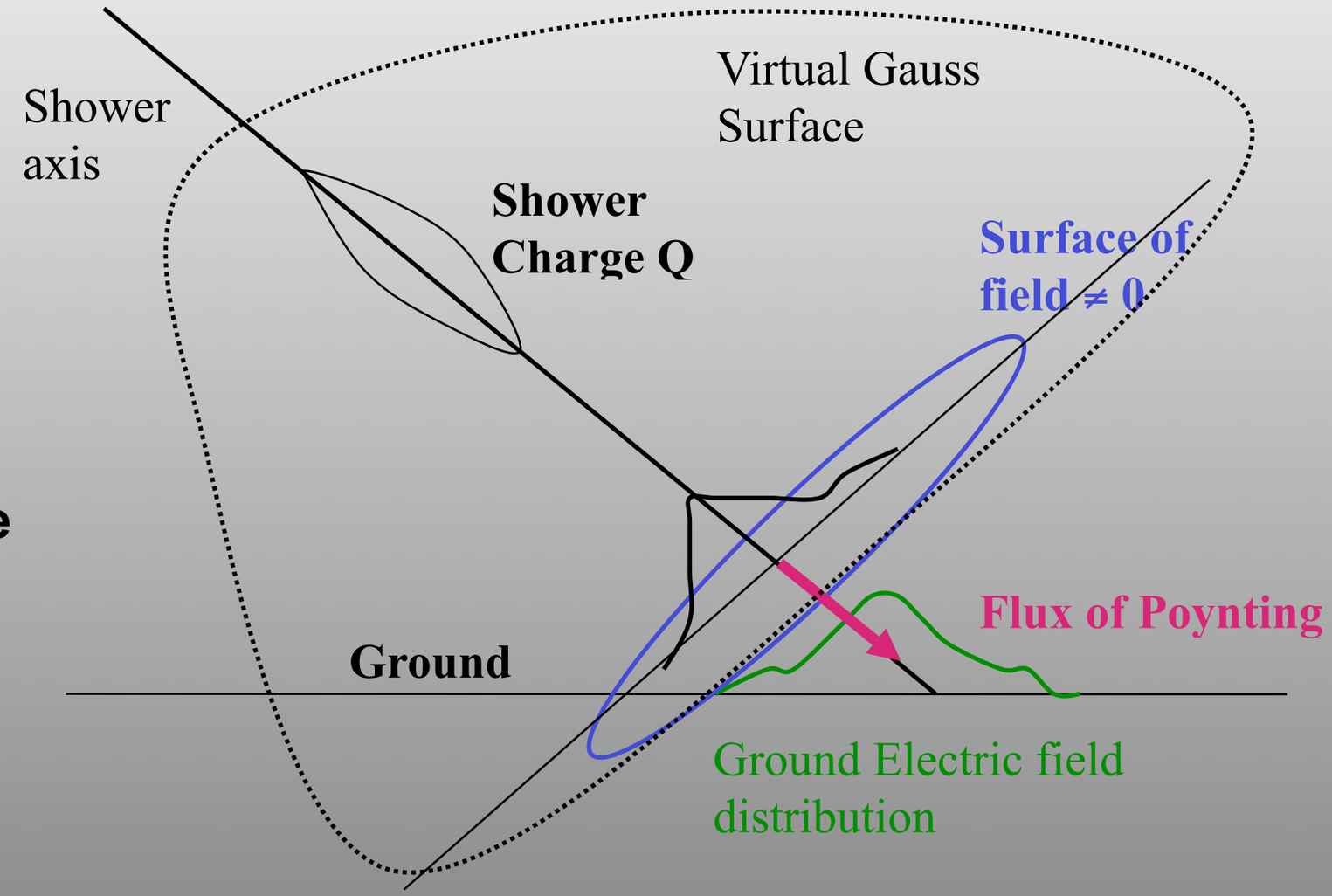
Most power in polarization direction ⊥ to B-field and shower axes

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…) ??

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

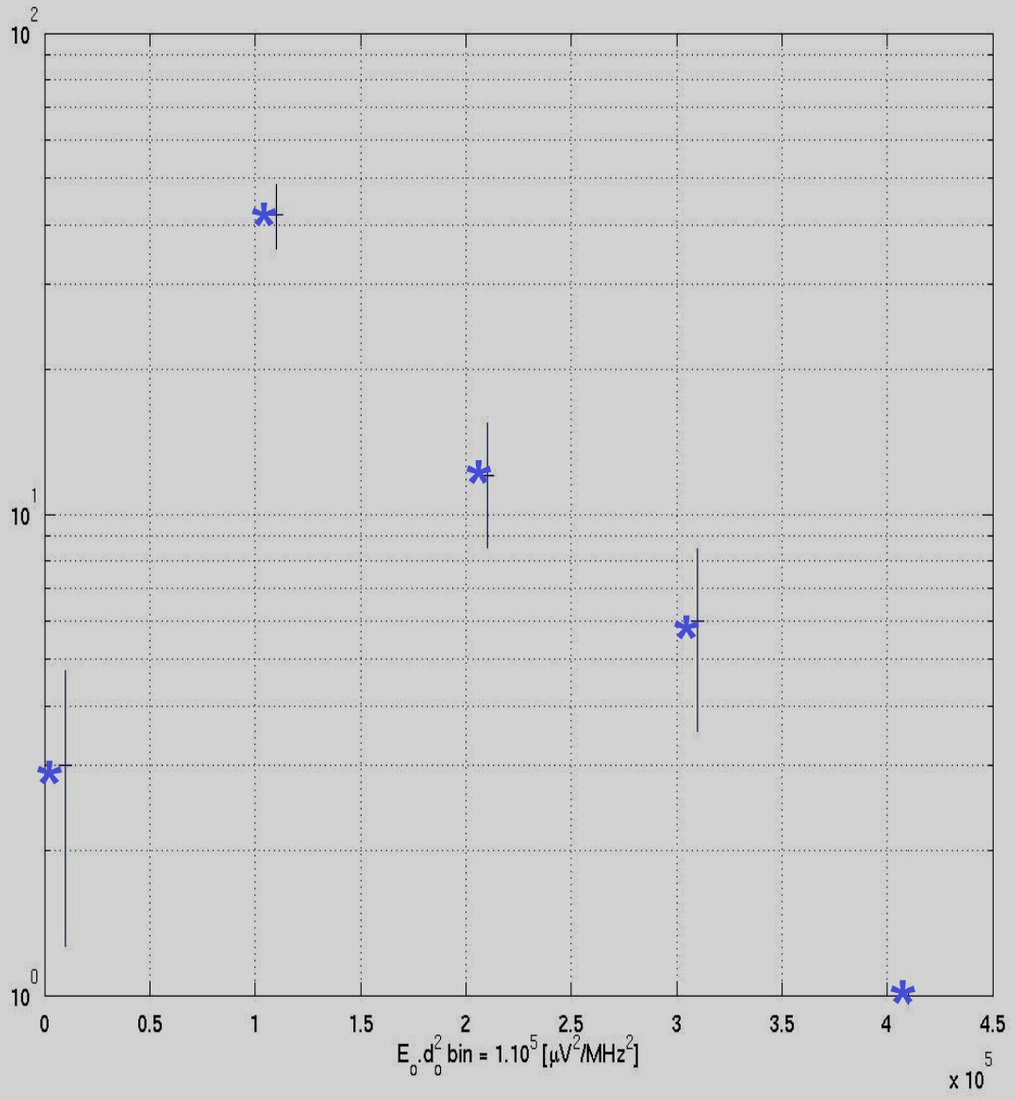
RADIATED ENERGY (geosynchrotron,…Poynting) ??

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

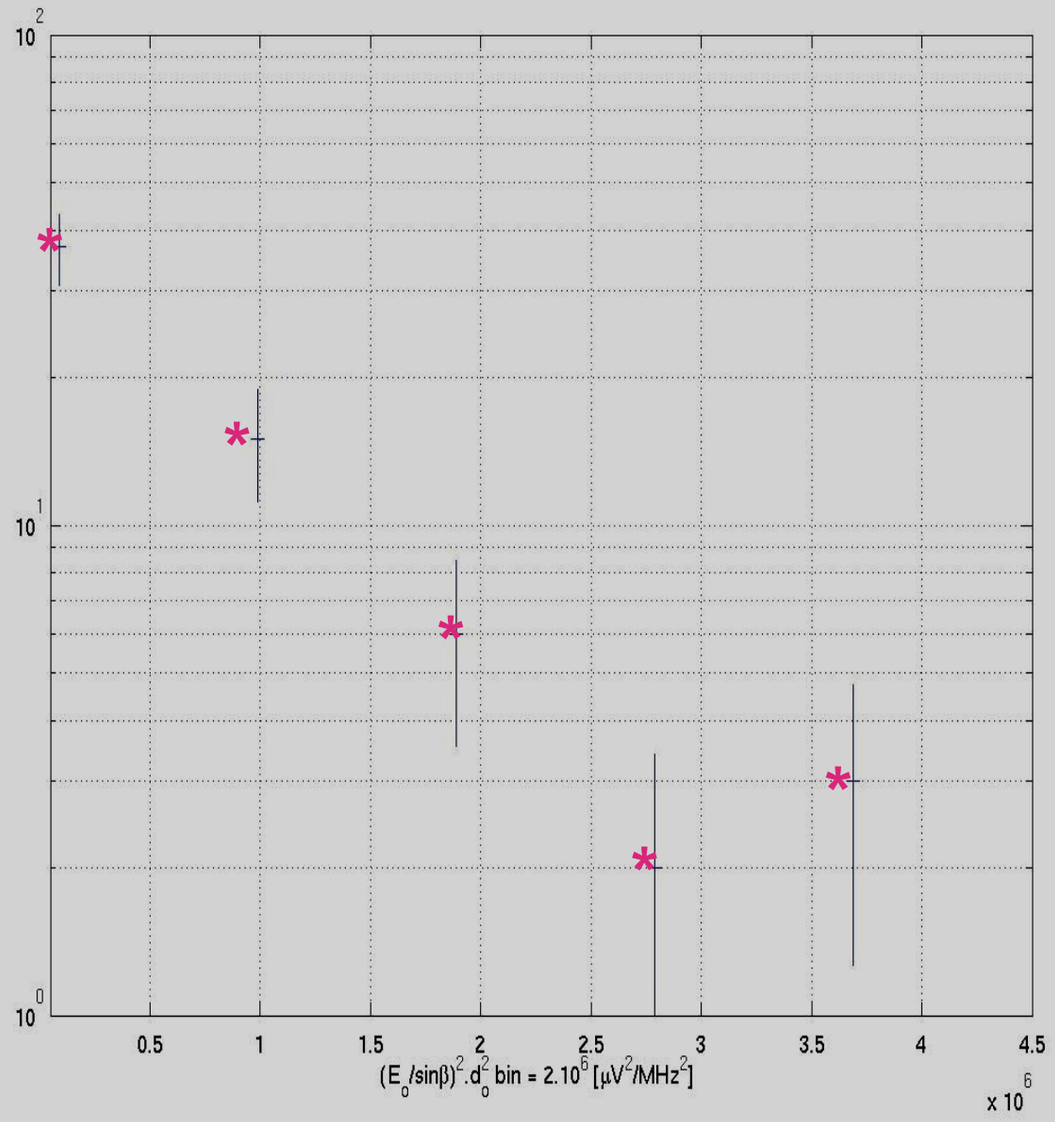
Tentative of energy estimation (2)

(very preliminary)

E_0 . d_0^2 spectrum (a.u.)



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



Need more statistics

Résultats « confidentiels »… Diapo supprimée.

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RAuger: Radio @ Auger

Radio tests on the South Auger site, Malargüe, Argentina

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For the CODALEMA collaboration

Goutelas 07/06/07

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

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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)

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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

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3 autonomous, self triggered antennas

- Independent power
- Independent trigger
- Digitization system
- Time tagging system
- Data transmission (WiFi)
- Central acquisition system

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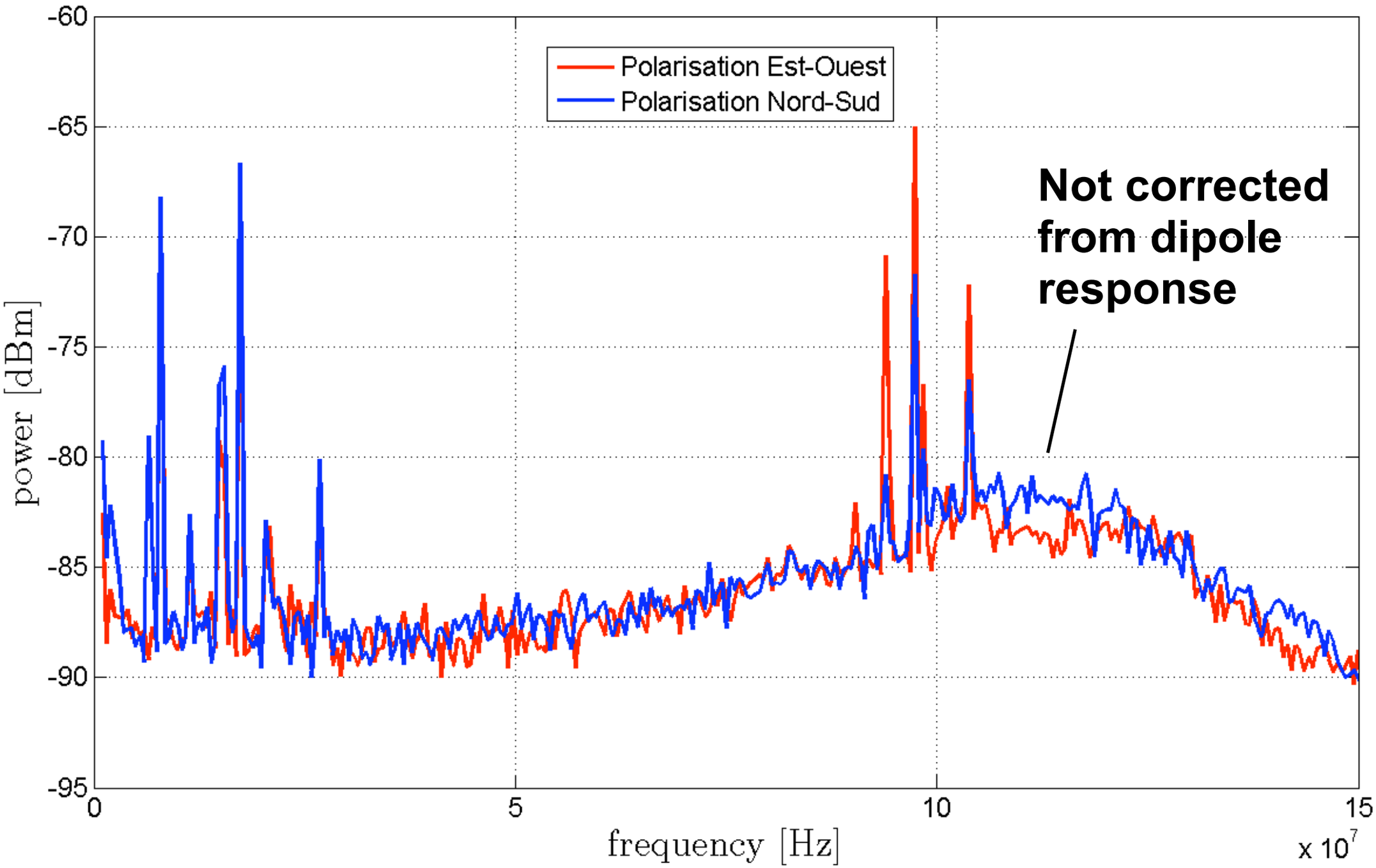
Sky background @ Auger



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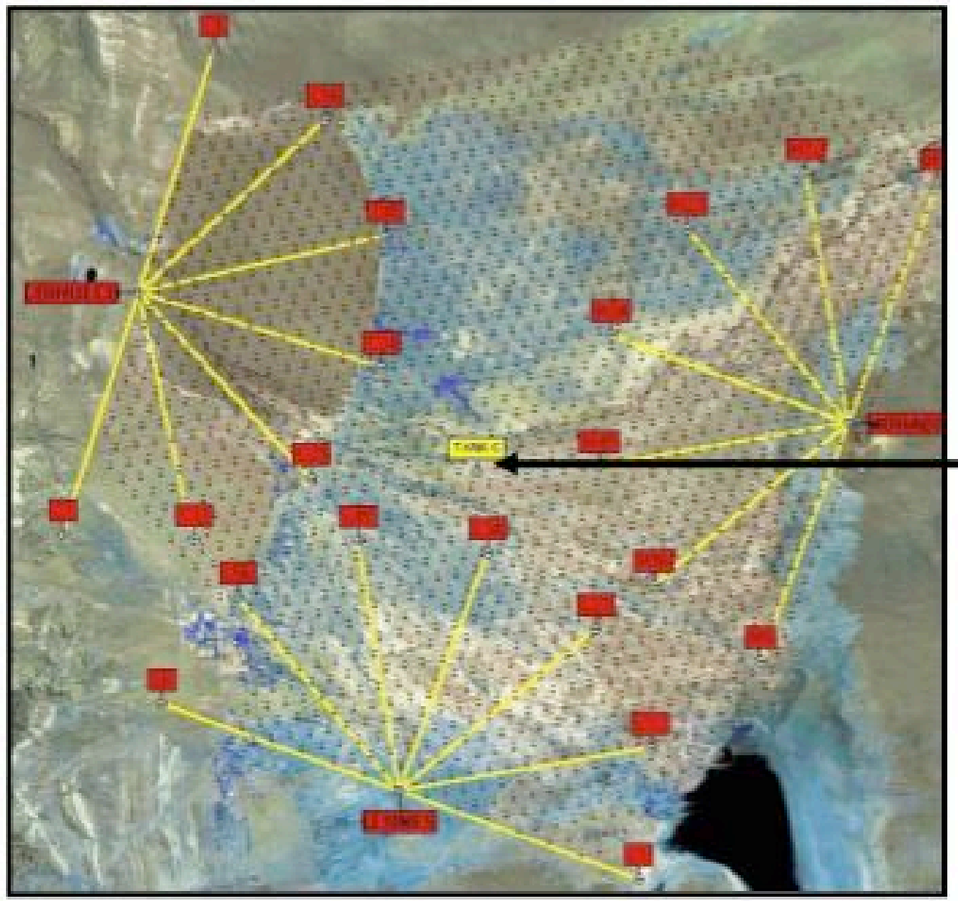
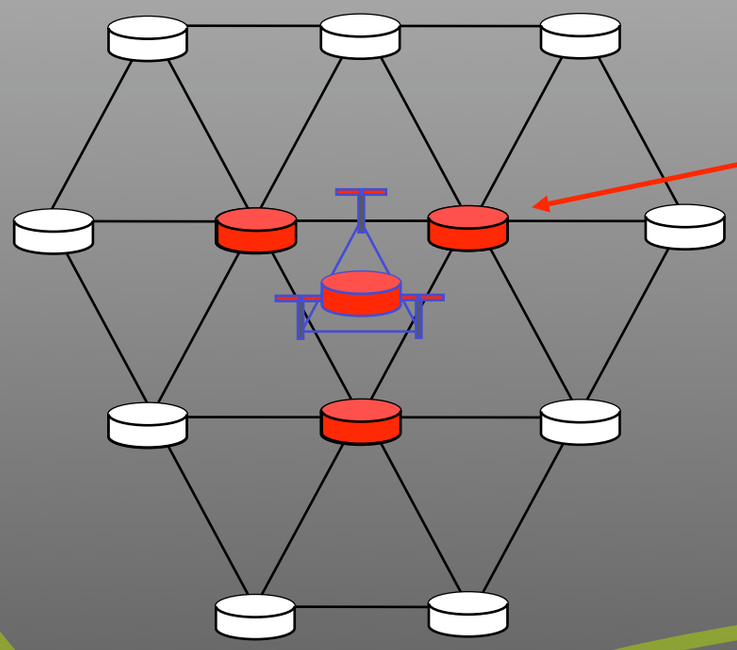


Pierre Auger Observatory

Central Laser Facility

SD Tank



Location: CLF

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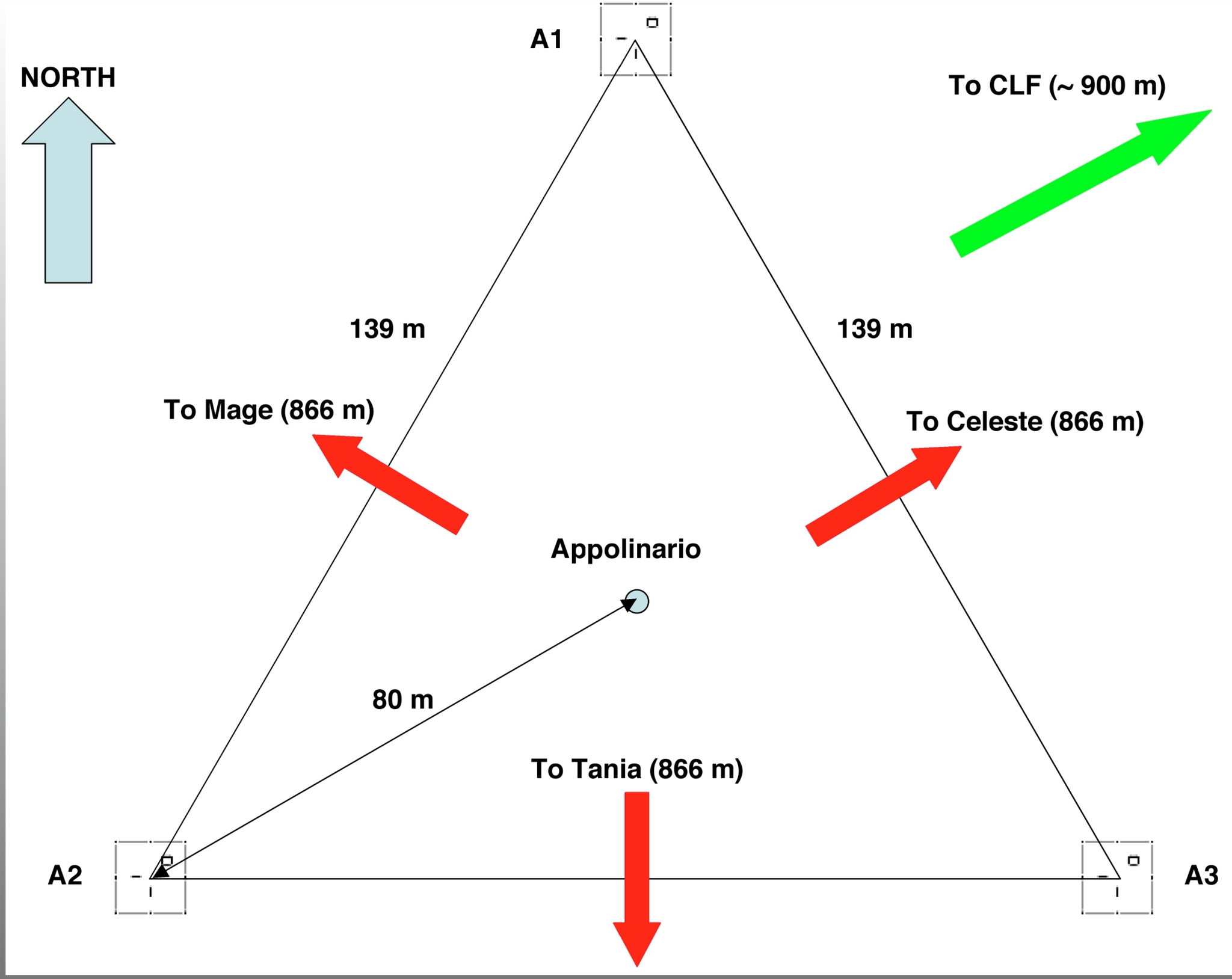

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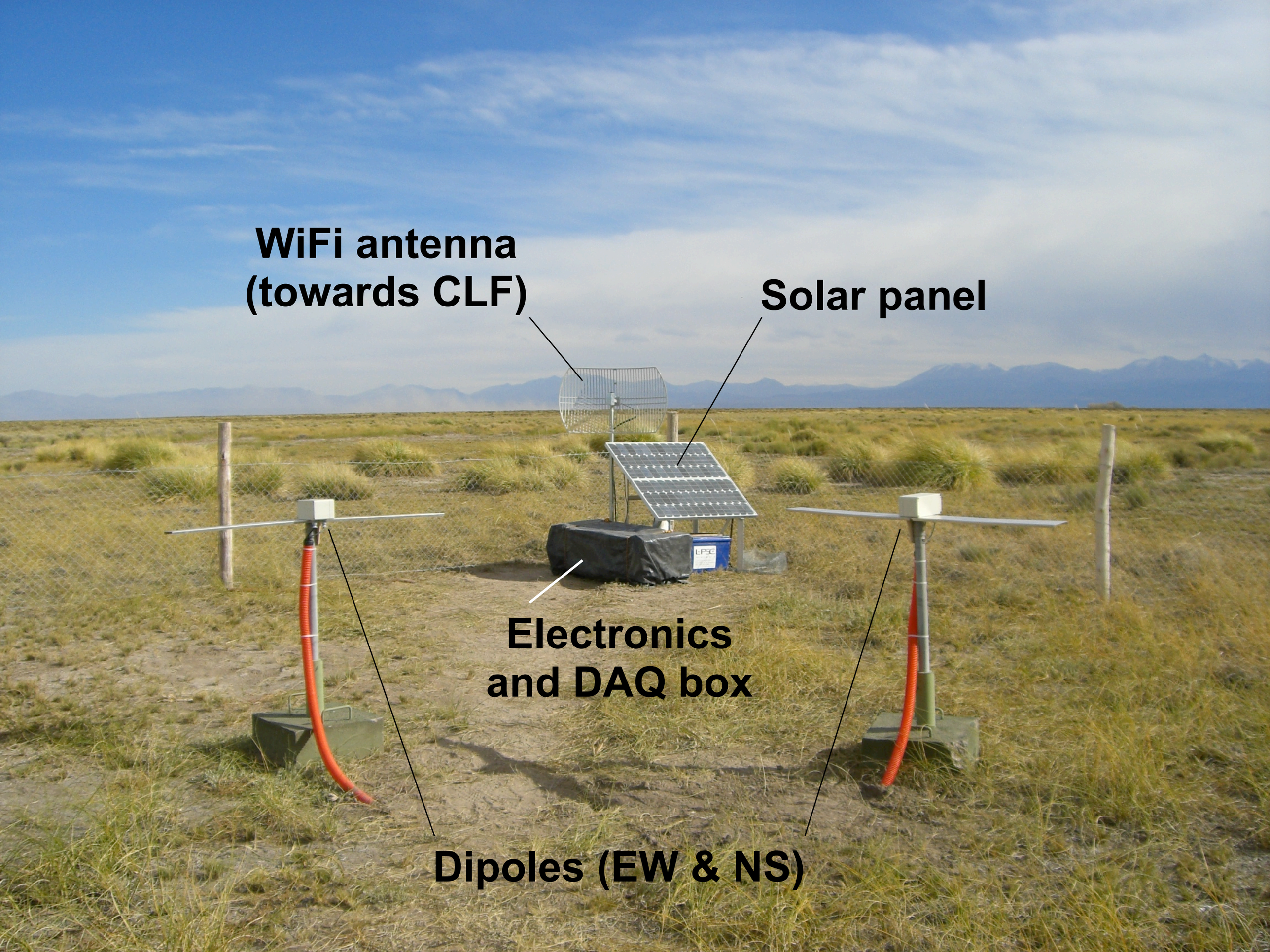
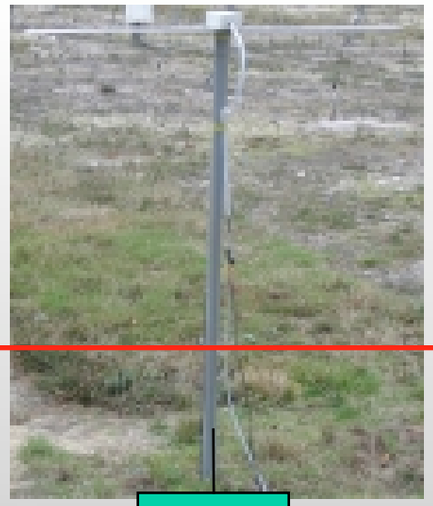

WiFi antenna
(towards CLF)
Solar panel
Electronics
and DAQ box
Dipoles (EW & NS)

Single autonomous detector layout



Dipole antenna

+ Front End (ASIC)

Splitter 1
50 Ω

Filter

Splitter 2

Trigger

F
B

R
B

Unified Board

CPU

GPS time tagging

Memory buffer

Ext. TRG

Serial link

Scope

Serial link

FB : Full Band 1-100 MHz
RB : Restricted Band 24-82 MHz or less

Central PC (storage)

Receiver

Radio modem link

Emitter

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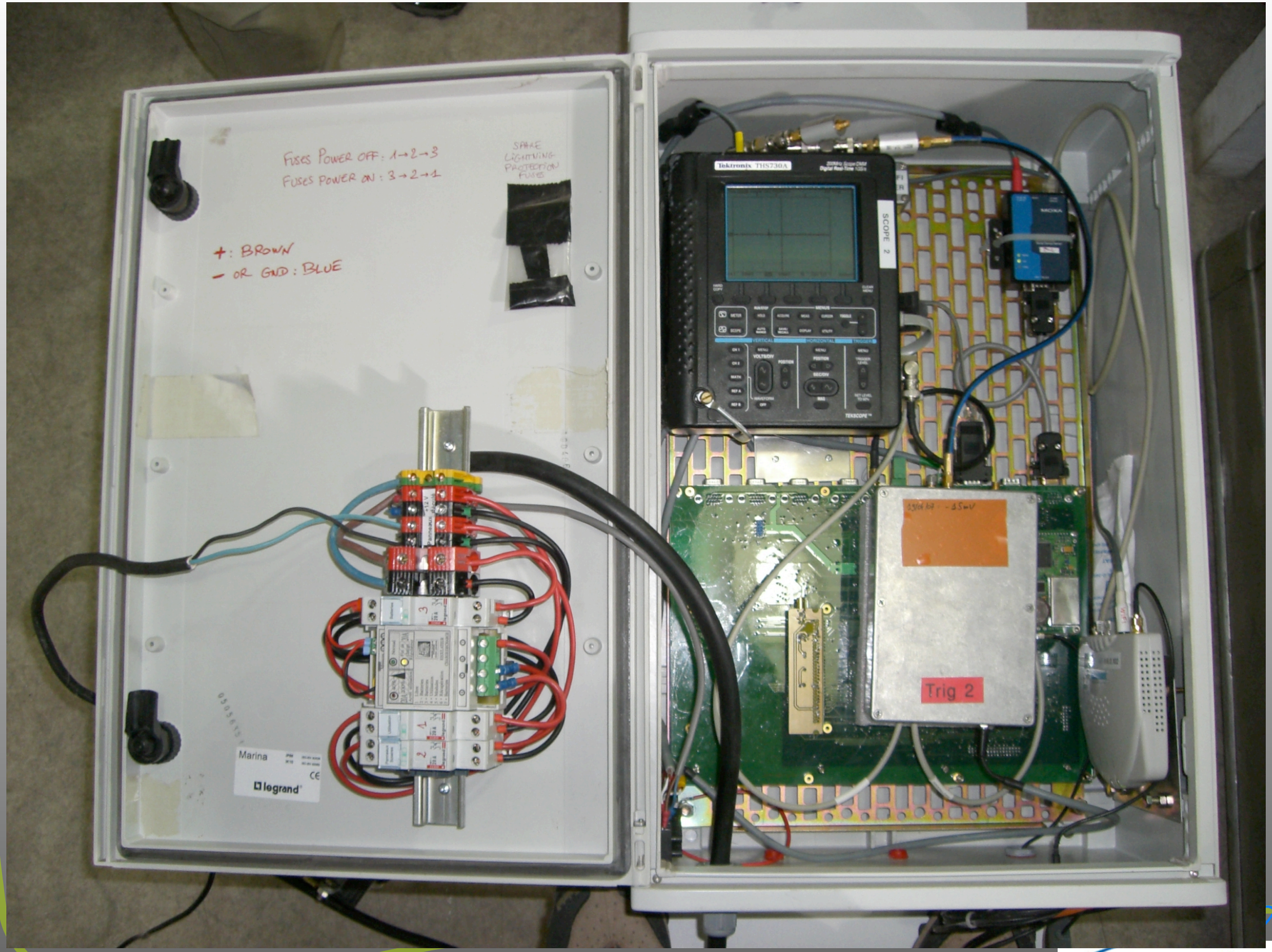
Goutelas 07/06/07



Goutelas 07/06/07

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- **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**

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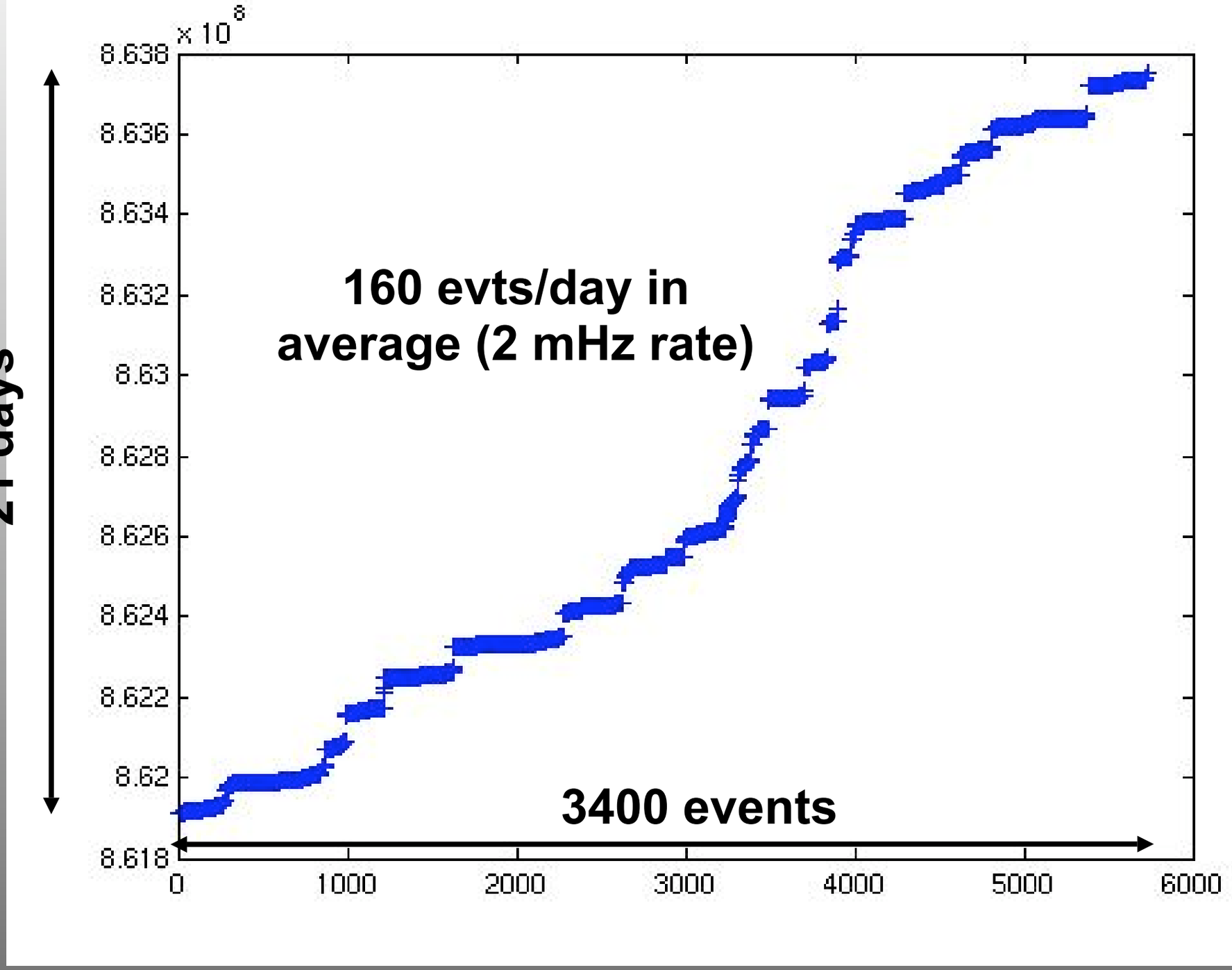
Trigger rate on 1 station



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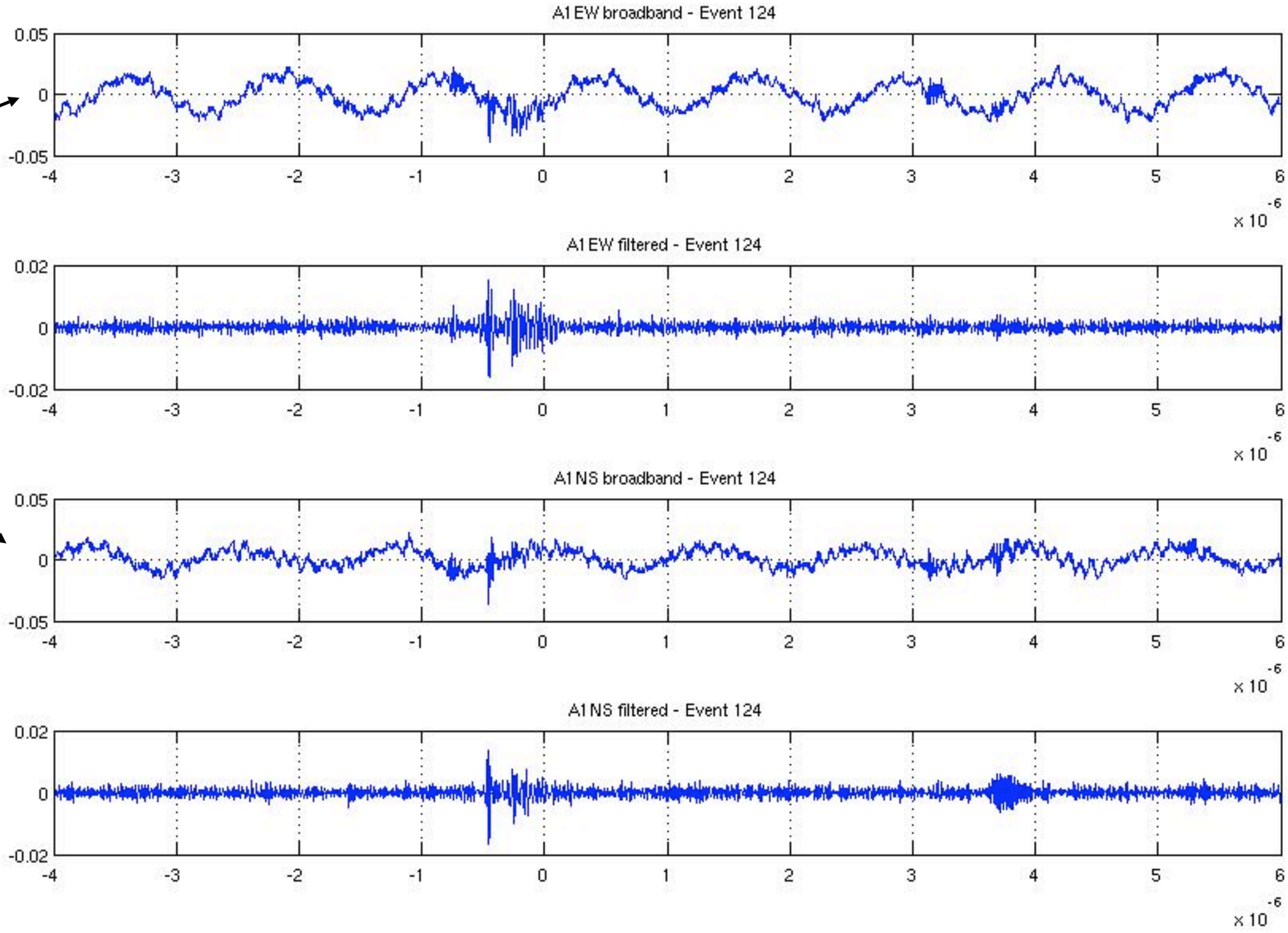
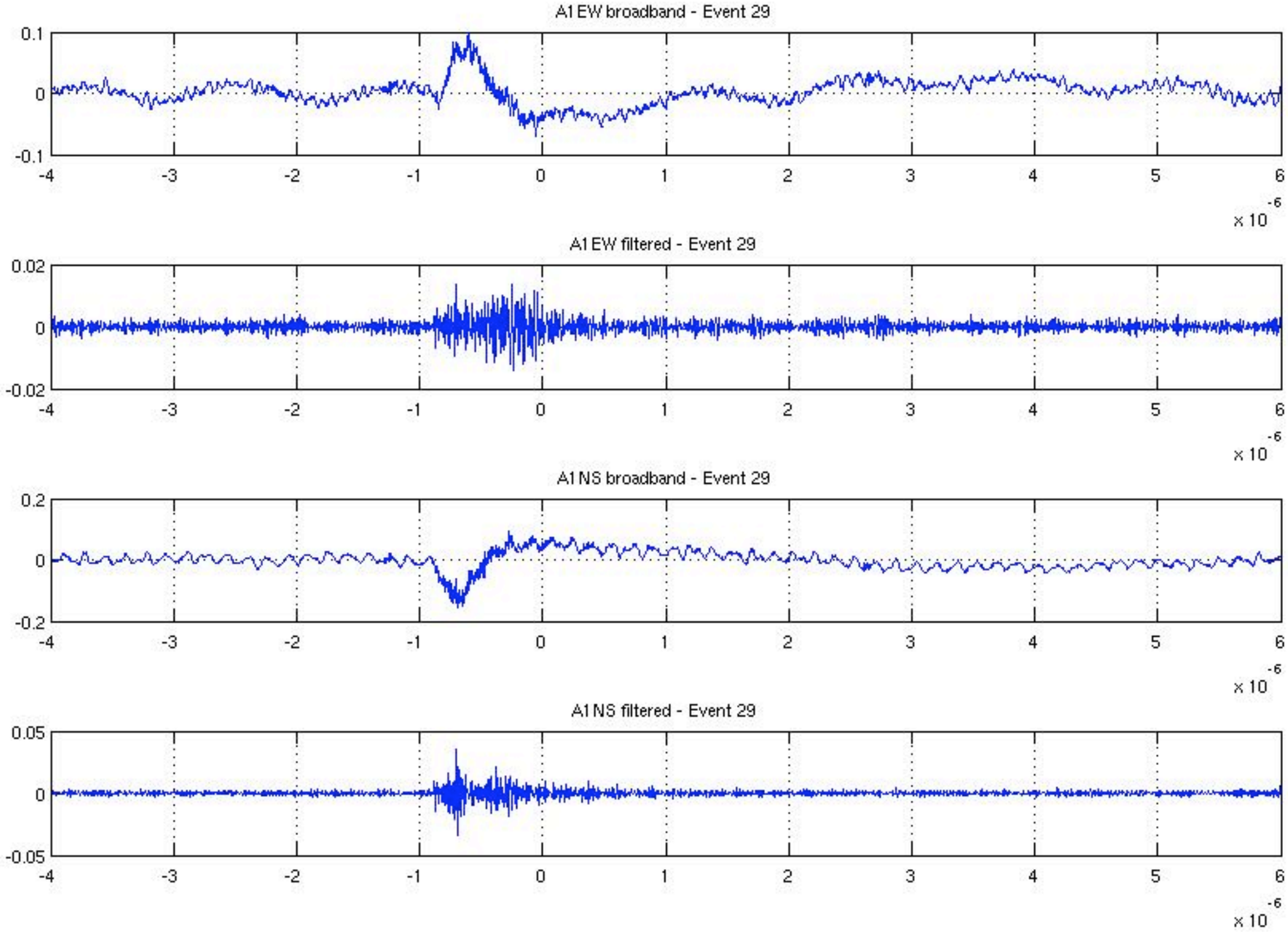
Zoology of events: 1- Fast "electronics" transients

LW radio @ 780 kHz



2- Slower "natural" - at least external - transients

Inverted polarity



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3- (quite certainly) Far storm events

Lightning precursor ?