Wavelet trigger

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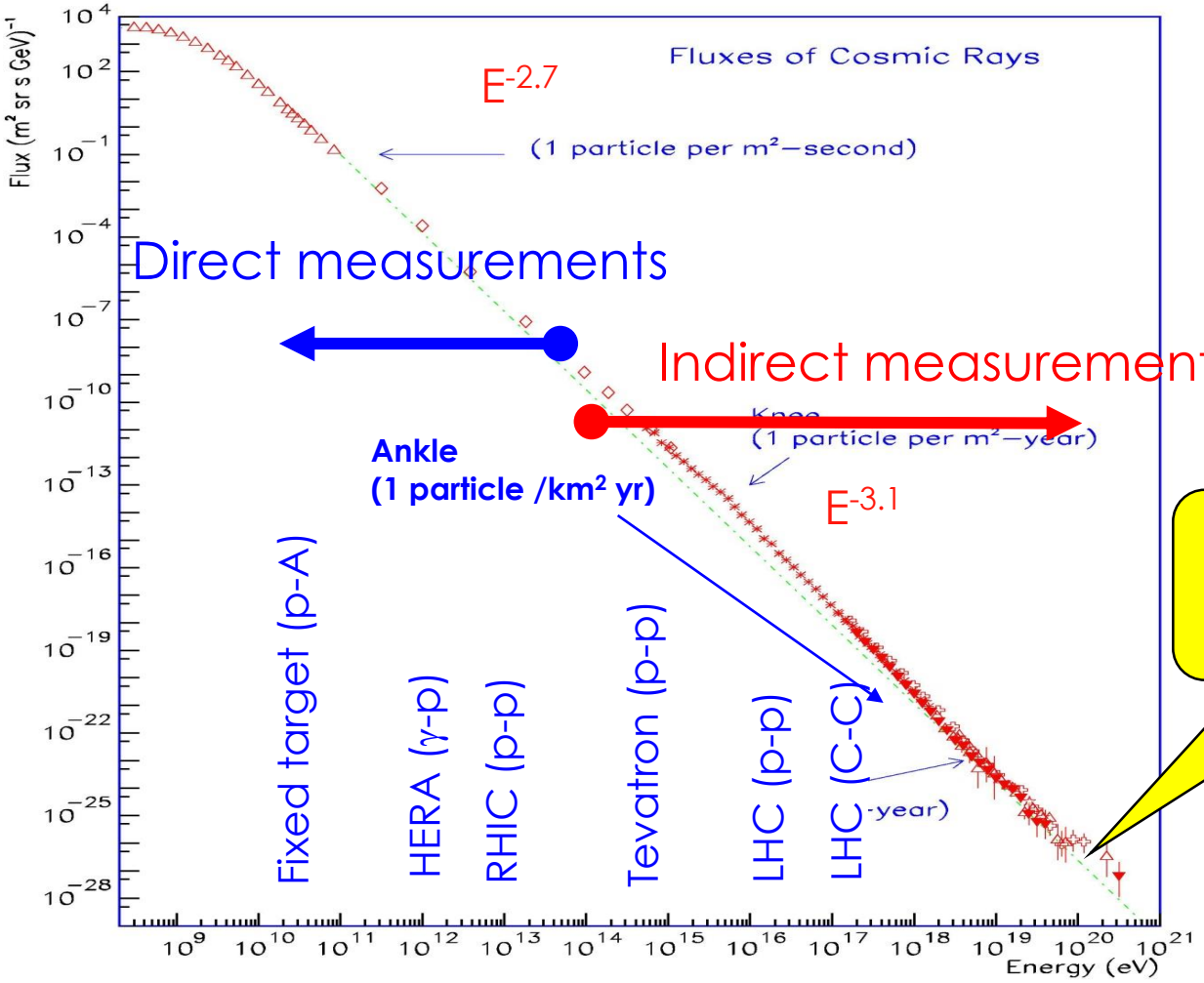
Fluxes of Cosmic Rays



32 orders of magnitude

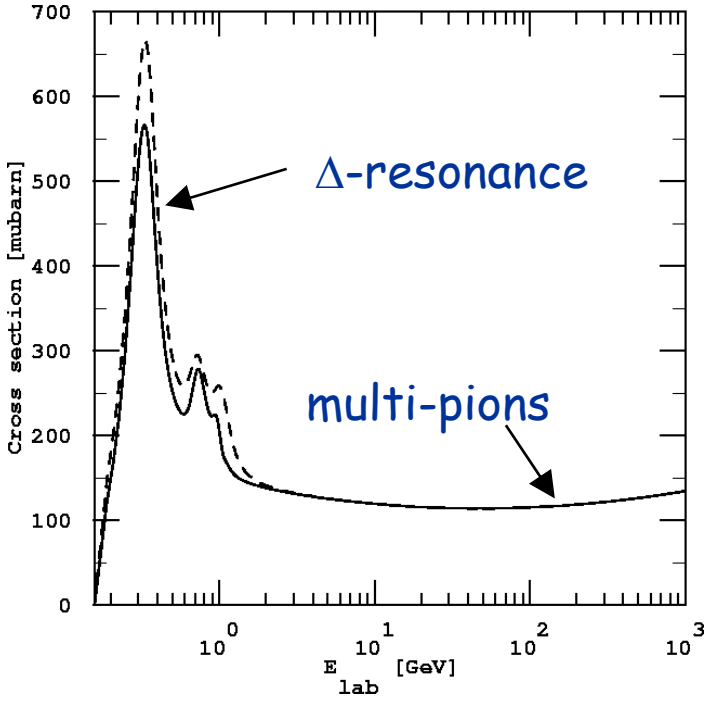
12 orders of magnitude

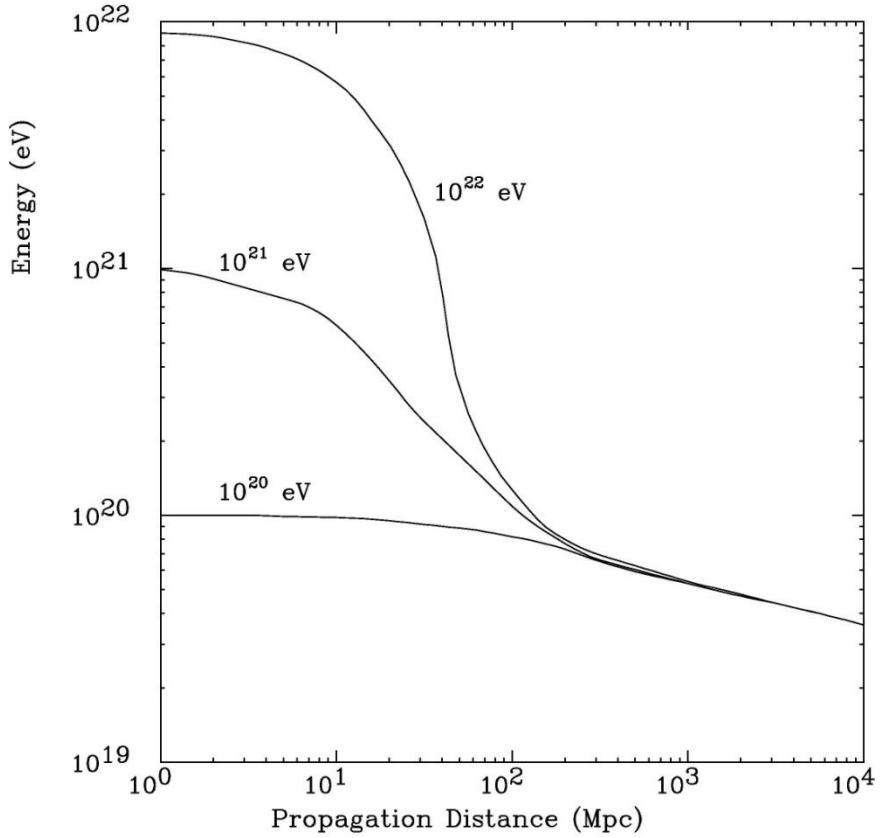
1 particle per km² sr century

GZK cut-off

$$p + \gamma_{CMB} \rightarrow N + \pi, \;\; E_p \geq 1.1 \times 10^{20} eV$$

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow N + \pi, \;\; E_N \geq 2.5 \times 10^{20} eV$$





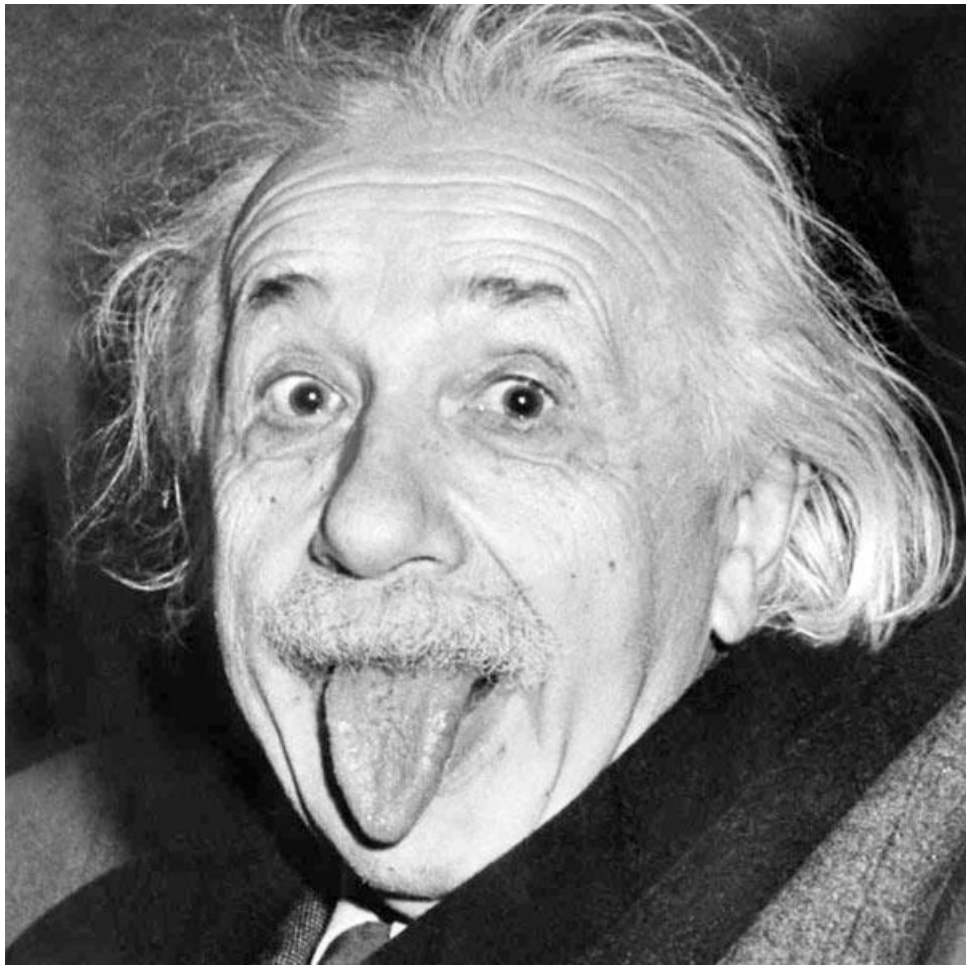
Bottom-up

- A particle penetrating such a cloud from the front can be kicked back, like a tennis ball hit by a racket, with energy larger than its initial value..
- A more efficient and faster process is acceleration by crossing shock fronts generated in explosive phenomena (1st order Fermi mechanism - $\Delta E > 0$). The energy of accelerating particles depends on the value and the size of the magnetic field and is limited by the Larmor radius related to their confinement.
- Many theories and models propose either sophisticated explanations or require some new physics. One of the models explores ultra relativistic shock acceleration such as in hot spots of powerful radio galaxies and **G**amma **R**ay **B**ursts. Relativistic jets are produced perpendicular to the accretion disk around a super–massive black hole in the central part of an active galactic nucleus.

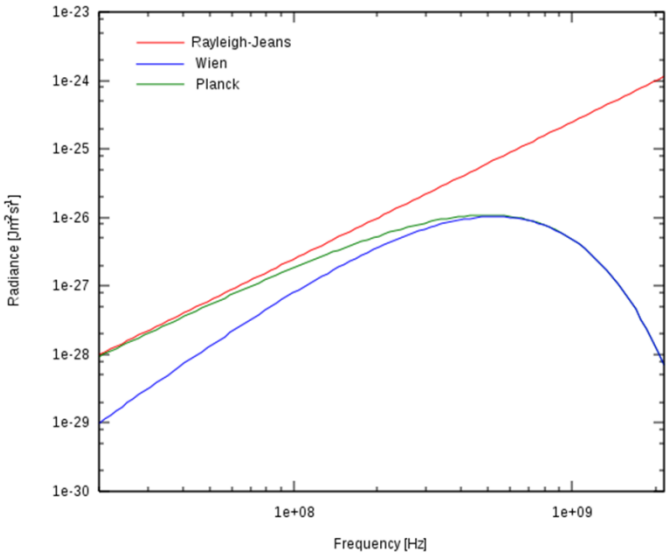
Top-down

- Many theories propose top–down mechanism, decay of super–heavy, super–symmetric or **G**rand **U**nified **T**heories (GUT) particles. The only problem is a justification of their existence or their surviving after the Big Bang. They could have survived up to now by some yet unknown mechanism (a very weakly violated quantum number, particles trapped inside huge potential walls called topological defects and released via spontaneous symmetry breaking mechanism),
- Their decay into some ~10^4 secondary particles (mainly pions) by hadronization of quark – antiquark pairs would easily produce the ZeV energies we need and their decay products would then be dominated by photons (coming from the decay of neutral pions) and neutrinos (decay of charged pions).
- There are a few experimental consequences of this model, which constitute, if observed, a unique and irrefutable signature of the existence of the Grand Unification, a horizon toward which all the modern quantum field theories are supposed to converge, i.e. heavy nuclei would rather exclude the top-down mechanism.

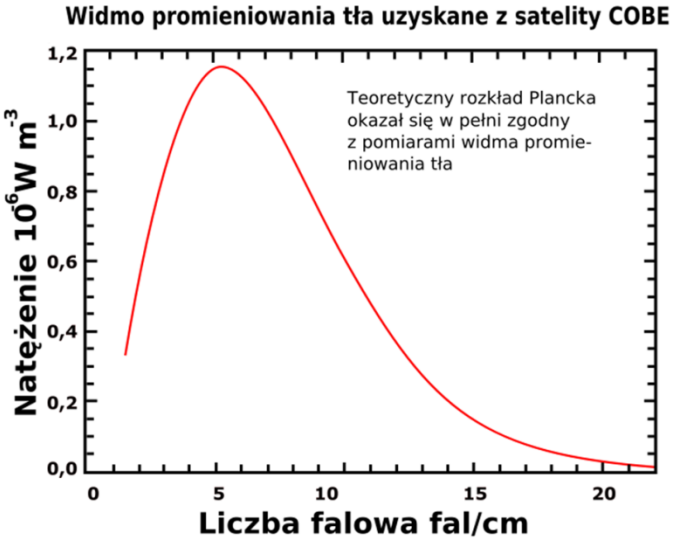
Max Planck & Albert Einstein

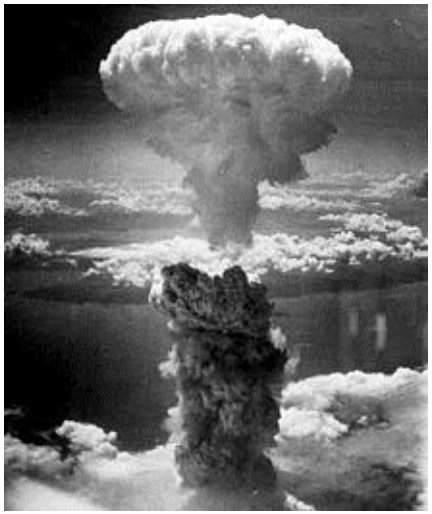


Black body spectrum



$$I(\nu) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1},$$





Electromagnetic waves

Special Theory of Relativity

$$E = m_0 c^2$$

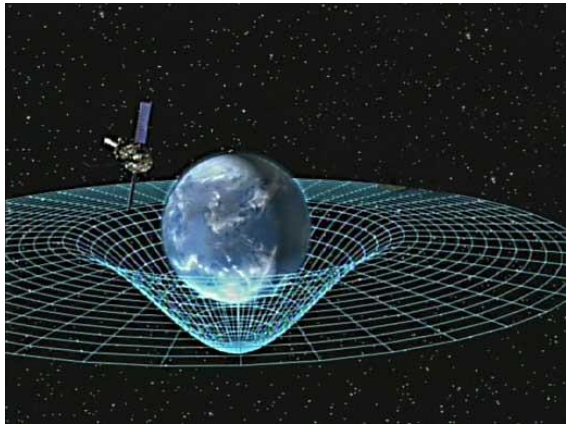
$$t \to t' = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\left(t - \frac{v}{c^2}x\right), \qquad c^2t^2 - x^2 - y^2 - z^2 = \text{const}$$

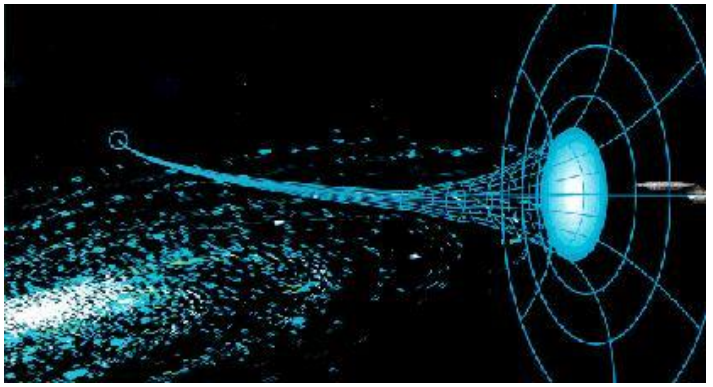
$$u = \frac{u' + v}{(1 + \frac{vu'}{c^2})}$$

$$x \to x' = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}(x - vt). \qquad (x^0)^2 - (x^1)^2 - (x^2)^2 - (x^3)^2 = \text{const}$$

General Theory of Relativity

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = -\frac{8\pi}{c^4}GT_{\mu\nu}$$





Origin of UHECRs

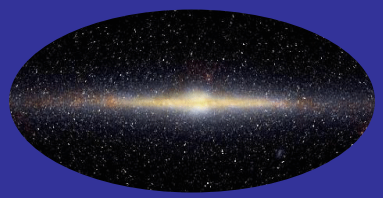
Galaxy Jets from Black Holes?

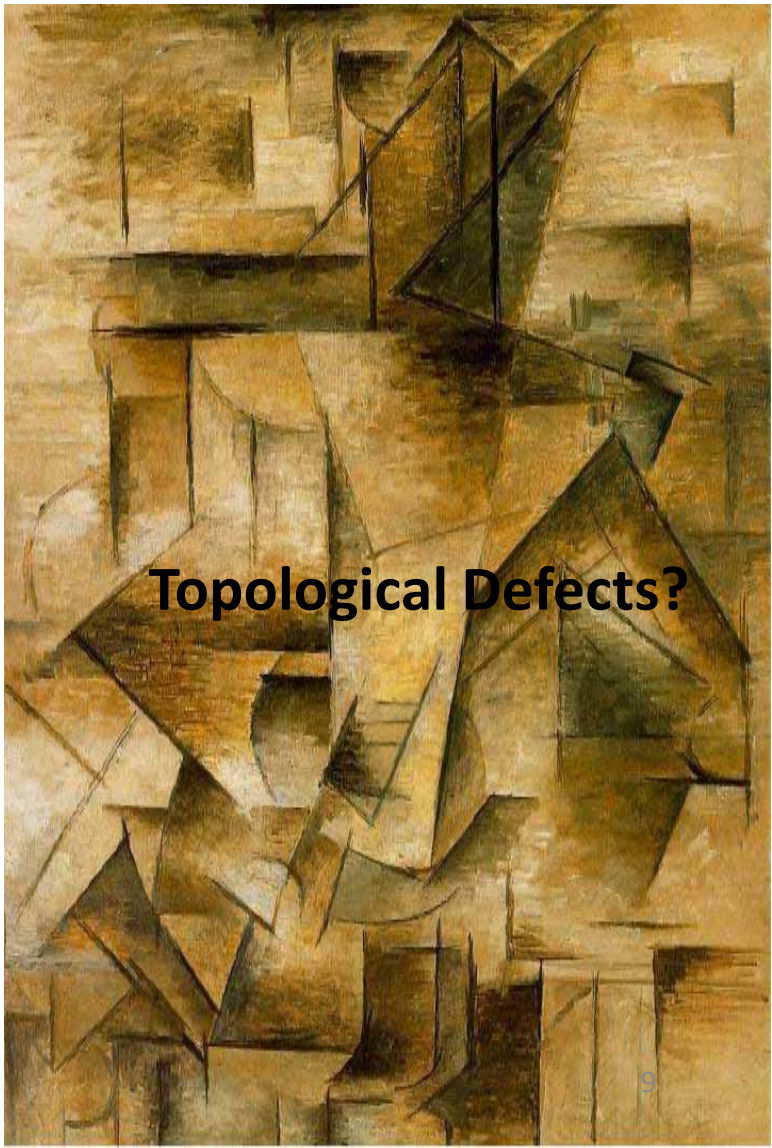
Gamma Ray Bursts?

Young Neutron Stars?

Fast Extra-galactic Magnetars?

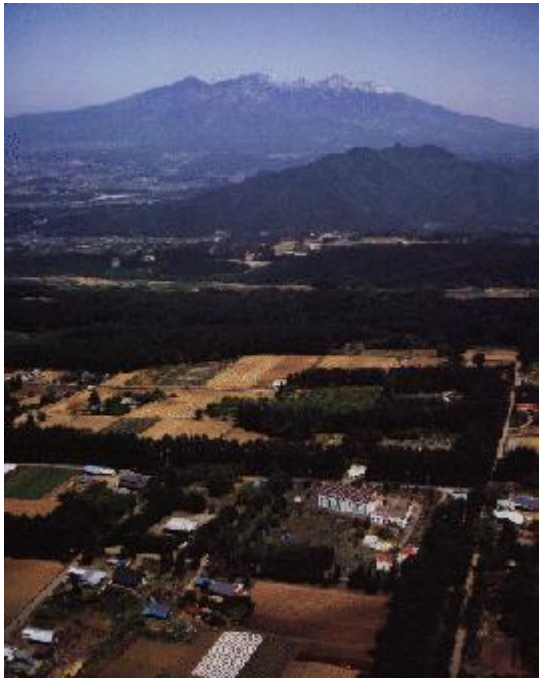
Super Heavy Relics in the Dark Halo of our Galaxy?



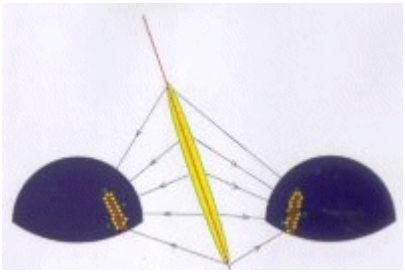


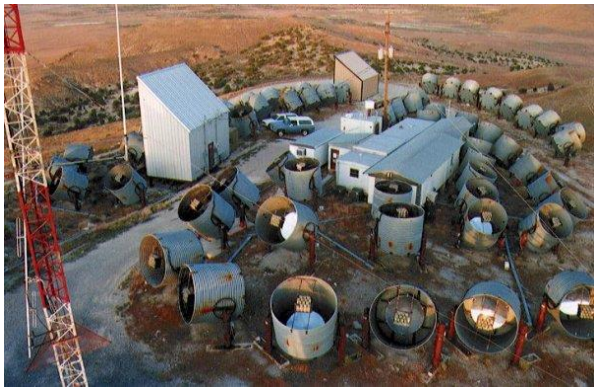
3 independent experiments observe Ultra High-Energy Cosmic Rays

AGASA

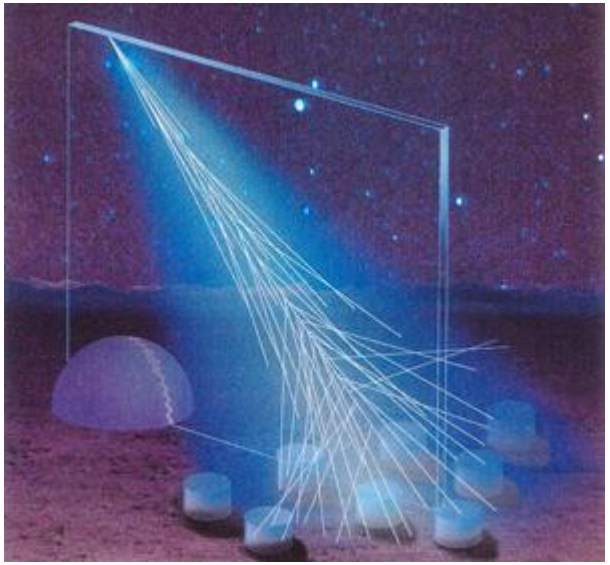


Fly's Eye

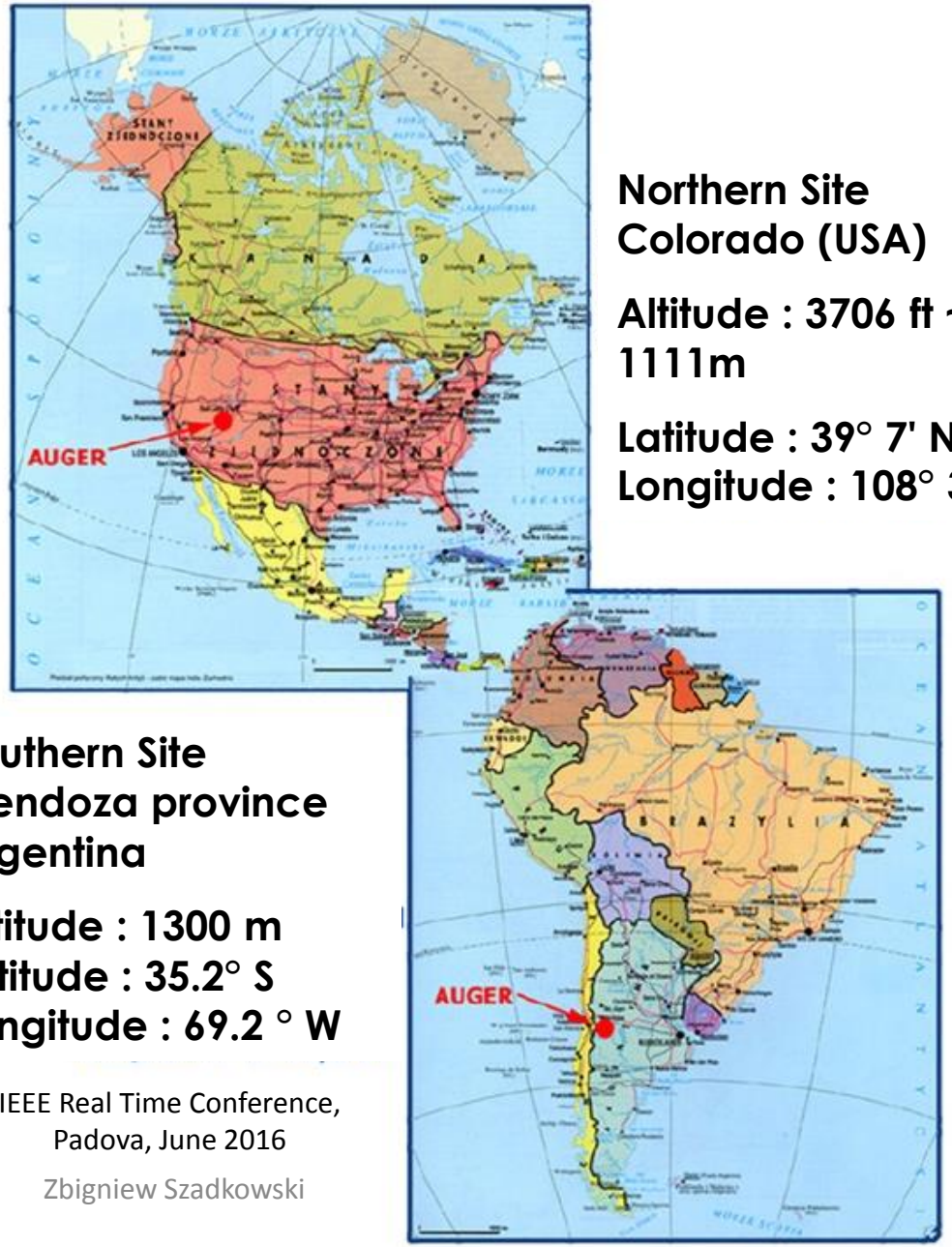




Pierre Auger Observatory



LOCATION OF PIERRE AUGER OBSERVATORY SITES



Northern Site
Colorado (USA)

Altitude : 3706 ft ~ 1111m

Latitude : 39° 7' N
Longitude : 108° 3' W

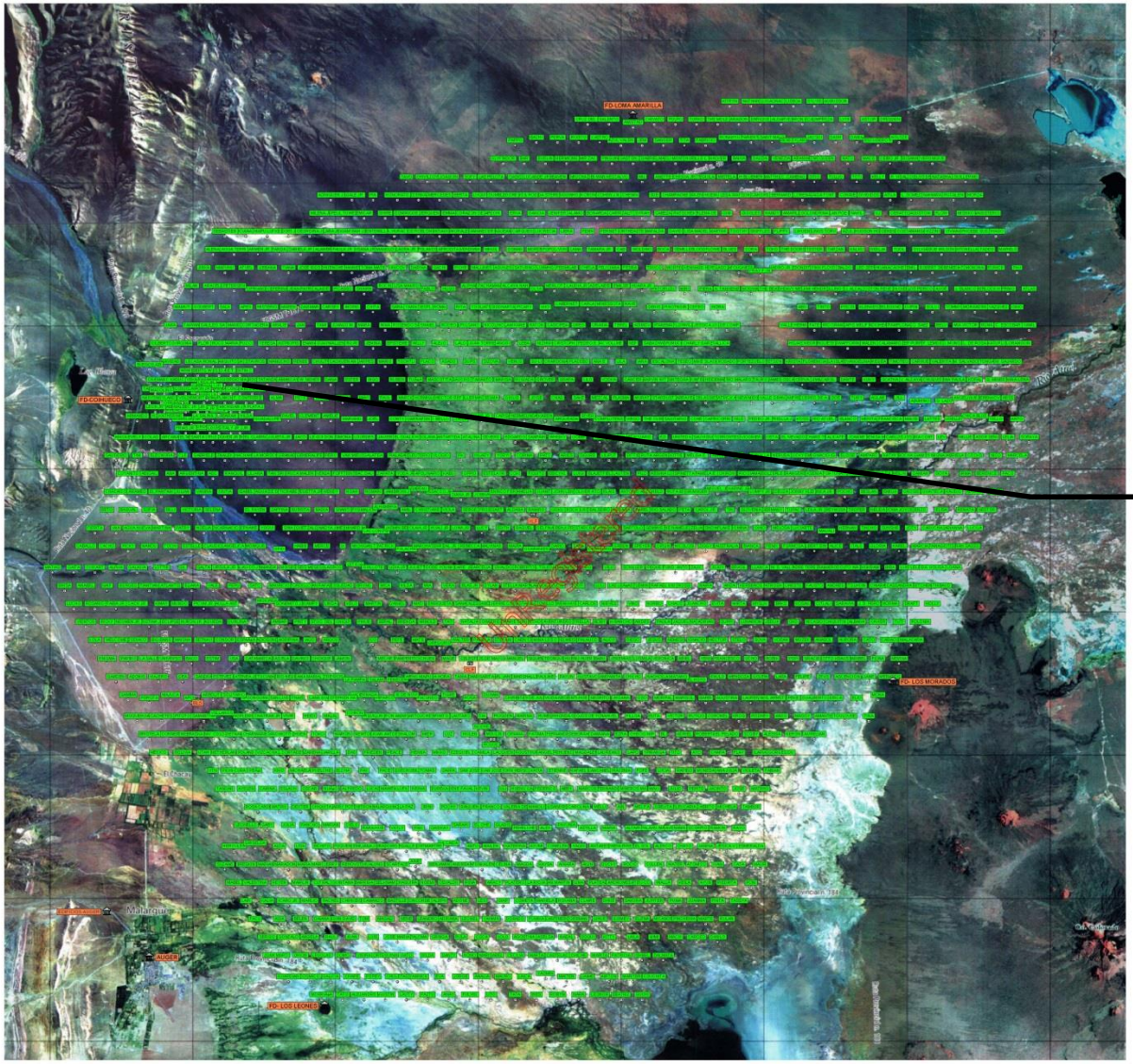
Southern Site
Mendoza province
Argentina

Altitude : 1300 m
Latitude : 35.2° S
Longitude : 69.2 ° W

Auger North and Auger South

- Investigation of the origin and propagation of UHECR
- GZK cut-off ?
- Directions - isotropy ?
  - Extragalactic? Galactic?
  - DM halo? Space?
- Sources ?
  - SM BHs? NSs? Shocks?
  - Jets? DM? TD?
  - Acceleration or Decay?
  - Injection Spectrum?
- Mass sprectrum ?
  - Protons, Mixed Nuclei?
  - Any Gammas? Neutrinos?
- Beyond the current physics

Location of the Auger South detectors

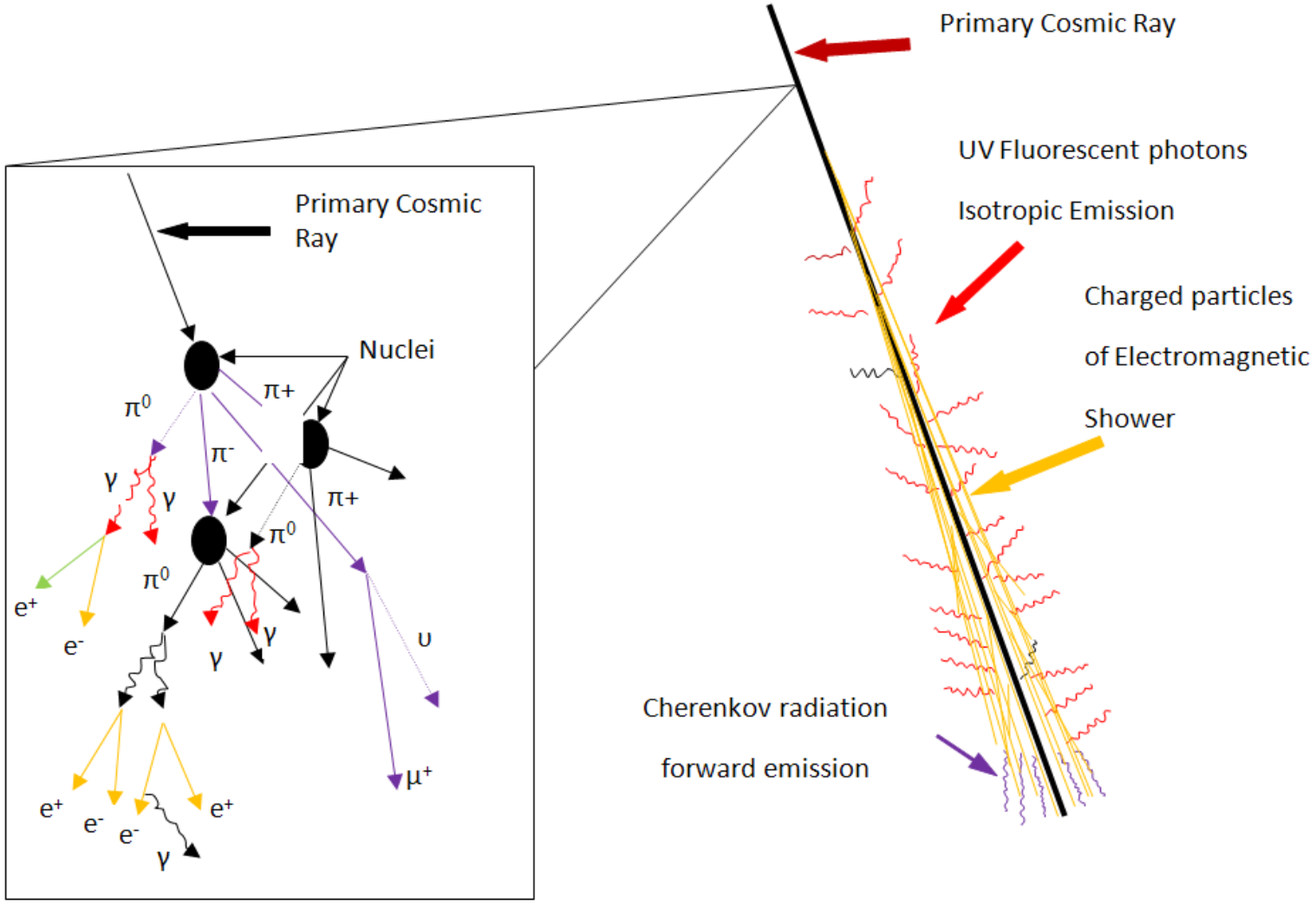


Surface Array
1660 detector stations
1.5 km spacing
3000 km²

Infill Array

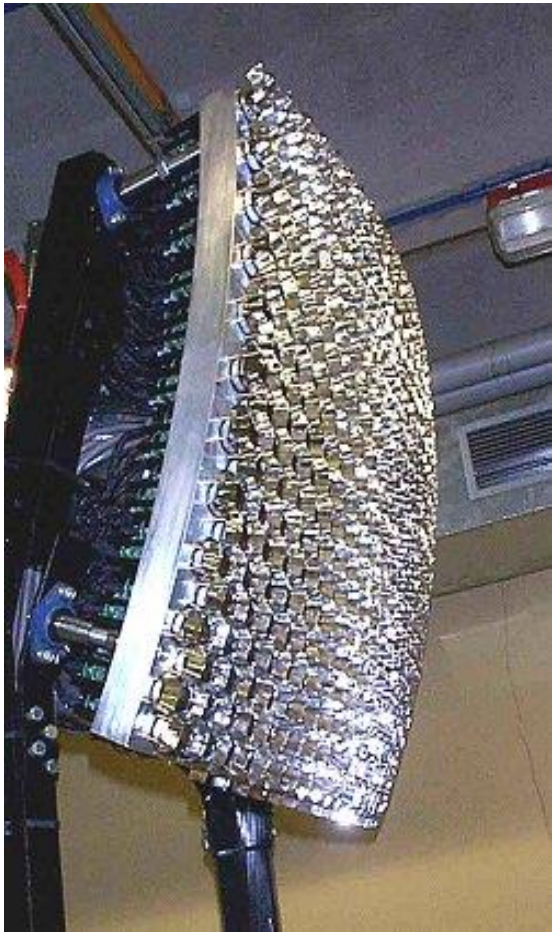
Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 Telescopes total

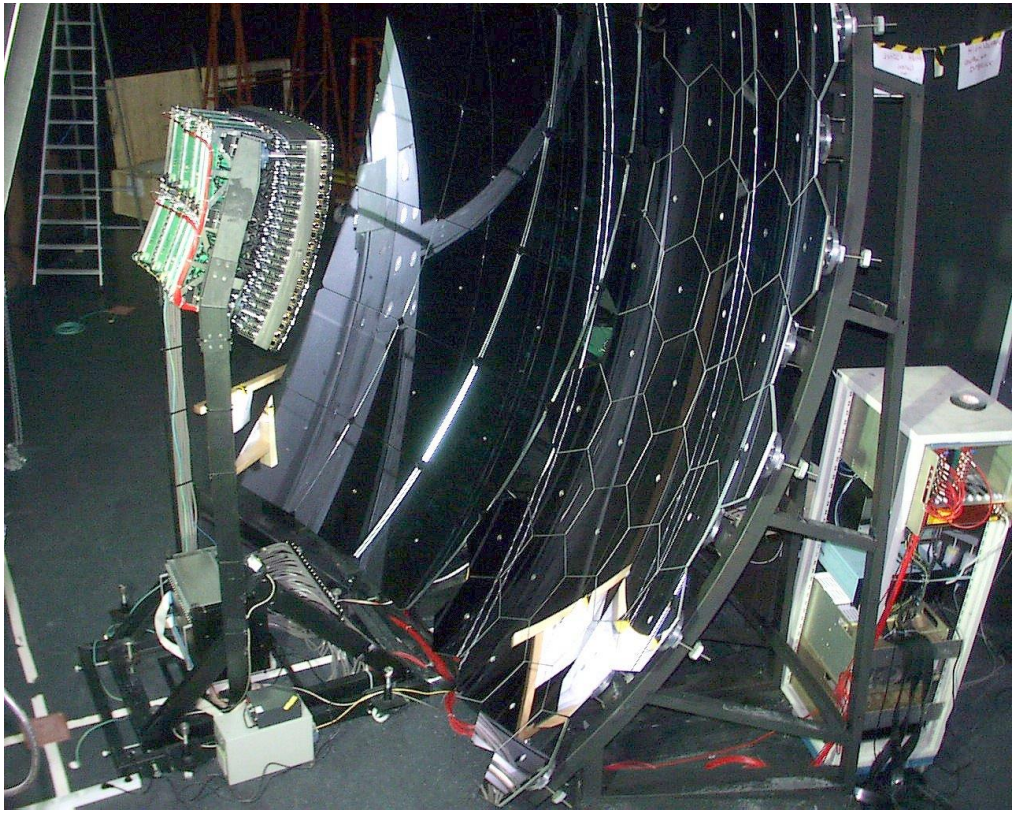
Extensive Air Showers



Fluorescence detector

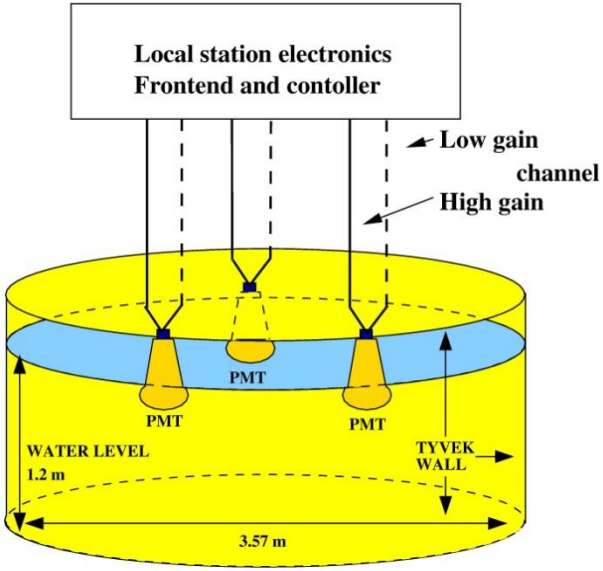
$$N_{fluorescence} \propto \frac{dE}{dx}$$

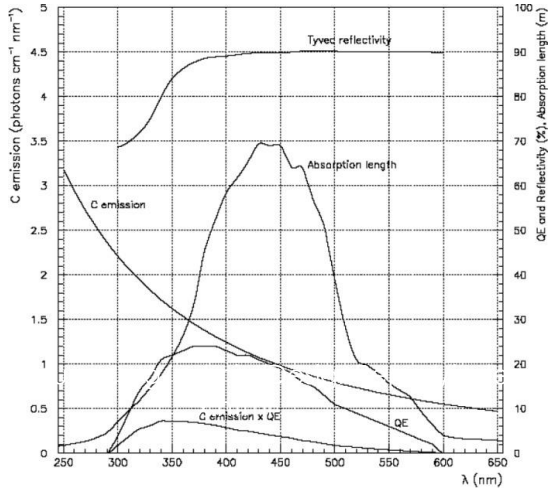


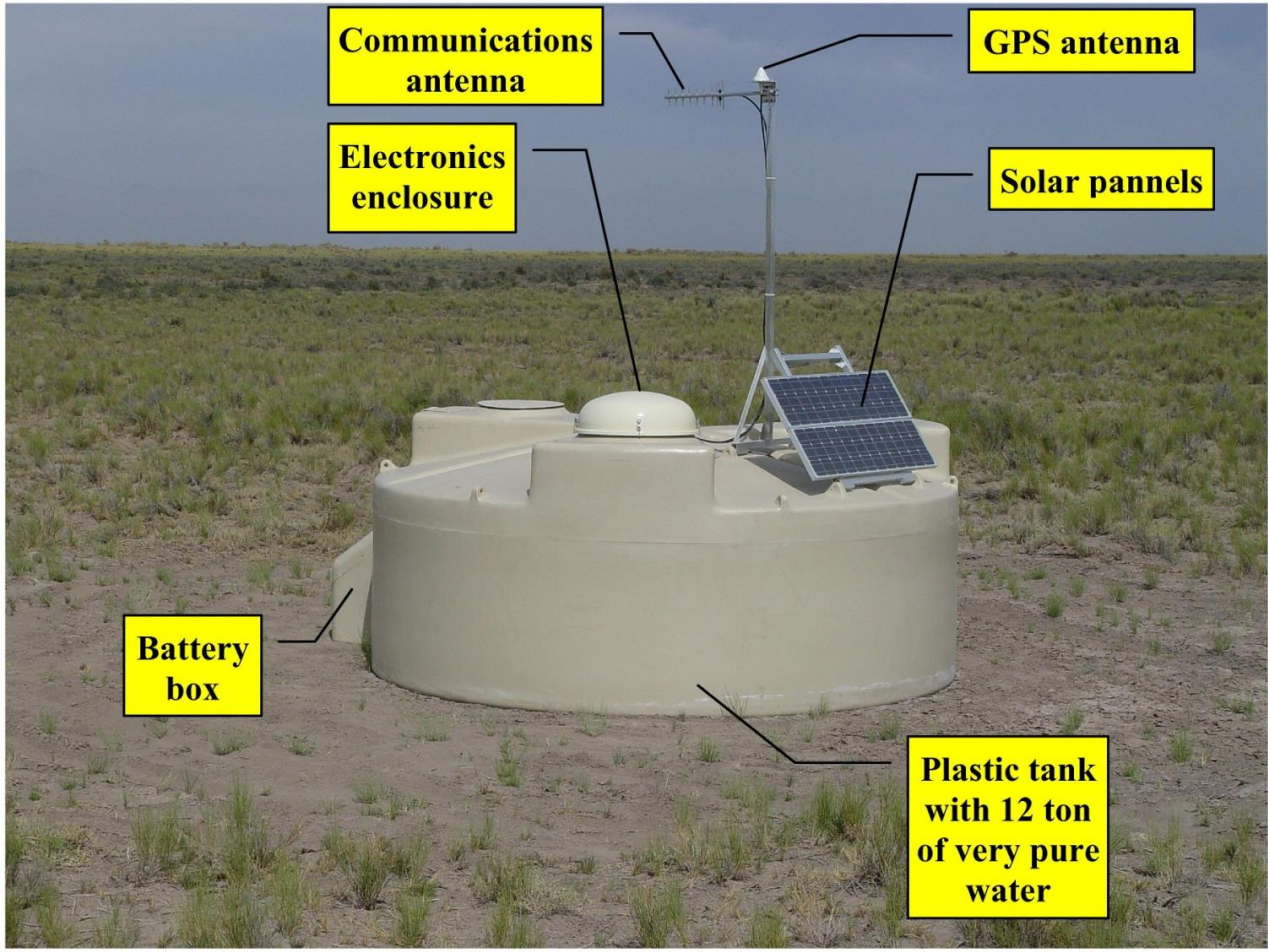


view of Los Leones FD

Surface Detector

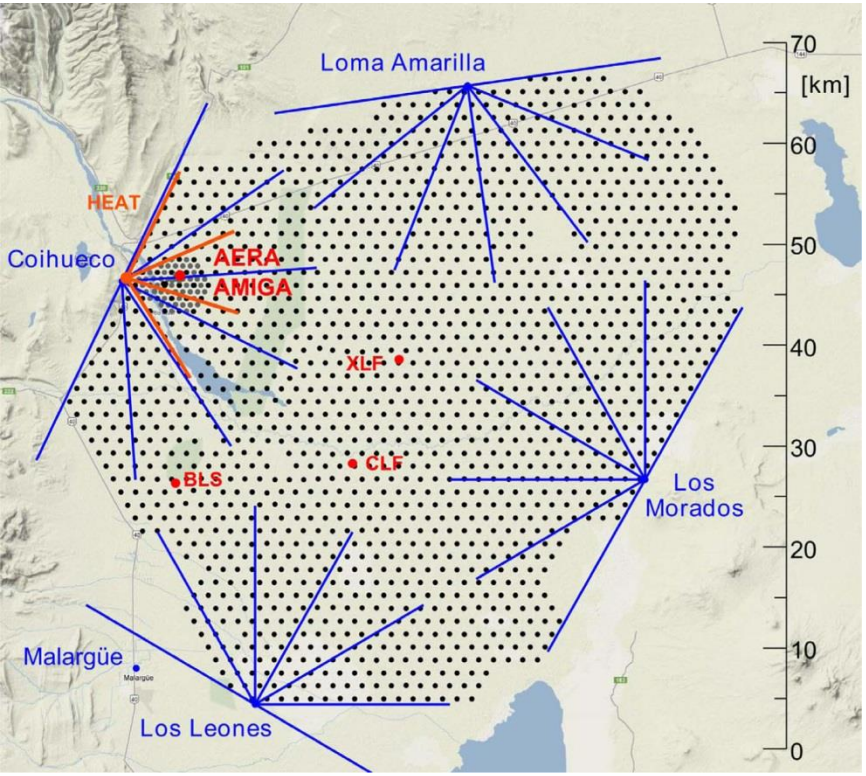


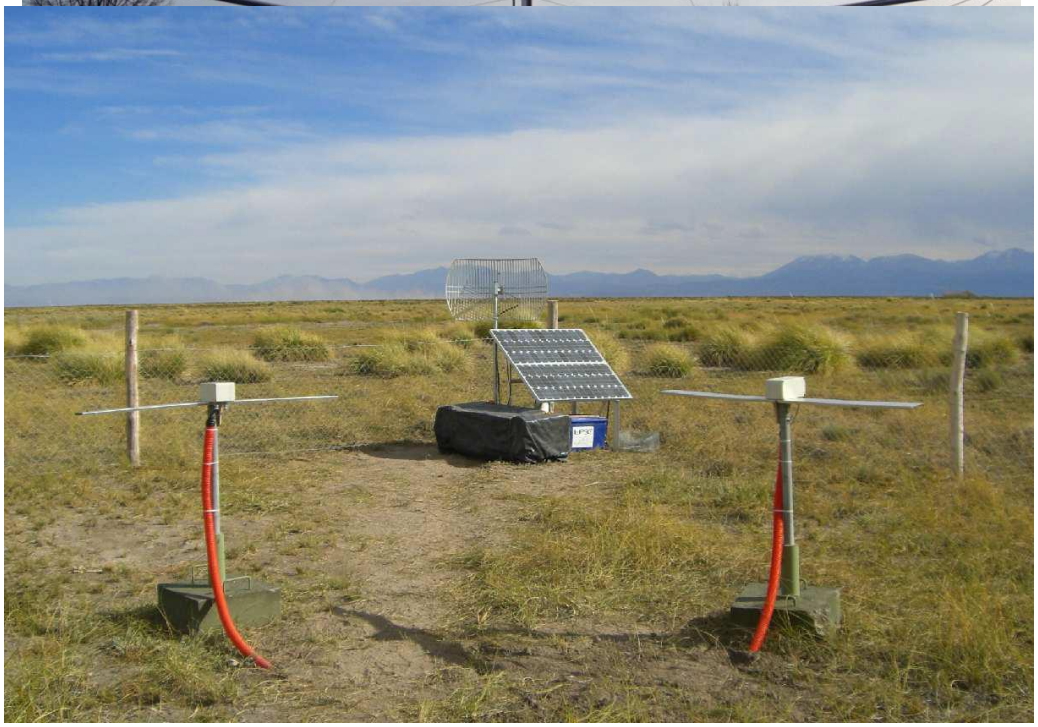




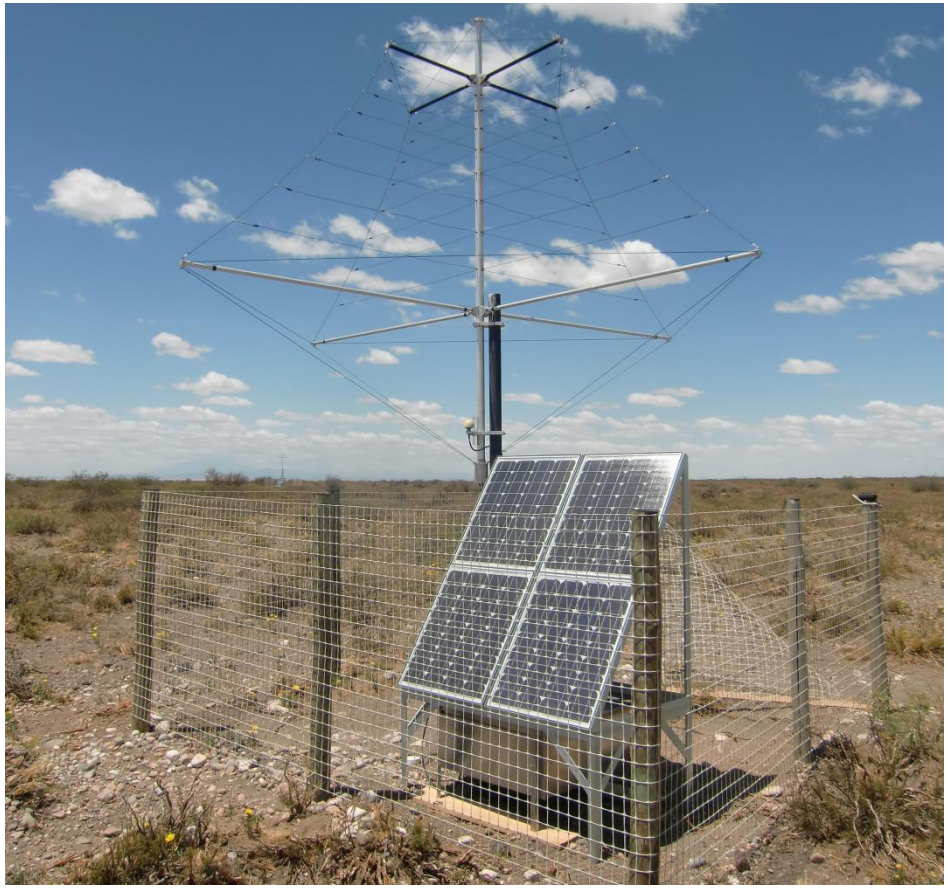
tanks aligned seen from Los Leones

Radio detector

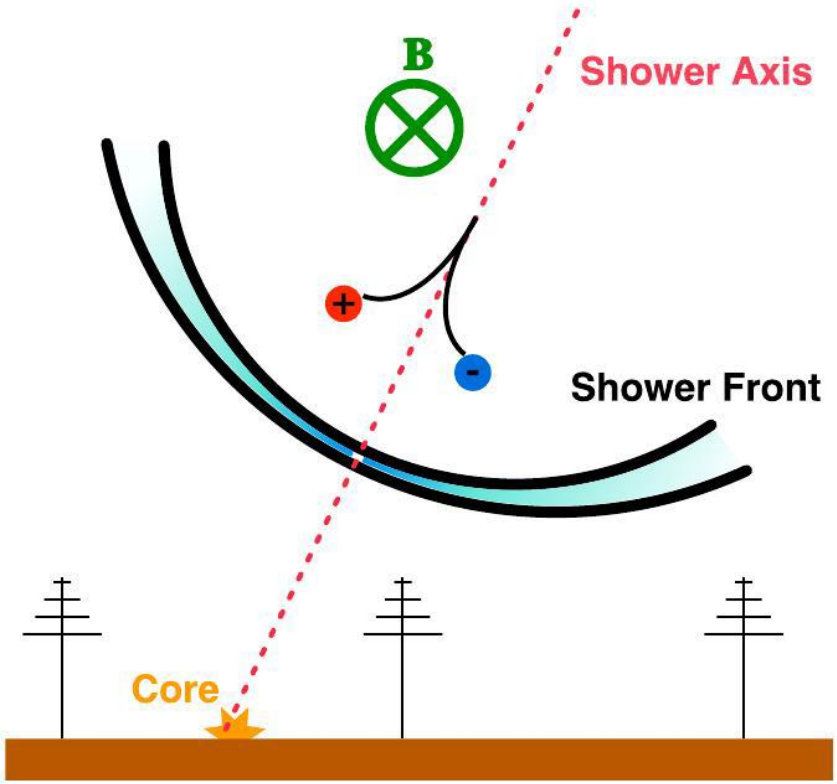


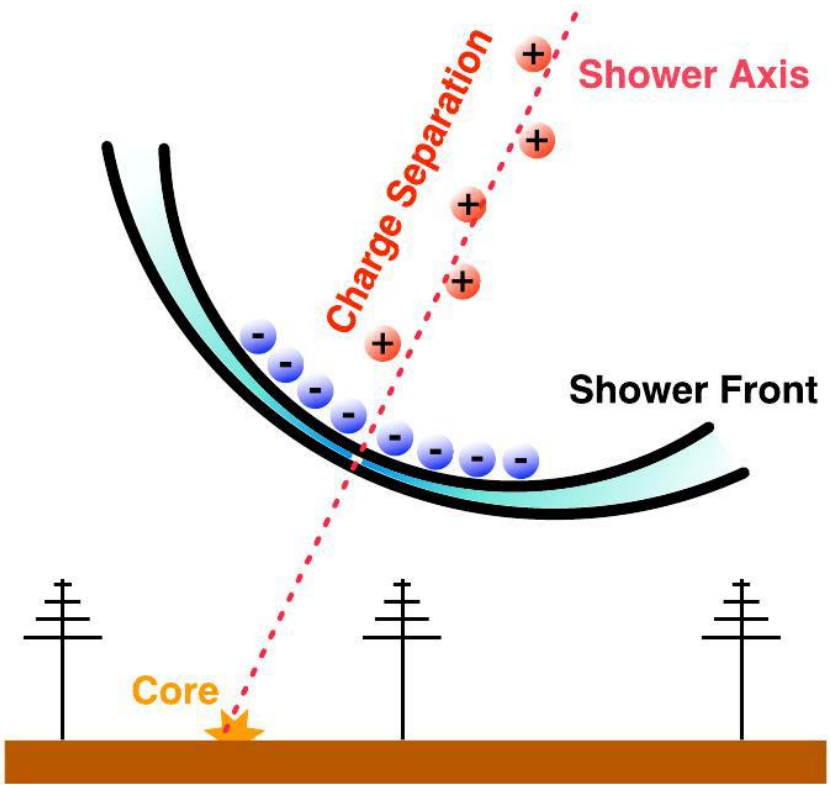


Auger Engineering Radio Array



Geo-magnetic radiation and charge excess





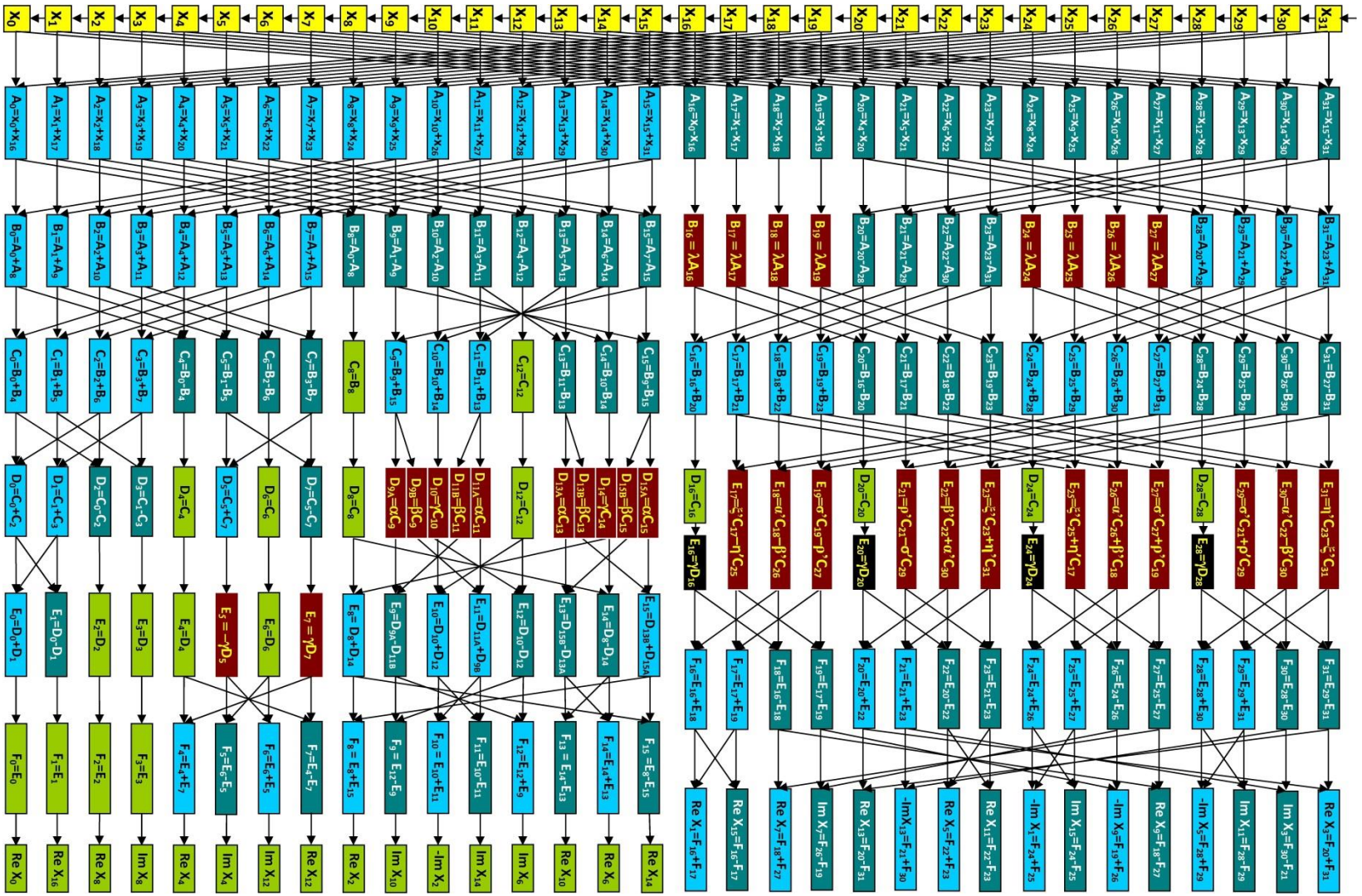
Wavelet formulas

$$W_n(s) = \sum_{m=0}^{N-1} x_m \psi^* \left[\frac{(m-n)\Delta t}{s} \right]$$

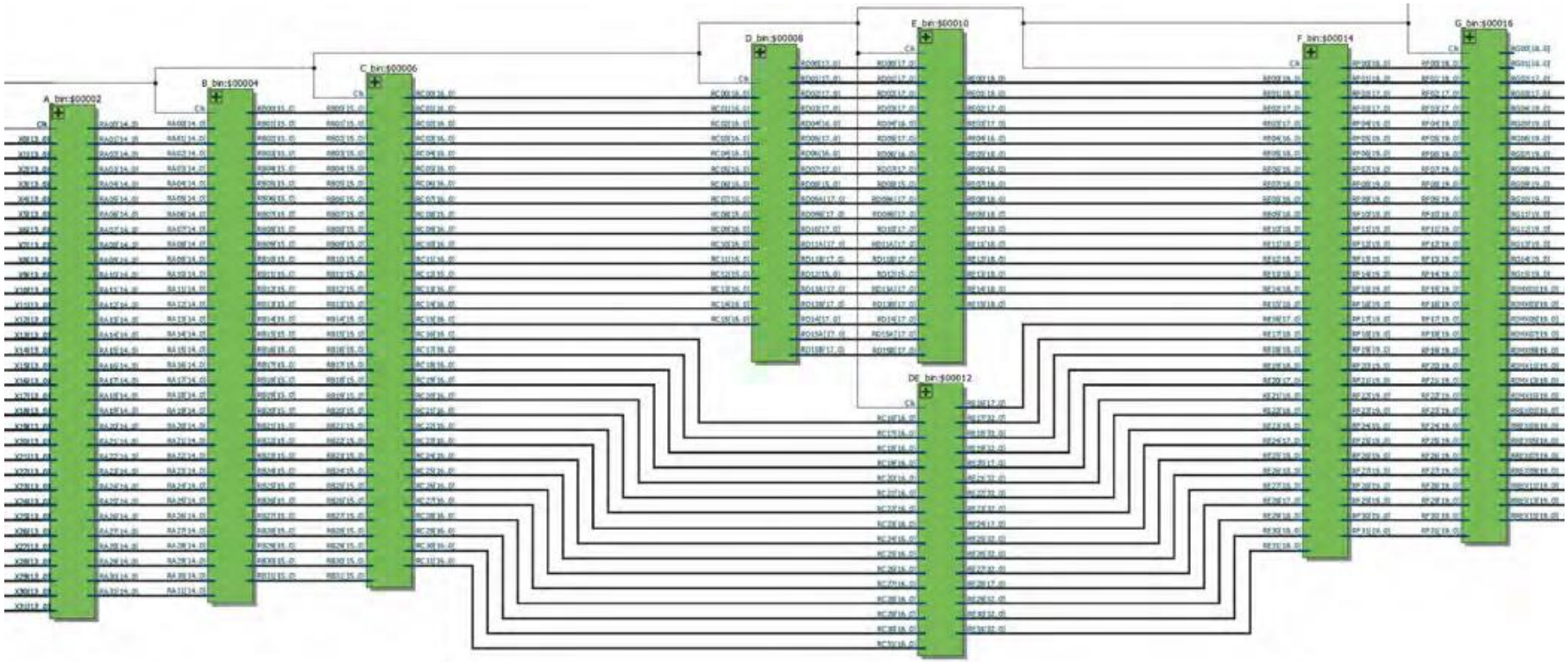
$$W_n(s) = \sum_{k=0}^{N-1} \bar{X}_k \bar{\Psi}^*(s\omega_k) e^{i\omega_k n \Delta t}$$

$$\sum_{j=0}^{M-1} |W_j|^2 = \frac{1}{N} \sum_{j=0}^{M-1} \sum_{k=0}^{N-1} |W_{k,j}|^2 = \frac{1}{N} \sum_{j=0}^{M-1} \sum_{k=0}^{N-1} |\bar{X}_k \times \bar{\Psi}_{k,j}|^2$$

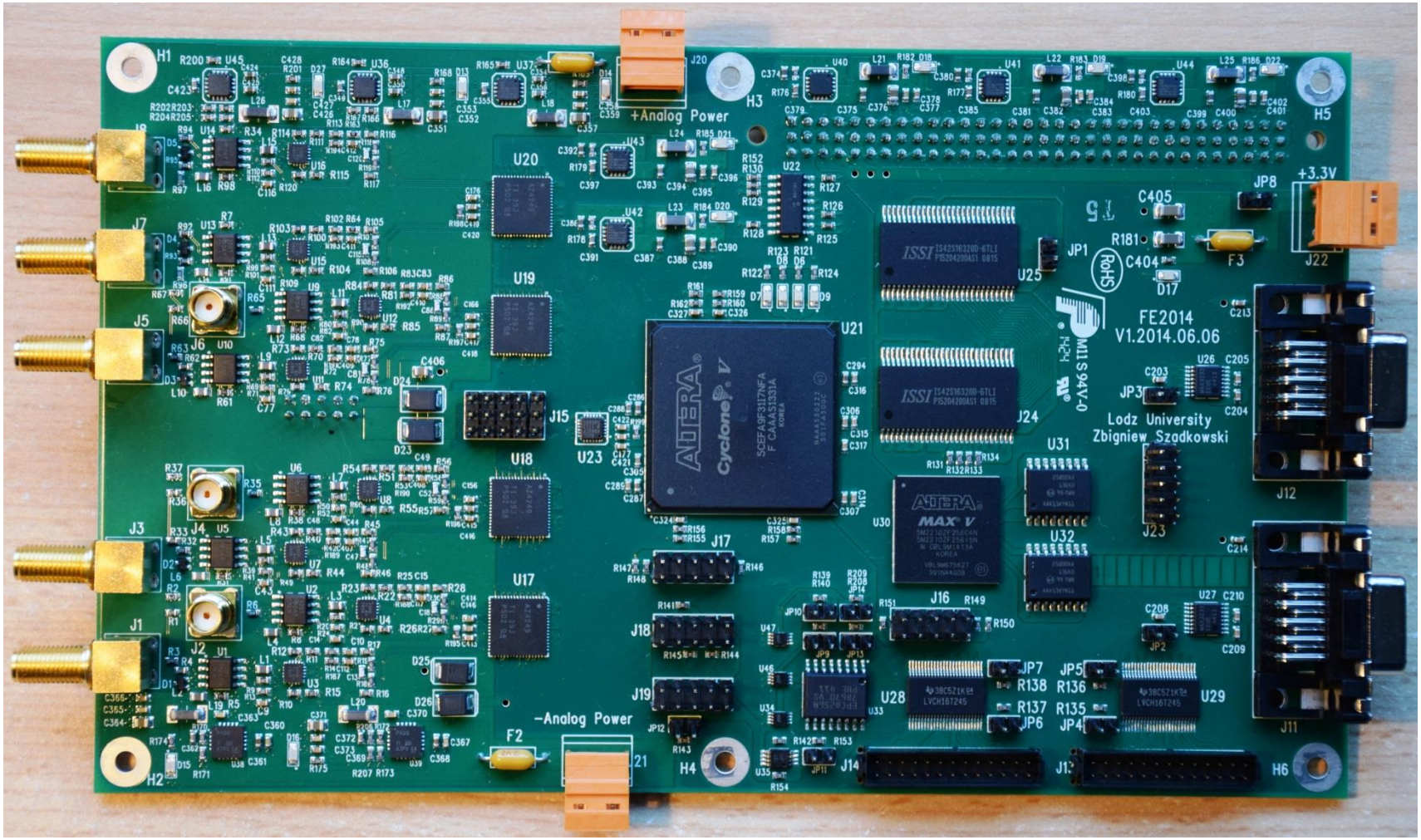
FFT32 in the FPGA



FPGA implementation

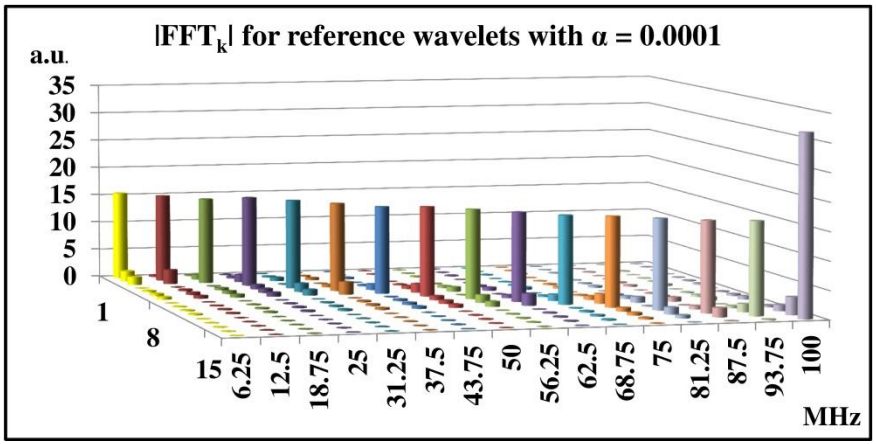


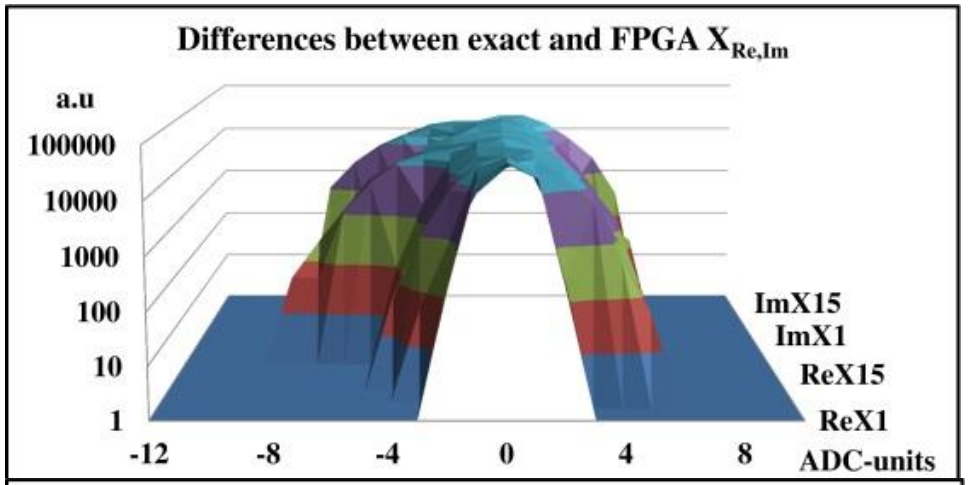
Front-End Board

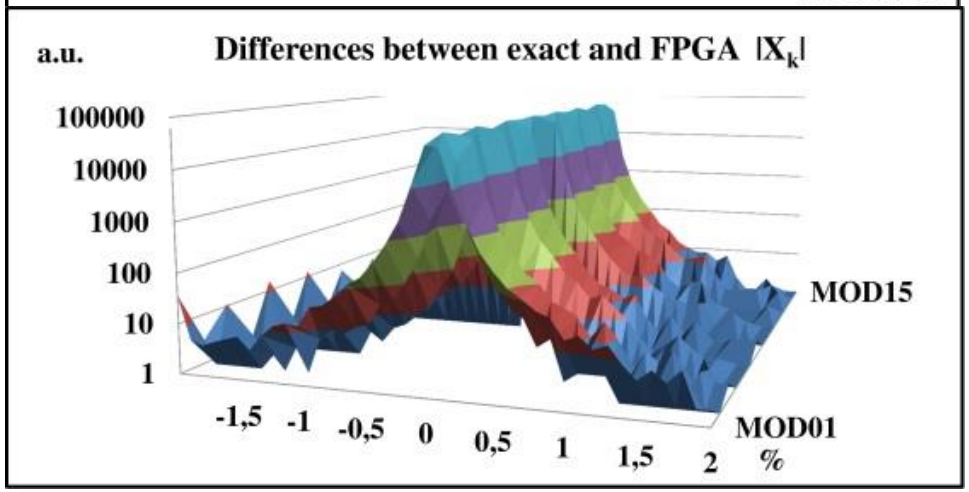


Accuracy

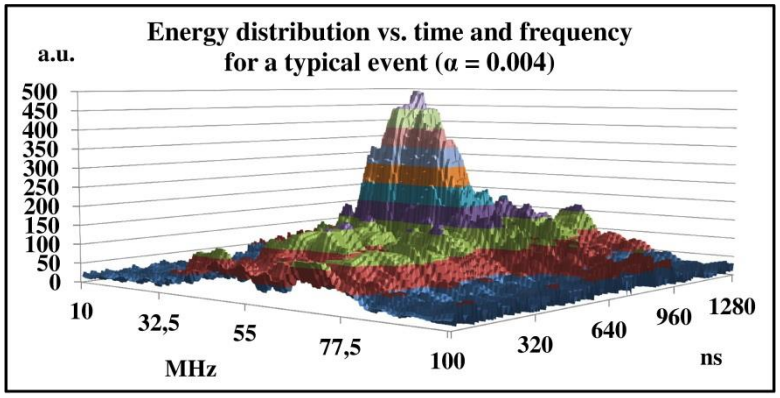
$$\sum_{j=0}^{M-1} |W_j|^2 = \frac{1}{N} \sum_{j=0}^{M-1} \sum_{k=0}^{N-1} |W_{k,j}|^2 = \frac{1}{N} \sum_{j=0}^{M-1} \sum_{k=0}^{N-1} |\bar{X}_k \times \bar{\Psi}_{k,j}|^2$$

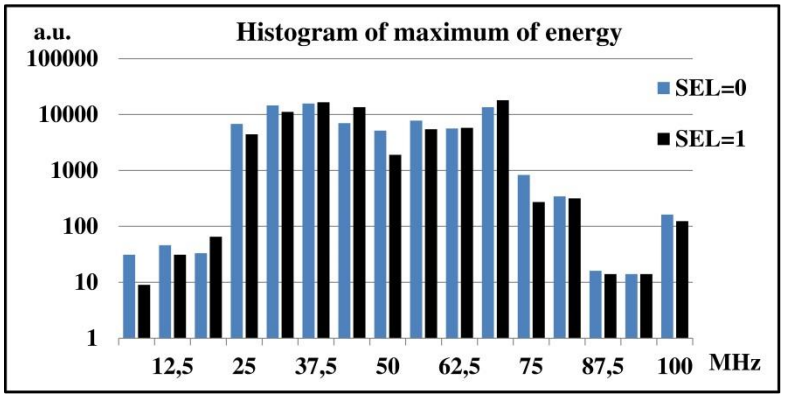


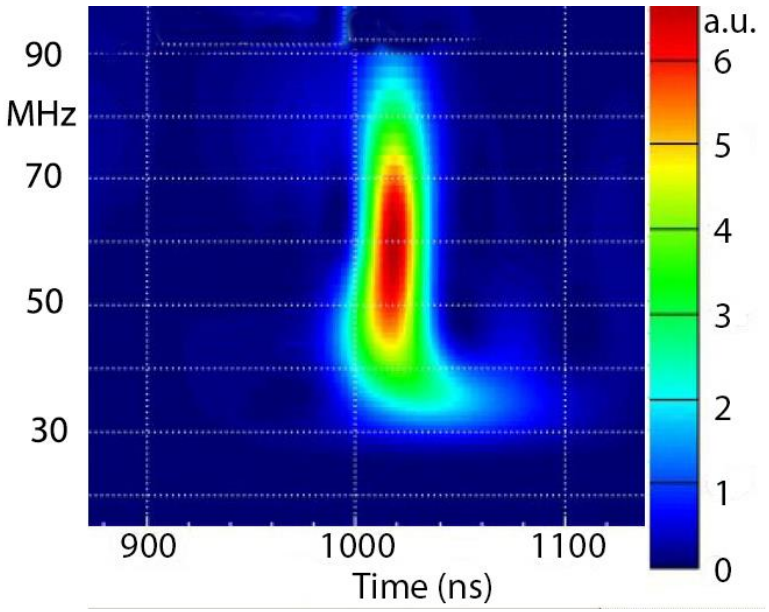


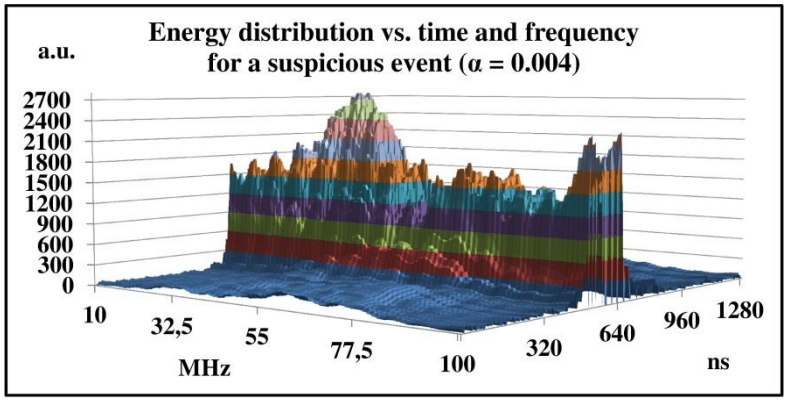


Motivations



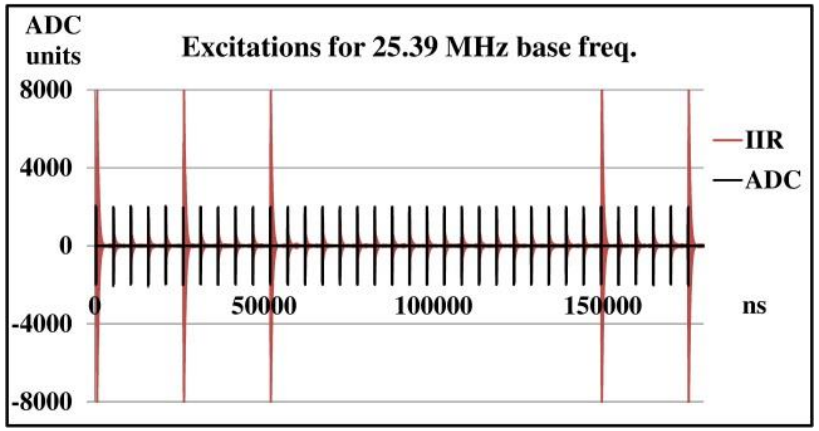


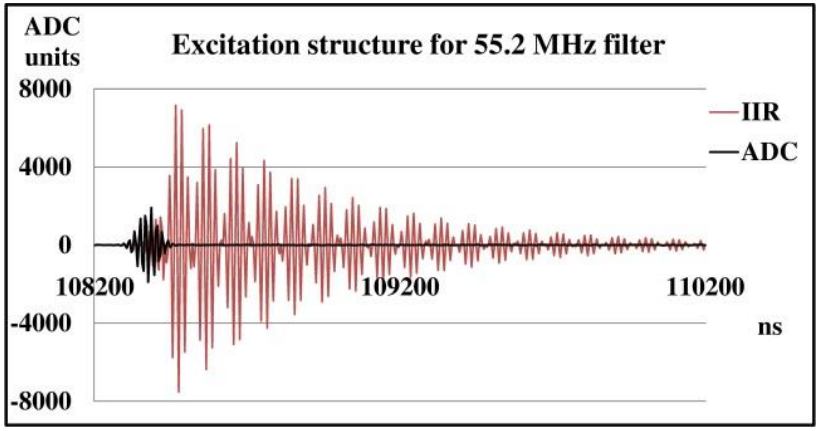


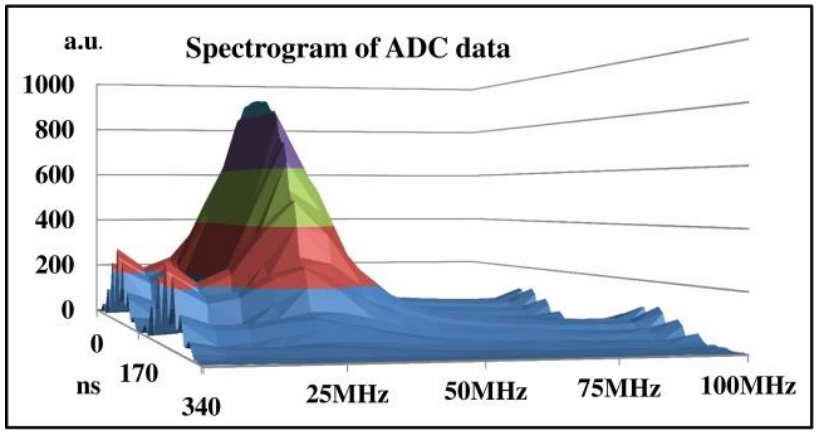


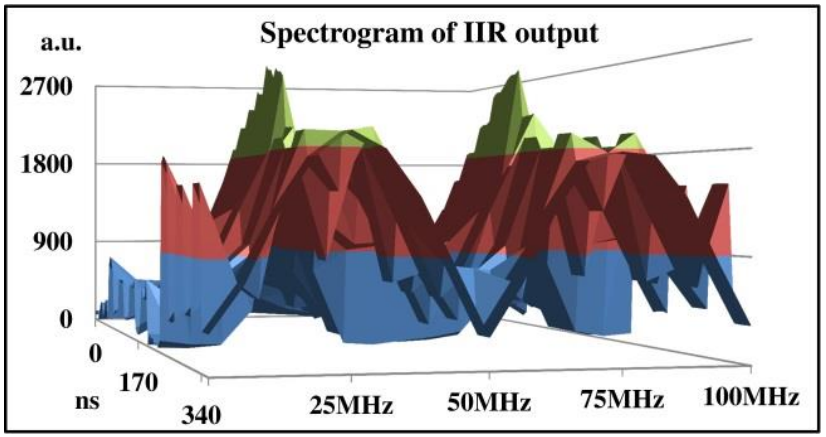
Suspicious event with a wide spectral characteristics – although 30-80MHz band-pass filter used for analog inputs

Spurious triggers

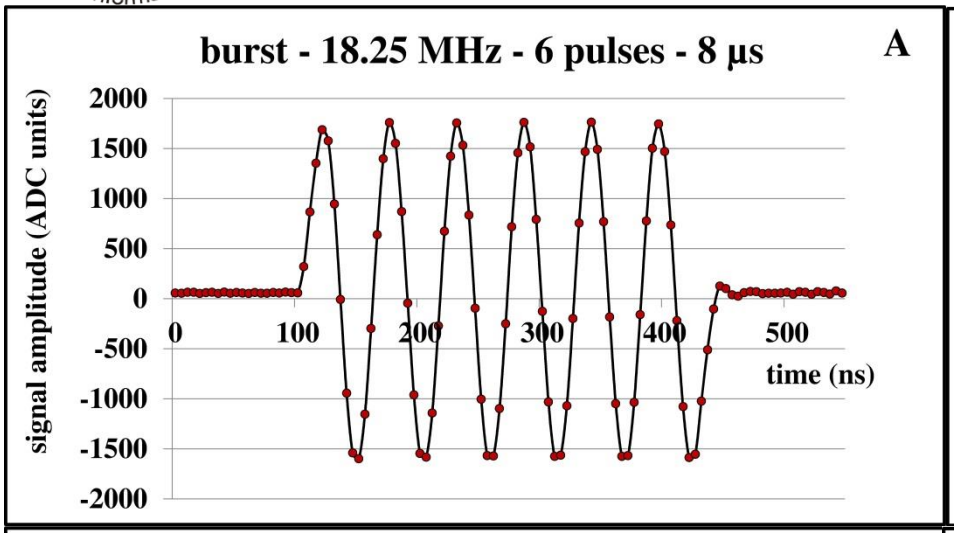


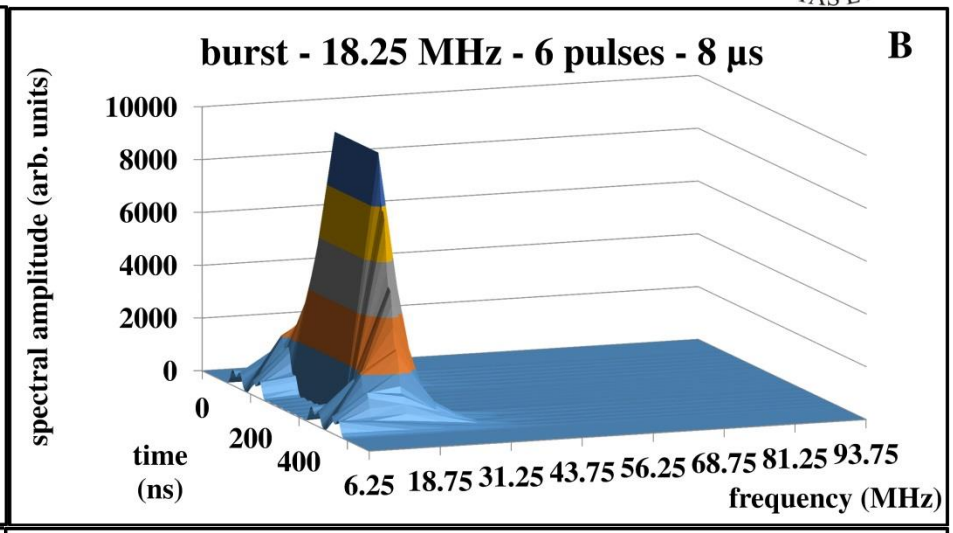


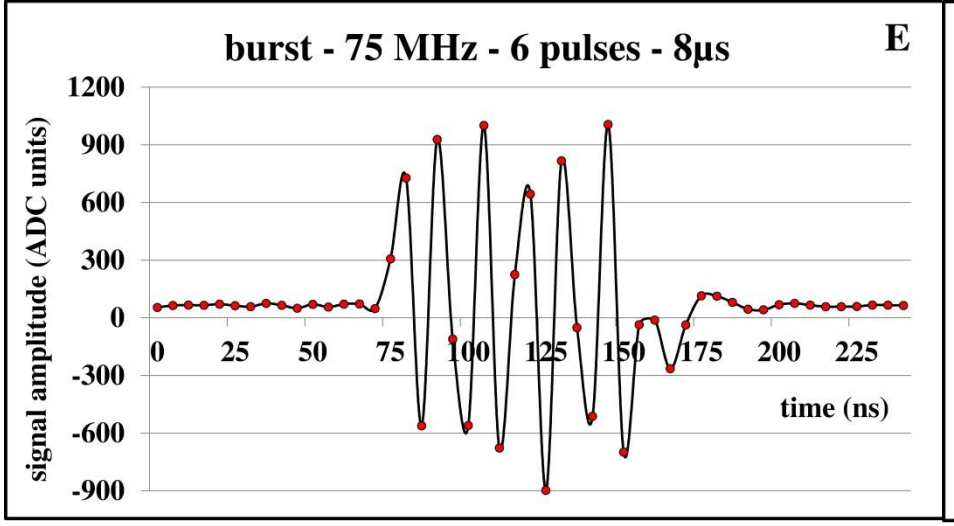


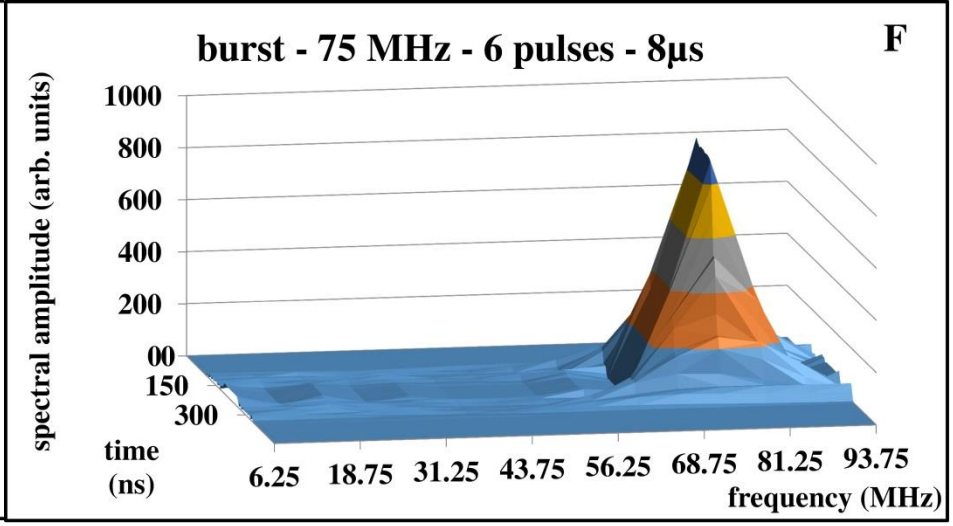


Burst pulses

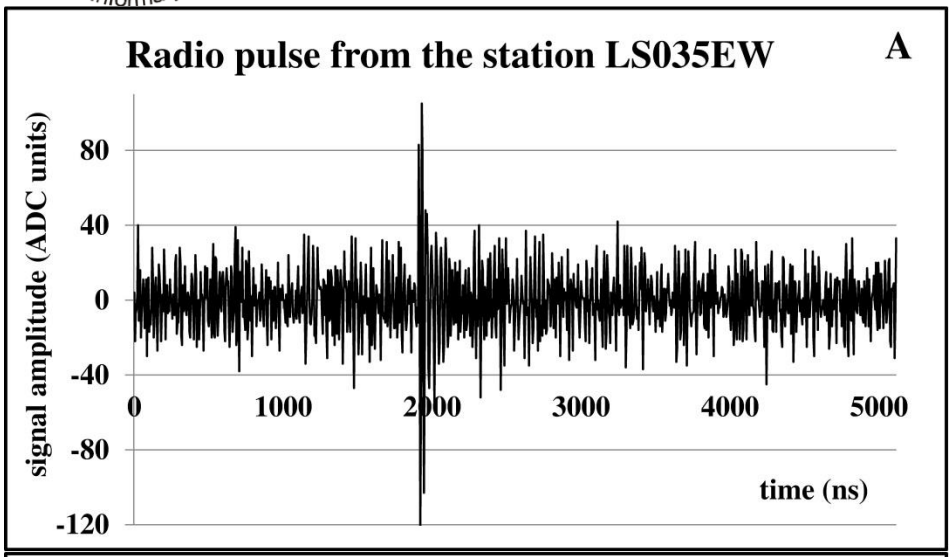


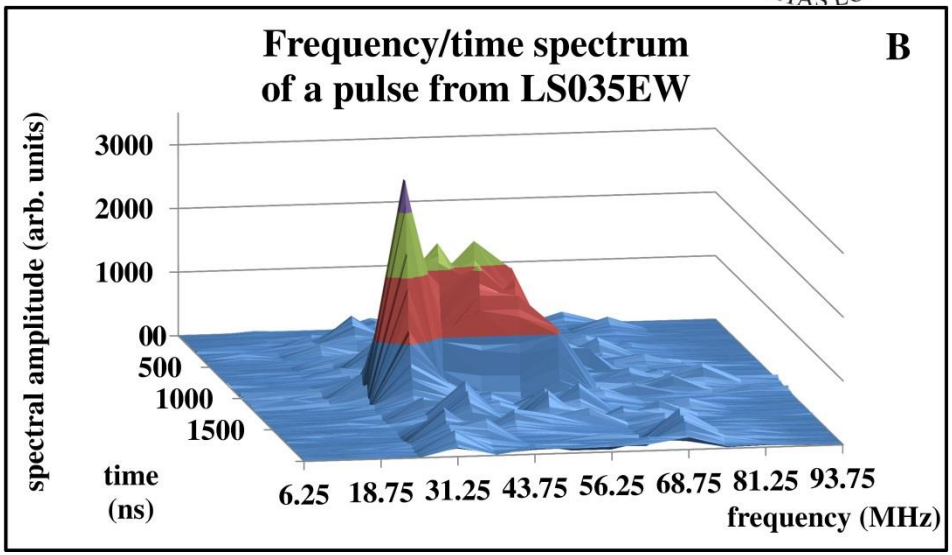


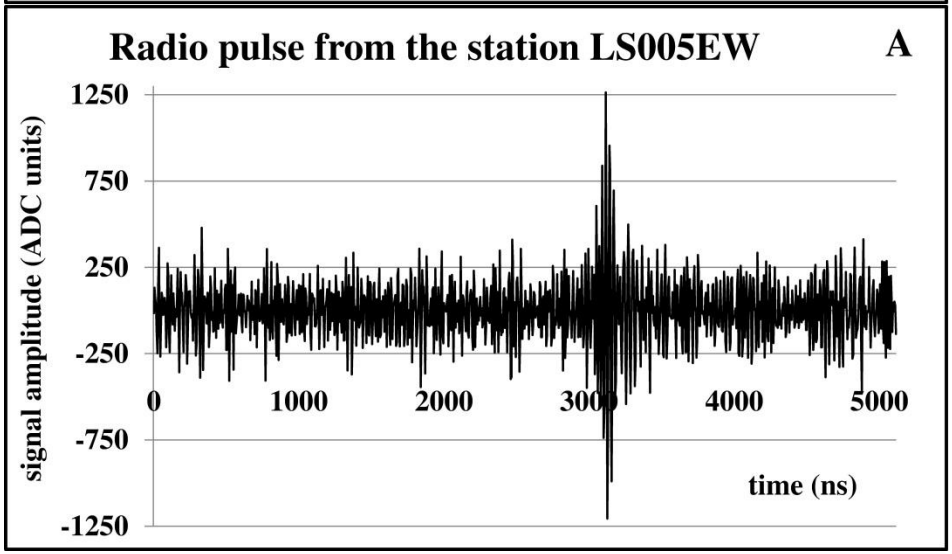


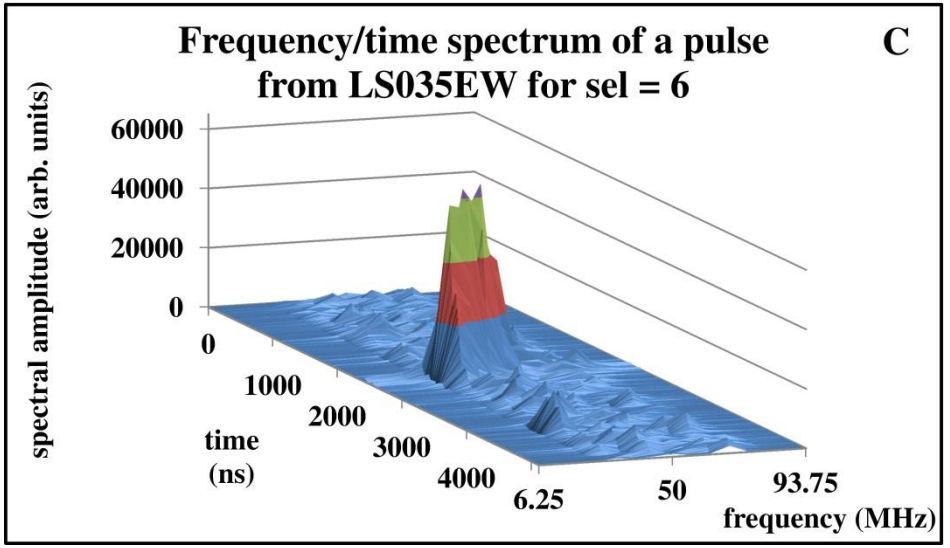


Real radio pulses

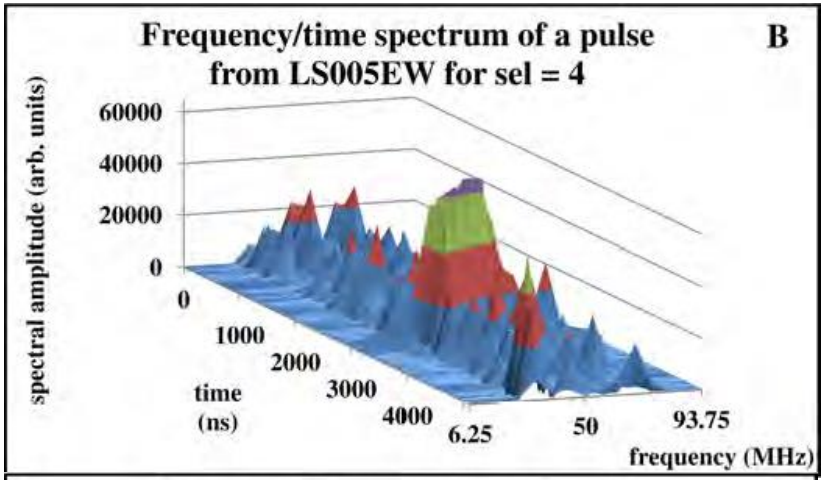


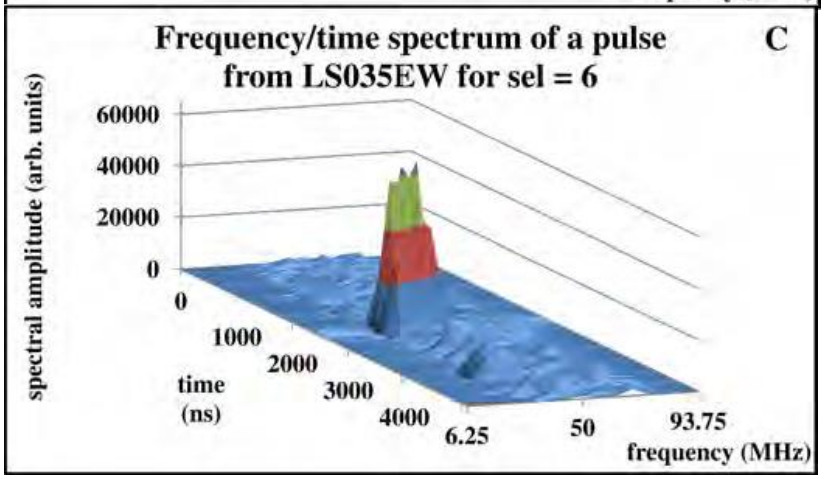


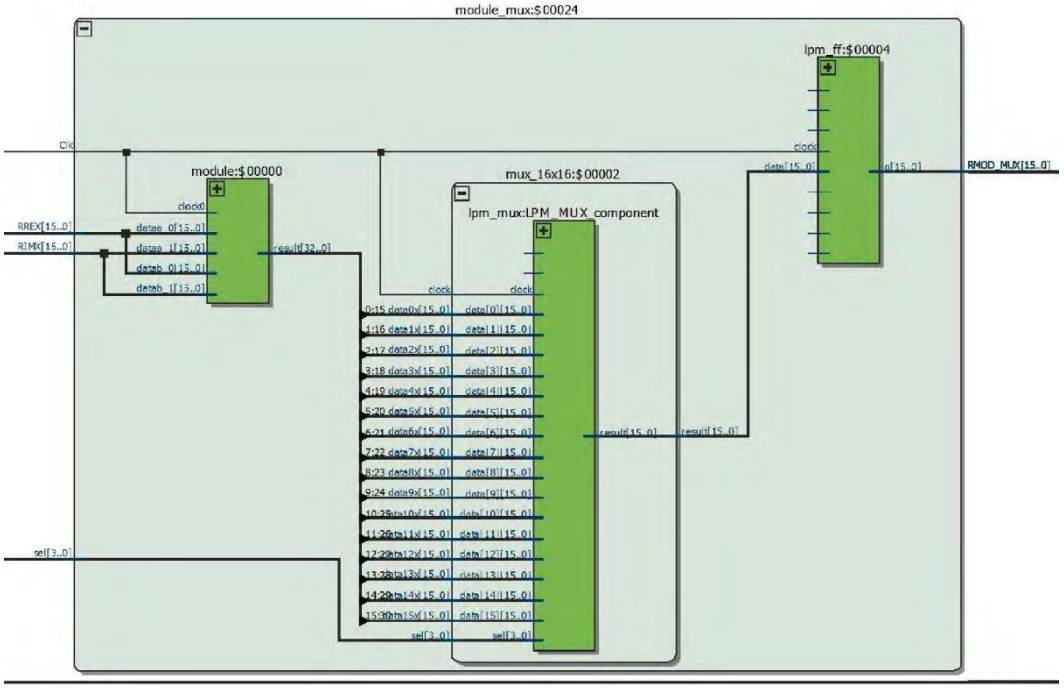




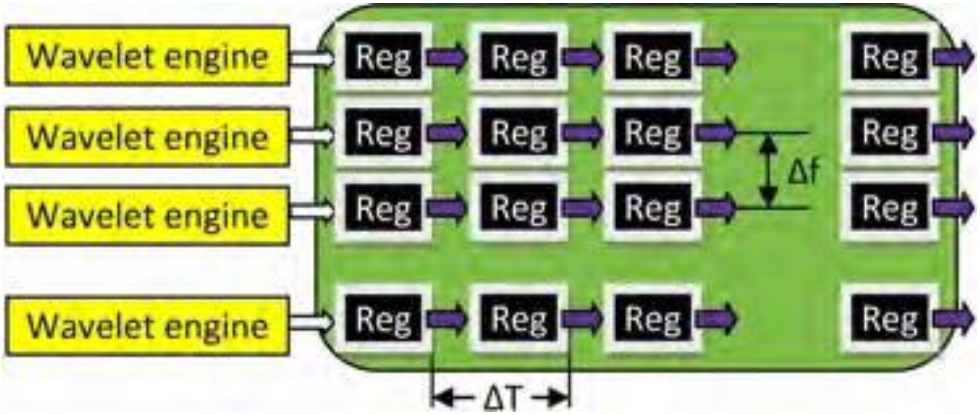
Optimization







Thresholds

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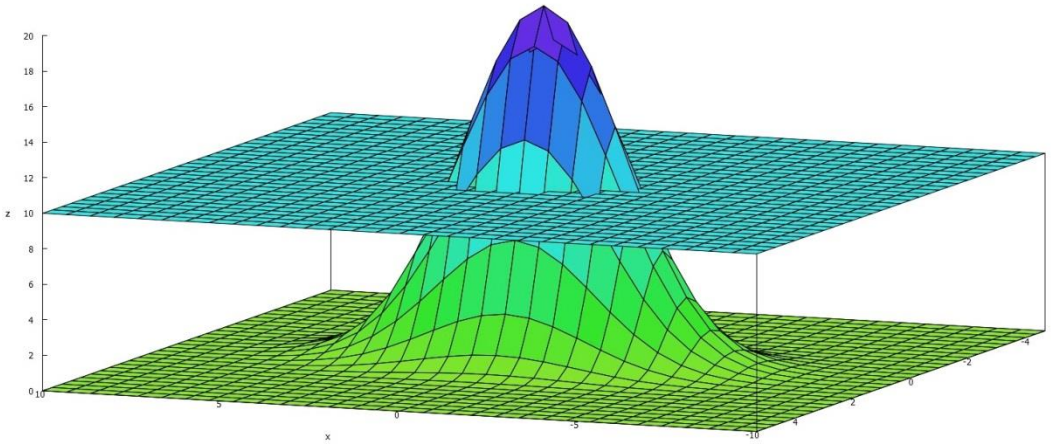
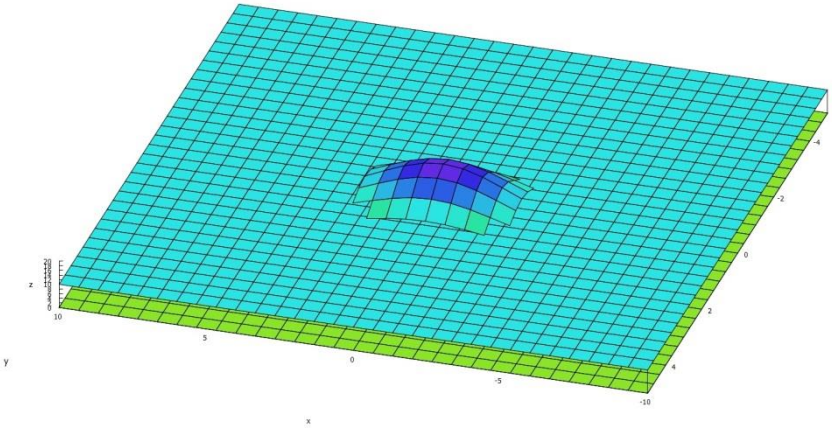
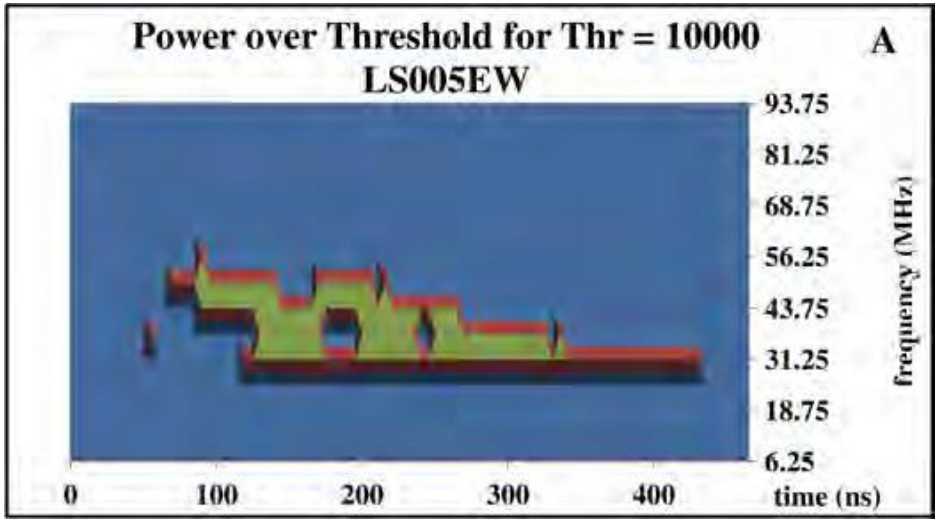
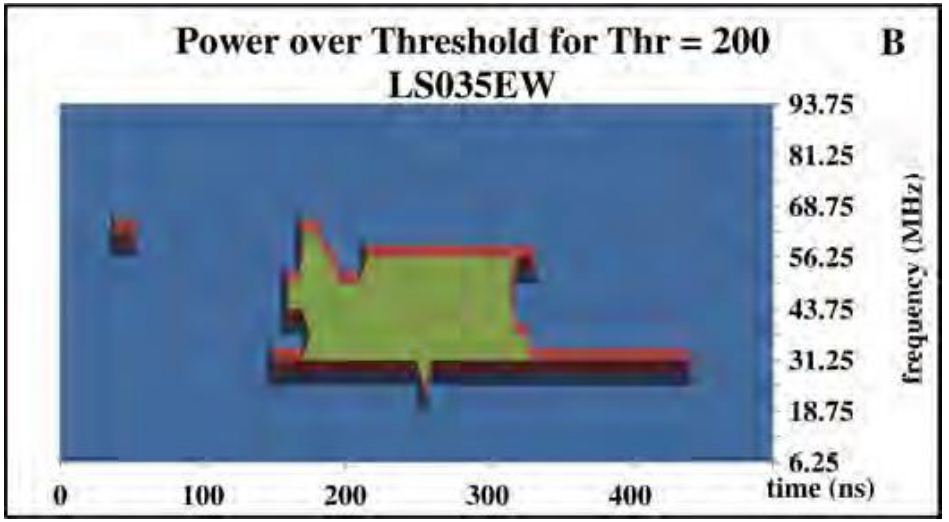
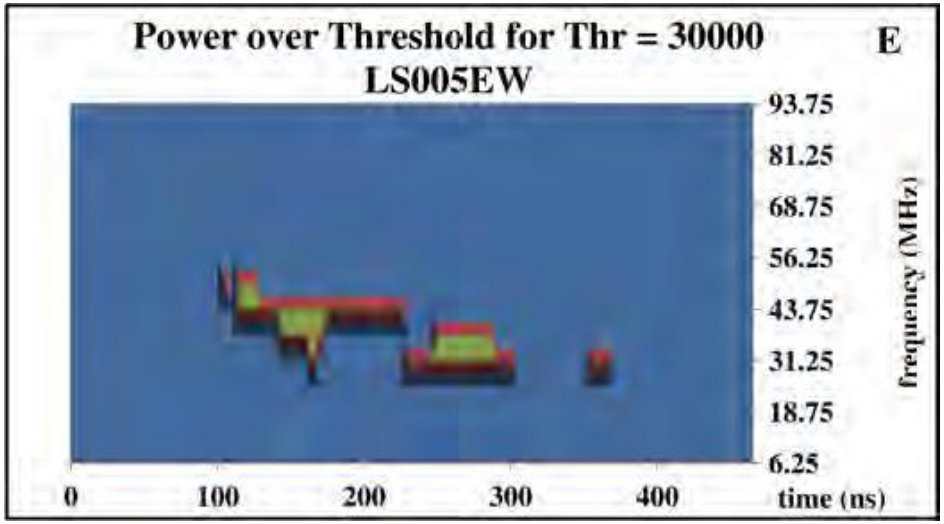


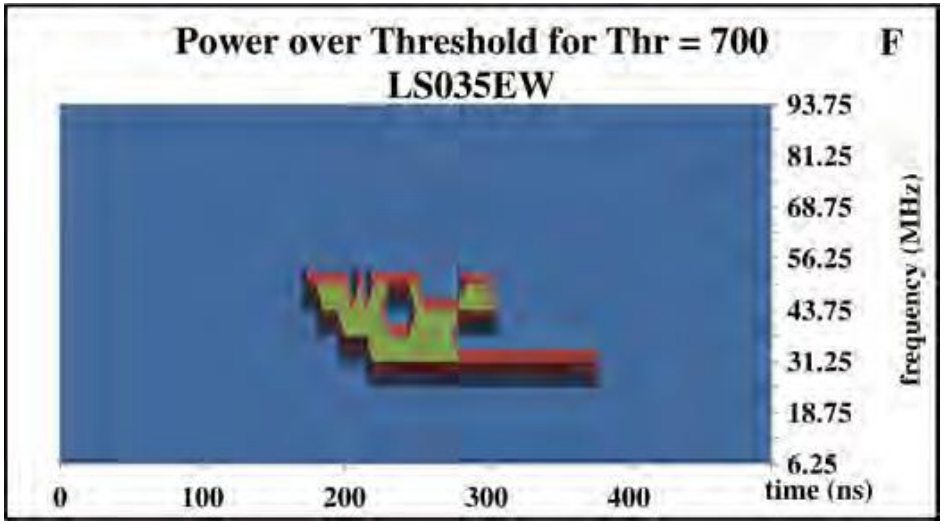


Power over threshold

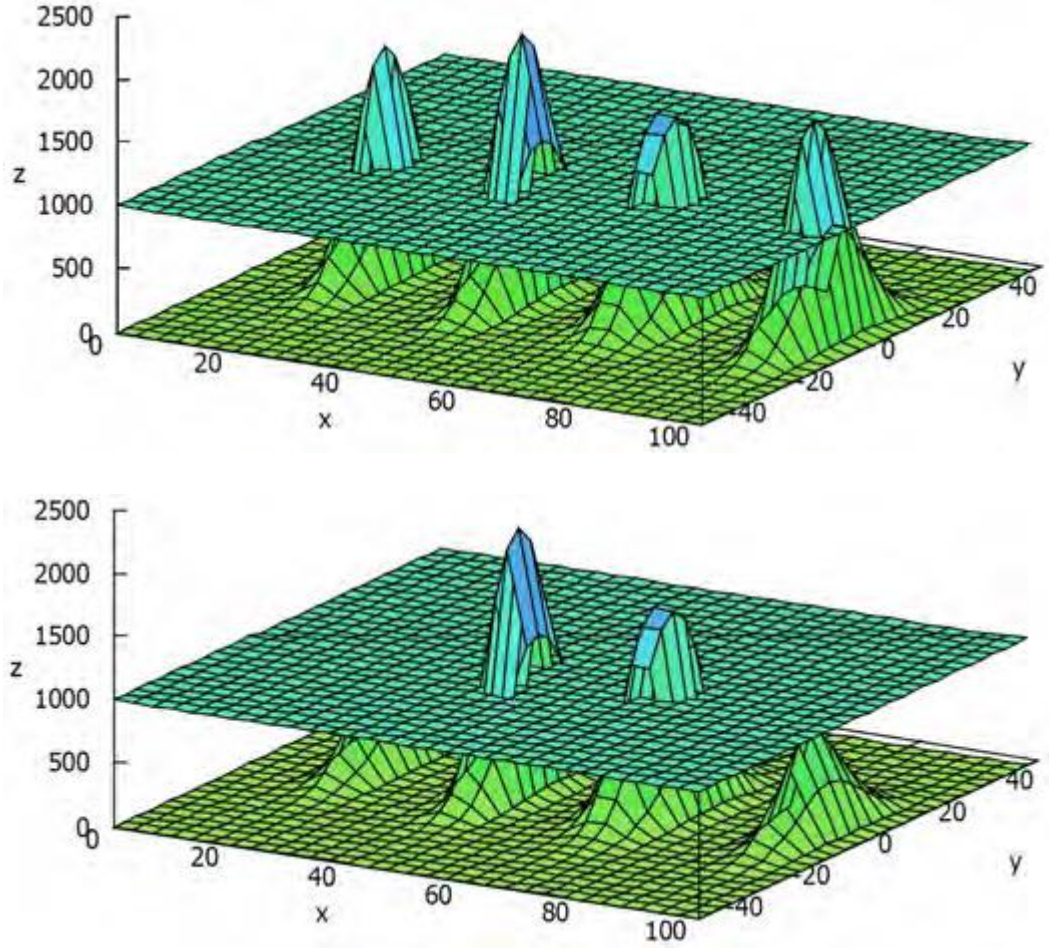


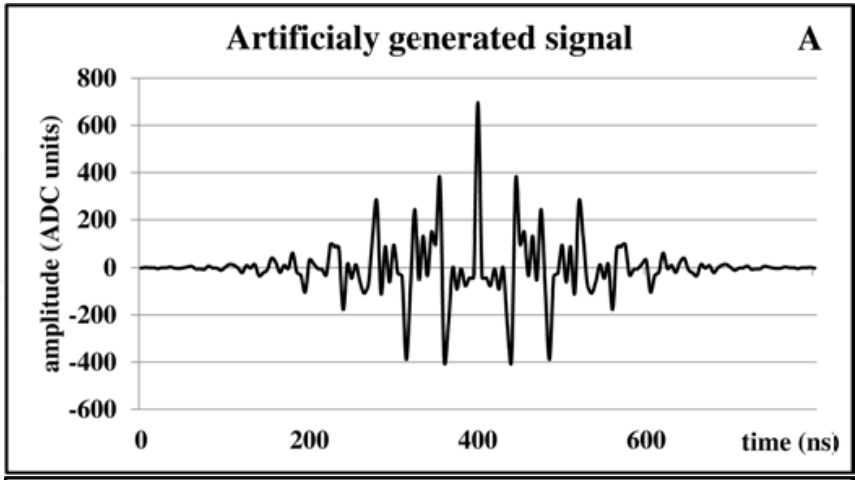


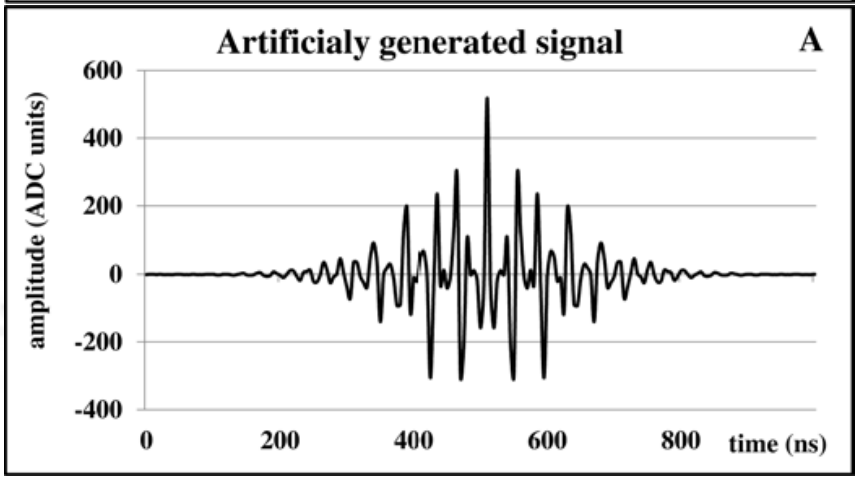




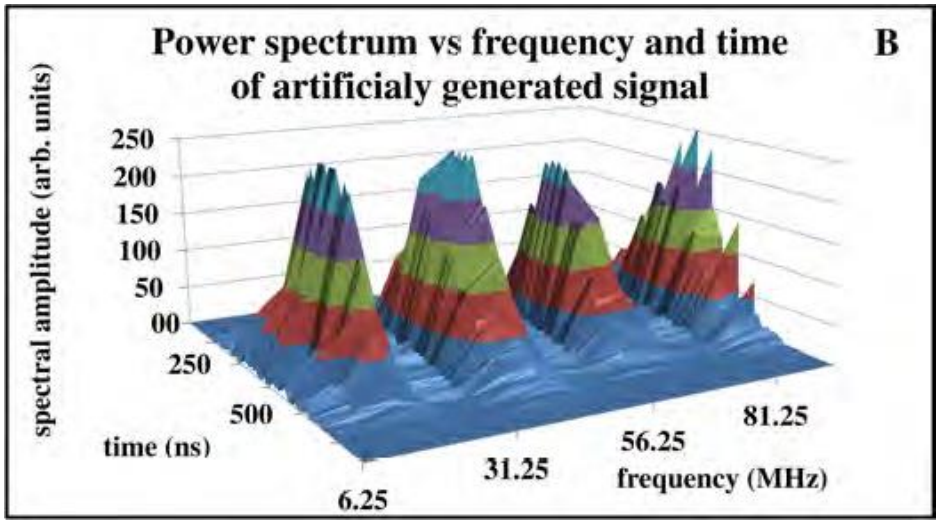
Artificially generated pulses

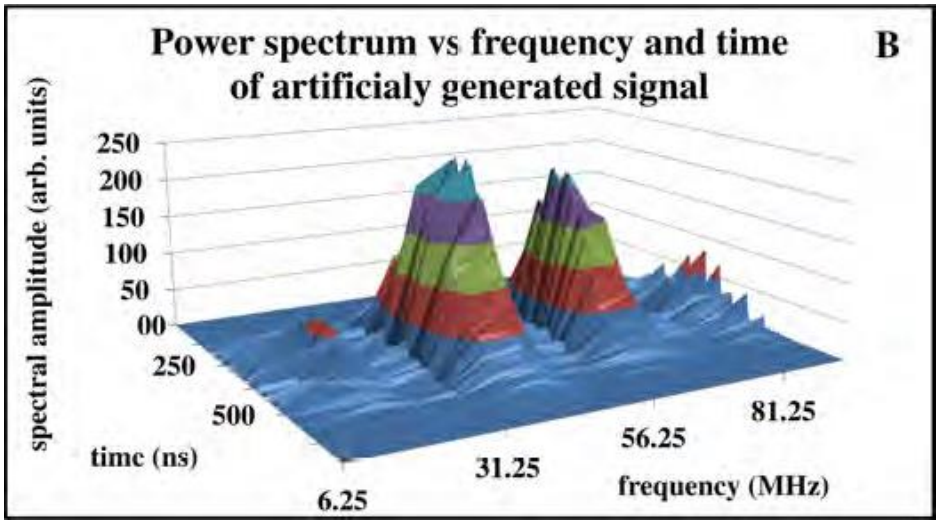


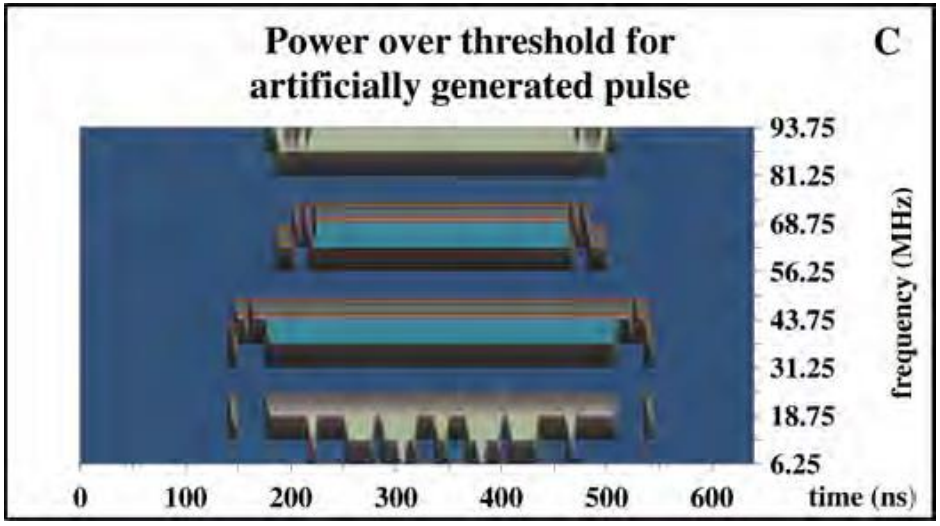


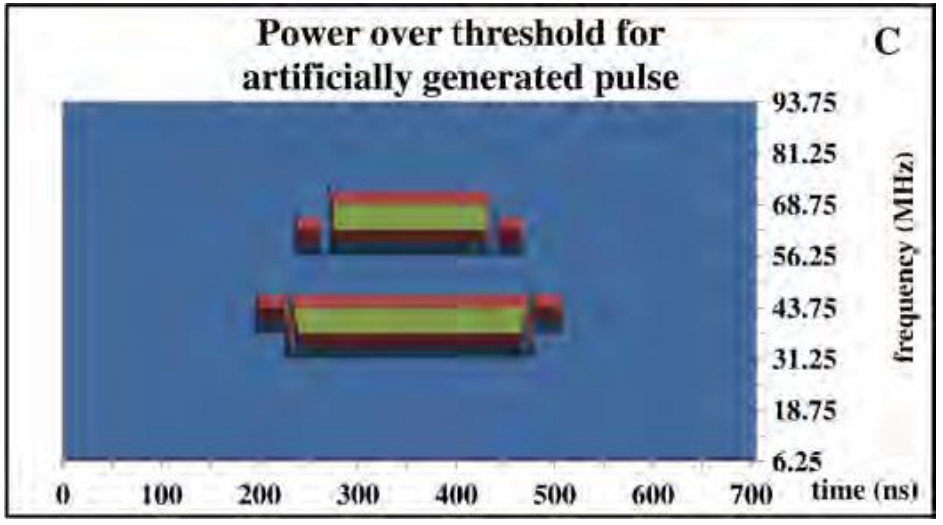


Artificially generated pulses









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PARTICLES AND FIELDS

FPGA Based Wavelet Trigger in Radio Detection of Cosmic Rays

Zbigniew Szadkowski · Anna Szadkowska

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 3, JUNE 2015 993

An Optimization of the FPGA Based Wavelet Trigger in Radio Detection of Cosmic Rays

Zbigniew Szadkowski

Conclusions

- **The wavelet trigger has been successfully implemented into prototype Front-End Board for the surface detector with 5CEFA9F31I7 FPGA from the Cyclone V family,**
- **Simultaneous analysis in real time in two-dimensional time-frequency domain allows an improvement of trigger efficiency and rejection of spurious triggers.**