# Вариации космических лучей во время гроз и новые геофизические эффекты

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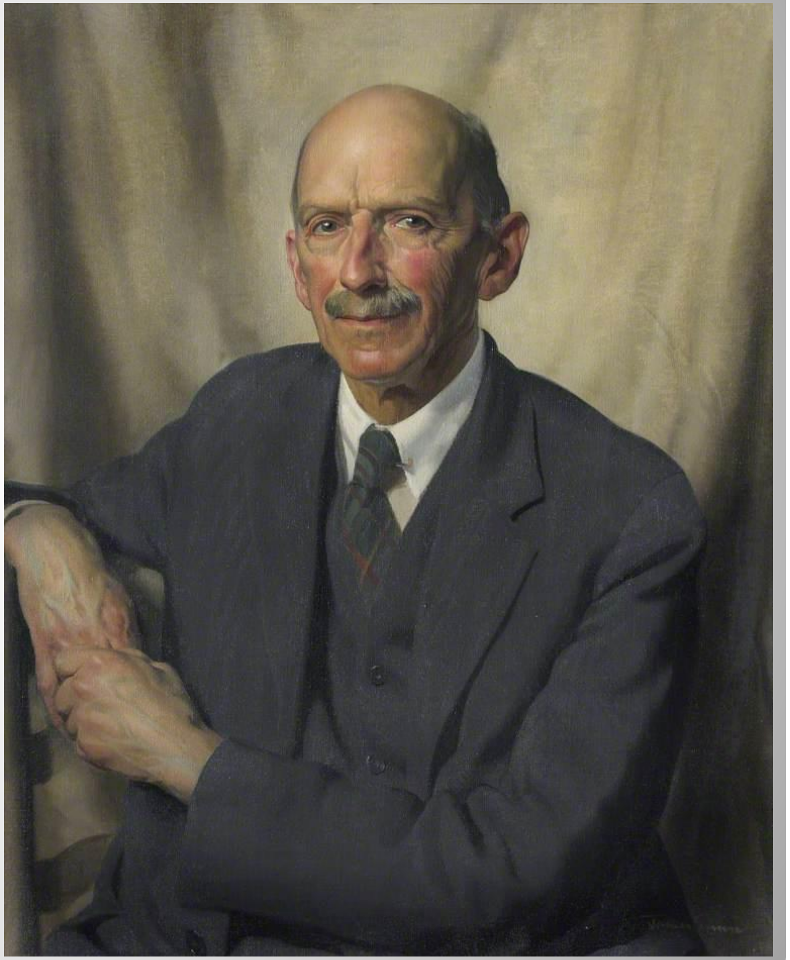
# Charles Thomson Rees Wilson

## The Nobel Prize in Physics 1927



“In a field of 20 kV/cm the energy supplied to β-particle will exceed the average loss; so that particle will be continuously accelerated until some accident occurs”

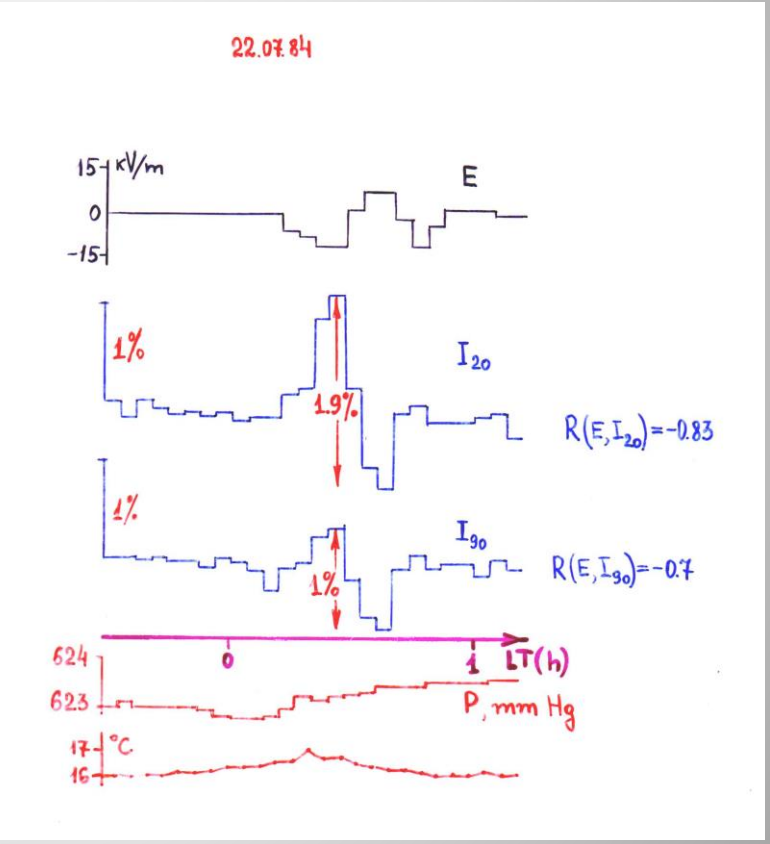
C. T. Wilson, Reader in Electrical Meteorology, 1924

Experiments of search for accelerated electrons and CR experiments LC denotes a correlation with lightning, while CI and CD mean the count increase and count decrease, respectively.

| Experiment | Location | Technique | Electric field measured? | Count changes or correlation with lightning |
|---|---|---|---|---|
| Schonland, 1930 | South Africa | Ionization chamber | Yes | – 20-30% |
| Schonland & Viljoen, 1933 | South Africa | G-M counters | No | LC |
| Halliday, 1934 | UK | Cloud chamber | No | LC |
| Steinmaurer, 1935 | Alps | Ionization chamber | No | CI for unshielded chamber, CD for shielded |
| Clay, 1933 | Bandoeng | Ionization chamber | Yes | + 4-6% |
| Clay et al., 1952 | Amsterdam | Ionization chambers and counters | No | – 20% |
| Fazzini et al., 1968 | Bologna | Scintillators | No | – 1% |
| Alexeenko et al., 1985 | Baksan | Scintillators | Yes | – 1% hard, +2% soft |
| Aglietta et al., 1999 | Gran Sasso | Scintillators | No | + 5% |
| Chubenko et al., 2000 | Ten Shan | G-M tubes, scintillators | Started | + 3.5% |
| Takami et al., 2001 | Norikura | Prop. counters, scintillators | Started | + 1% |
| Alexeenko et al., 2001 | Baksan | Scintillators | Yes | Different effects for hard and soft, LC |

# Baksan Experiment made by Chudakov and Sborshikov (1979-1985)

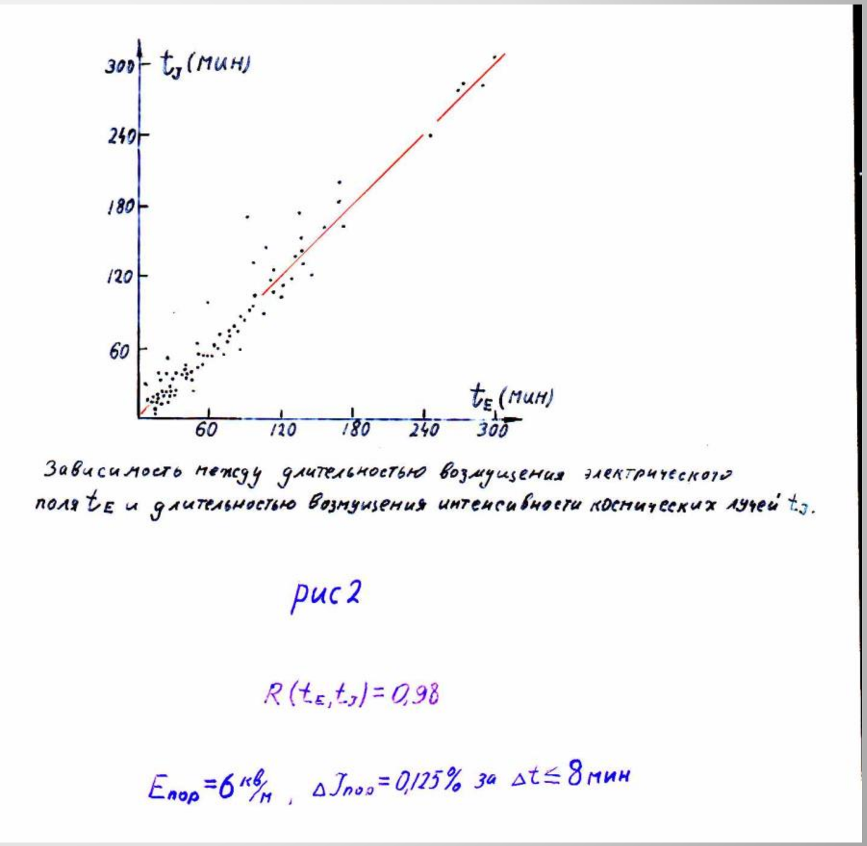
- Short (10-20 min) variations of CR intensity (positive and negative)
- No correlation with pressure and temperature
- Obvious correlation with the electric field ⇒



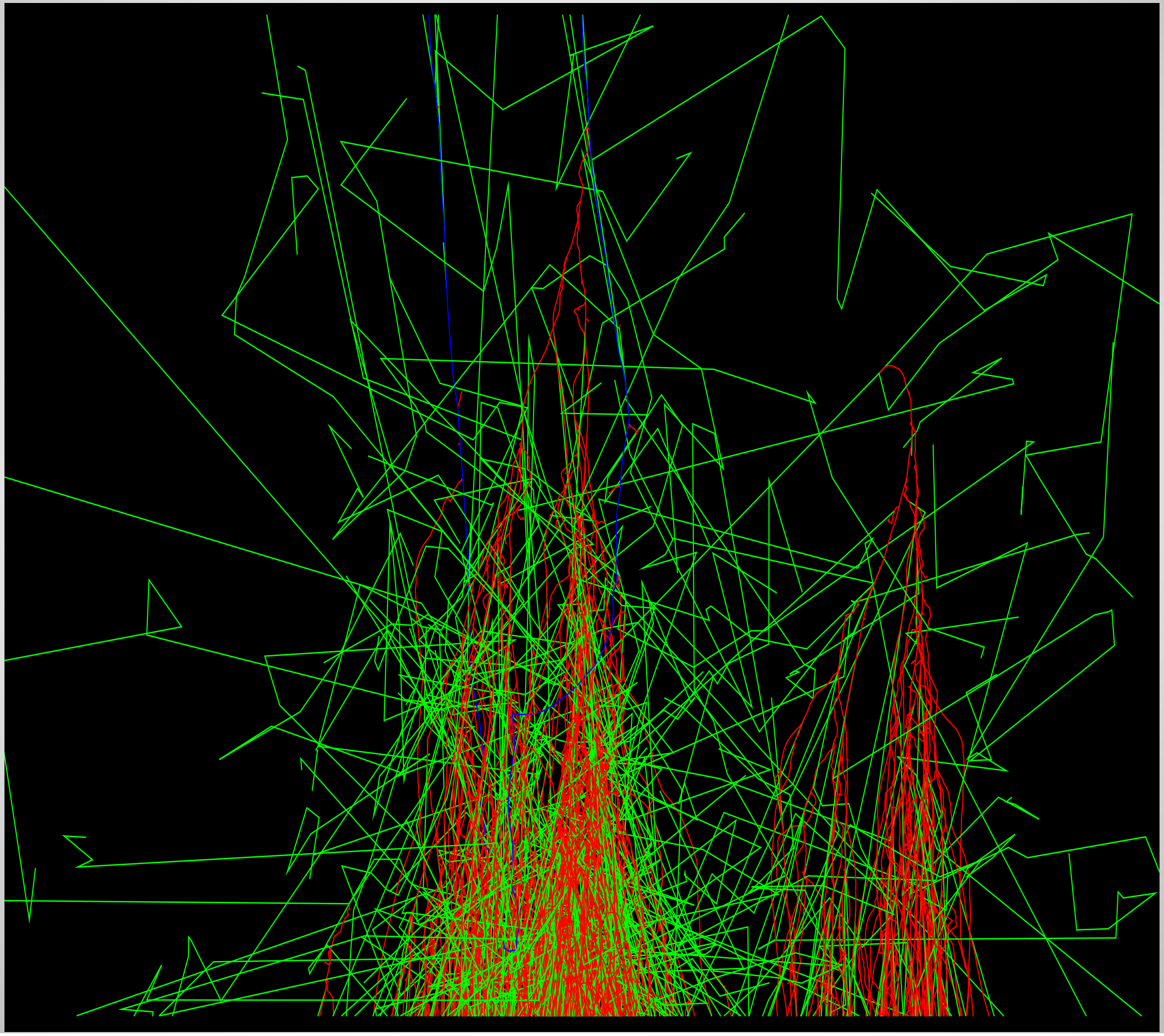
Professor A.E. Chudakov (1921-2001), “founding father” of gamma-ray astronomy (A. Wolfendale) and pioneer in studying CR variations during thunderstorms

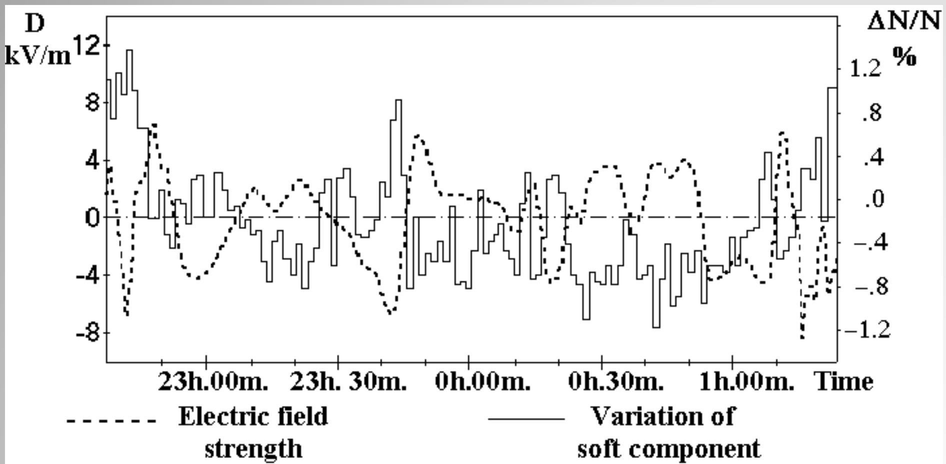
# Baksan Experiment made by Chudakov and Sborshikov (1979-1985)

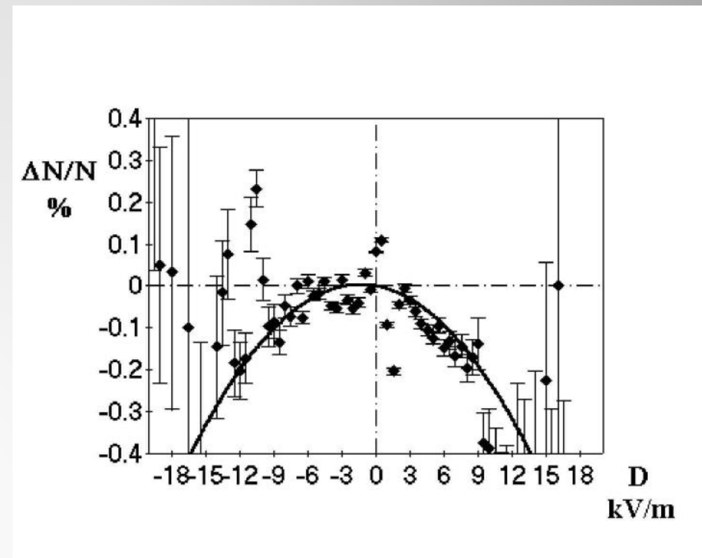
- The phenomenon was observed only in summer months
- Excellent correlation was observed for the time of disturbance in CR intensity and electric field strength $\Rightarrow$

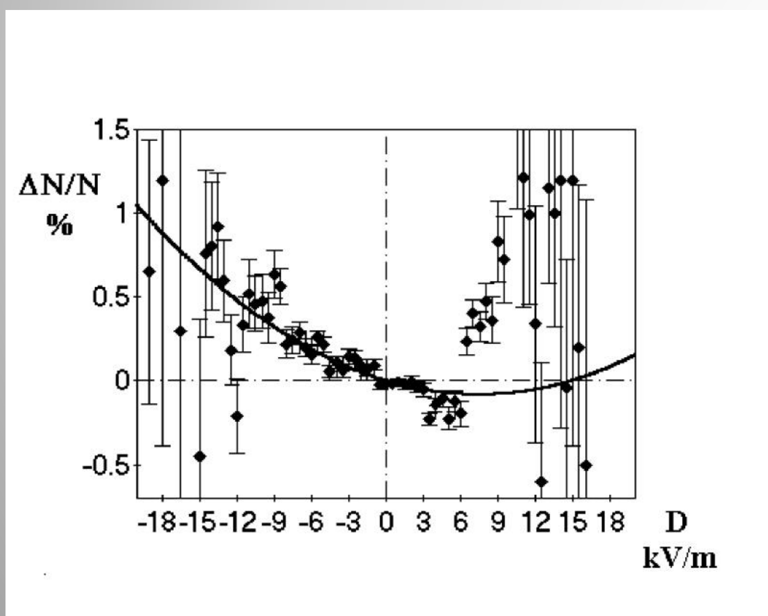


Cascades of particles generated by a single 1-MeV electron in the electric field 5 kV/cm






First results of the new version of the Baksan experiment: regression curves for muons and soft CR component

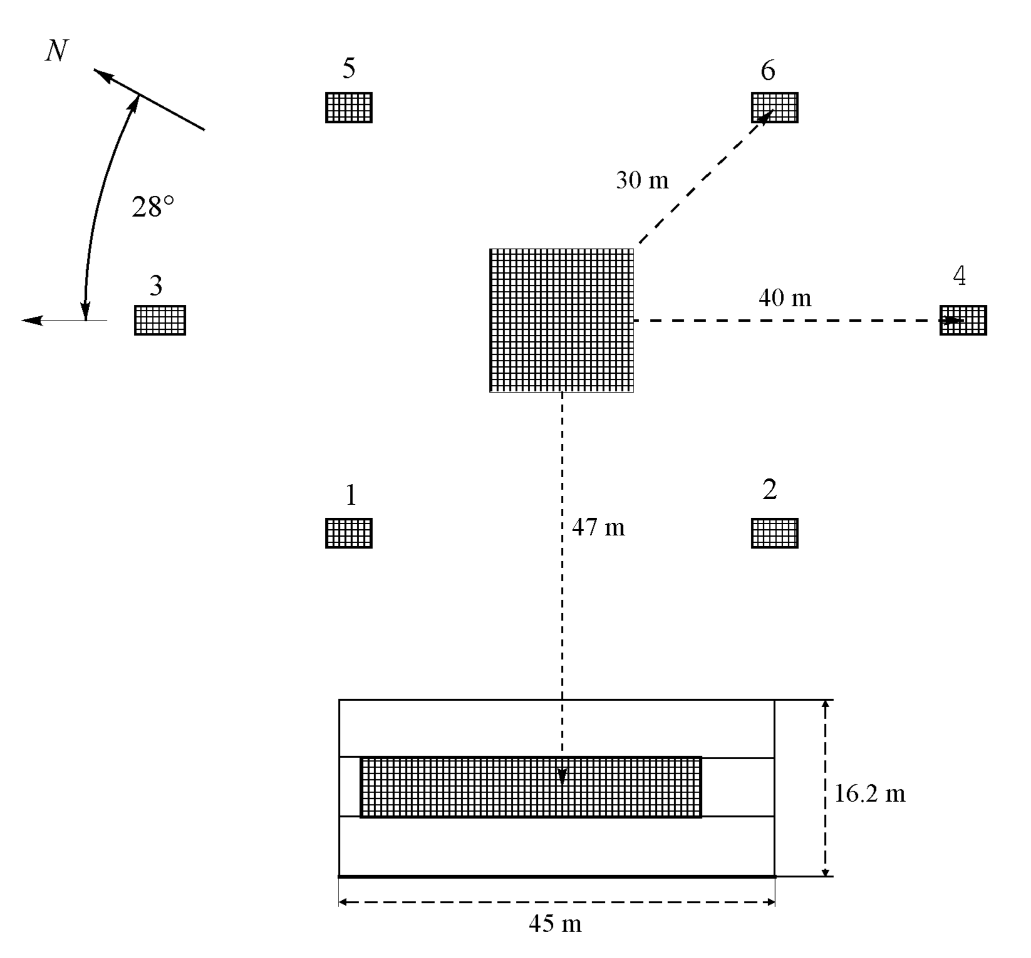
# Instrumentation

# Baksan Air Shower Array (BASA)

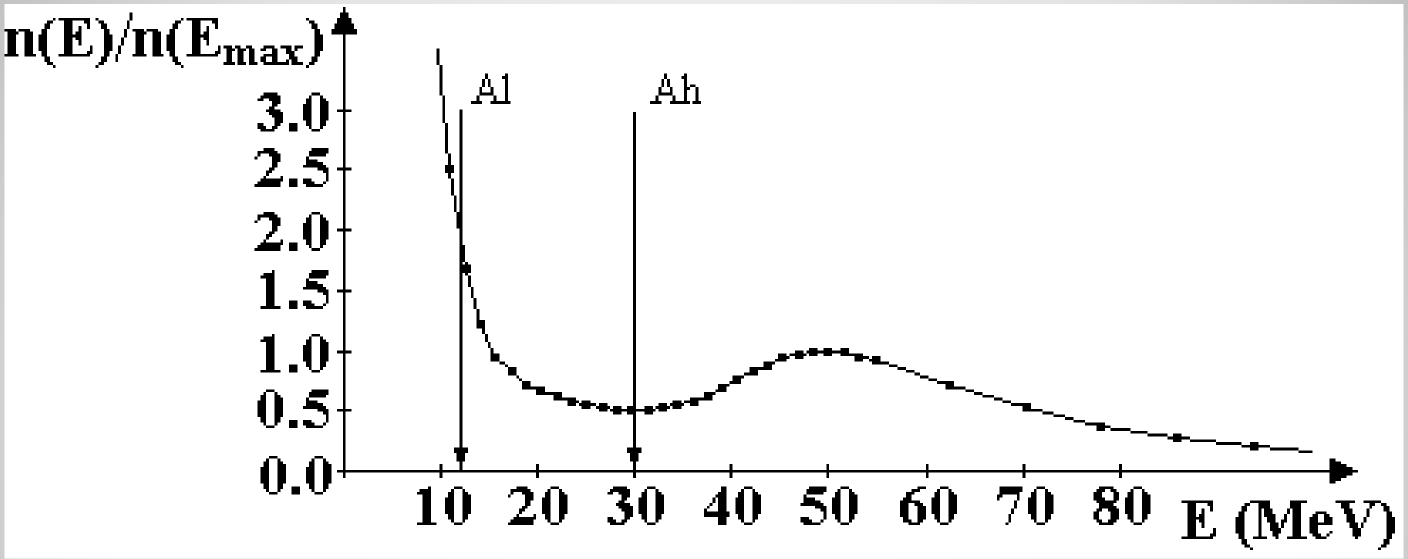
Central Carpet
(400 liquid scintillators)

Six huts
(108 liquid scintillators)

Muon Detector
(175 plastic scintillators
under 2 m of rock).
Energy threshold 1 GeV



## Amplitude spectrum from a layer of scintillators




Two thresholds are used to separate soft and hard components:

Soft component is detected by huts between low (Al) and upper (Ah) thresholds. Electrons – 20%, positrons – 10%, $\gamma$-rays – 50%, admixture of muons is less than 20%.

Hard component is measured by Carpet detectors (under concrete roof 29 g/cm$^2$) above upper threshold (muons 90%)

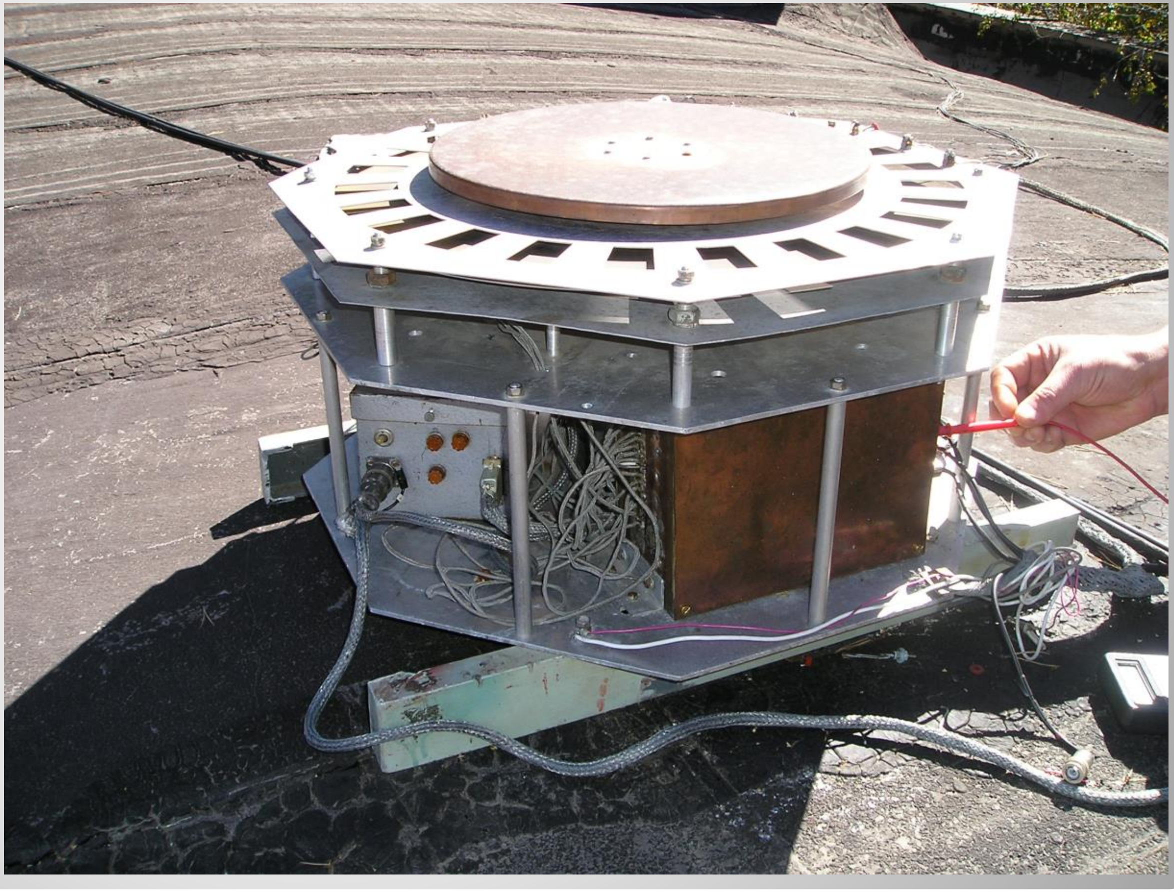

Mt. Andyrchi
EAS array
“Andyrchi”
“Carpet-2”
EAS array
Tunnel
entrance
Neutrino
village

# Universal instrument for measuring the near-ground electrostatic field of the atmosphere and precipitation electric current

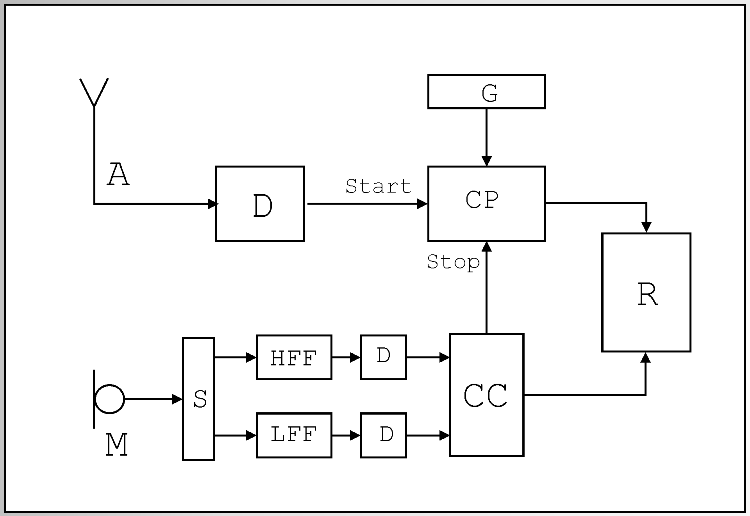
Measurements of electrostatic and slowly variable field in the range from from -40 kV/m up to +40 kV/m with an accuracy of ~ 10 V/m.

Precipitation electric current is measured in the range from -50 nA/m$^2$ up to +50 nA/m$^2$ with an accuracy of ~ 10 pA/m$^2$.

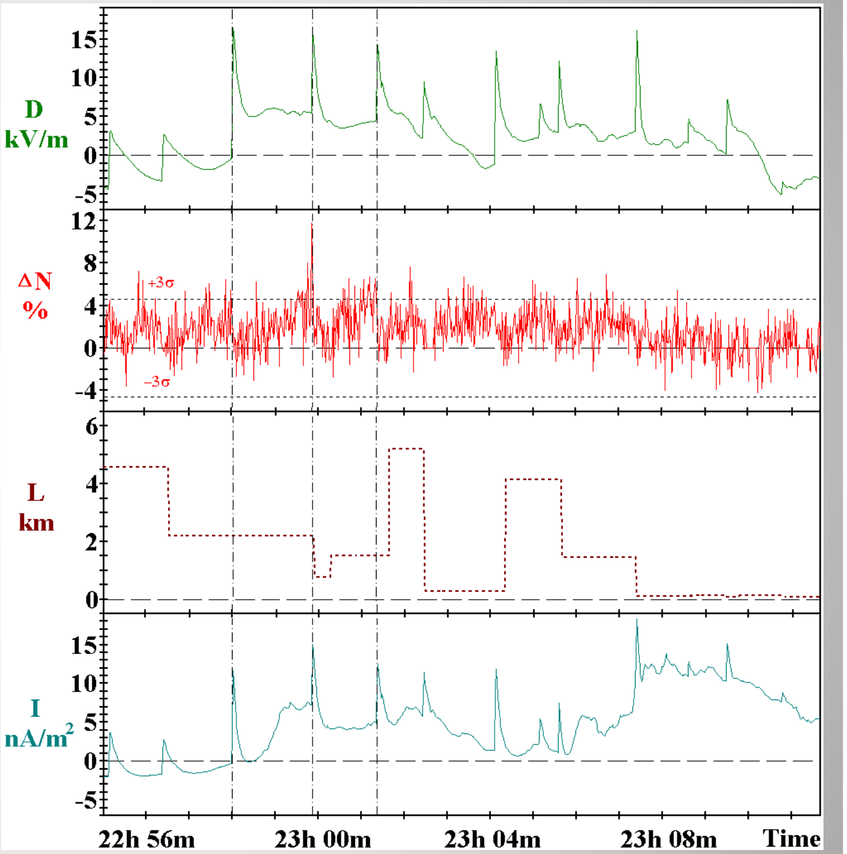
The instrument allows one to measure not only thunderstorm field but also the background (fair weather) electric field by a single method.



# Measuring the distance to lightning channels

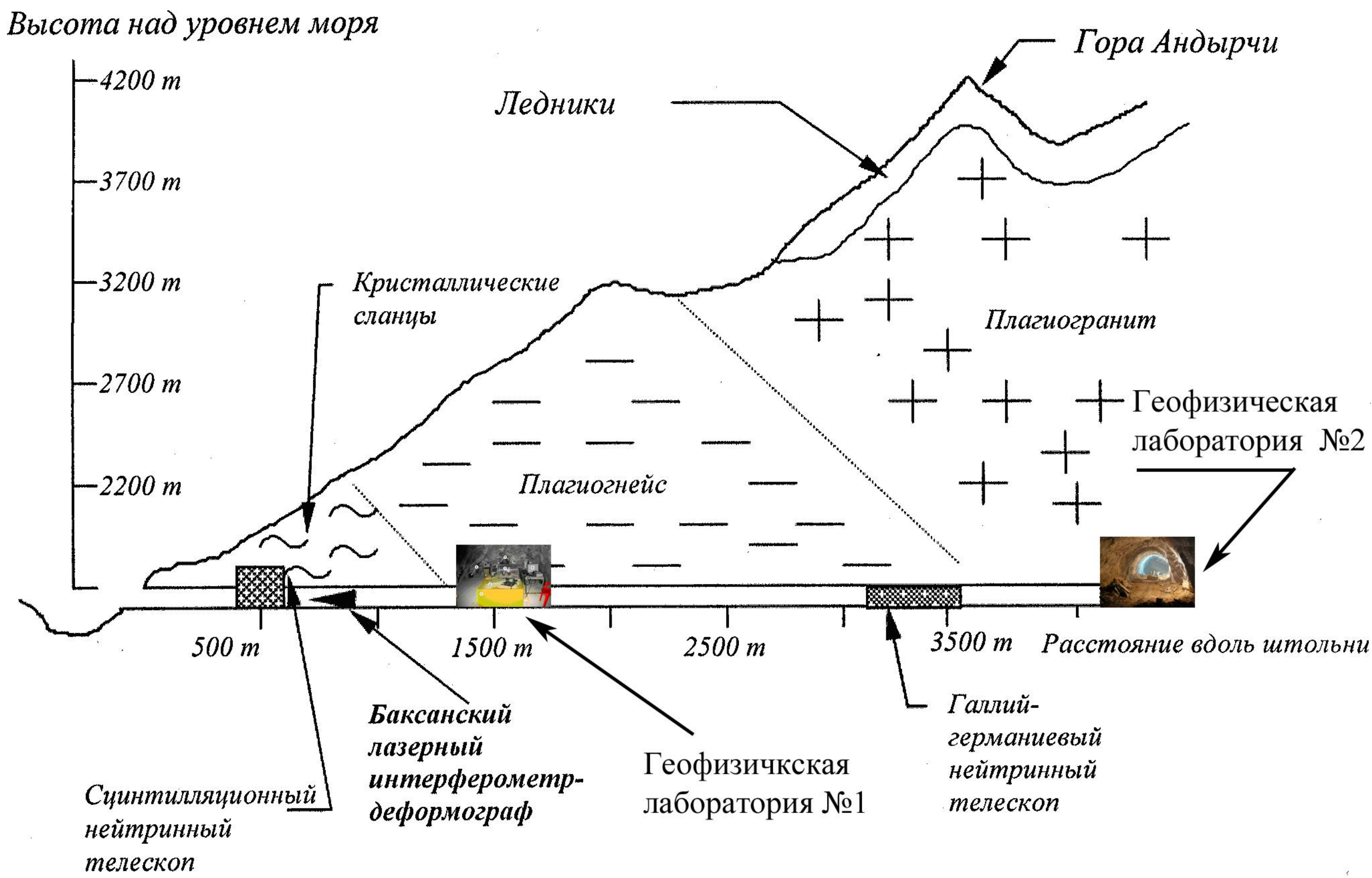



**A** is antenna, **M** is microphone, **D** is discriminator, **S** is splitter, **HFF** and **LFF** are high and low-frequency filters, respectively, **CC** is coincidence circuit, **G** is generator, **CP** is counter of pulses,
and **R** is recording device.

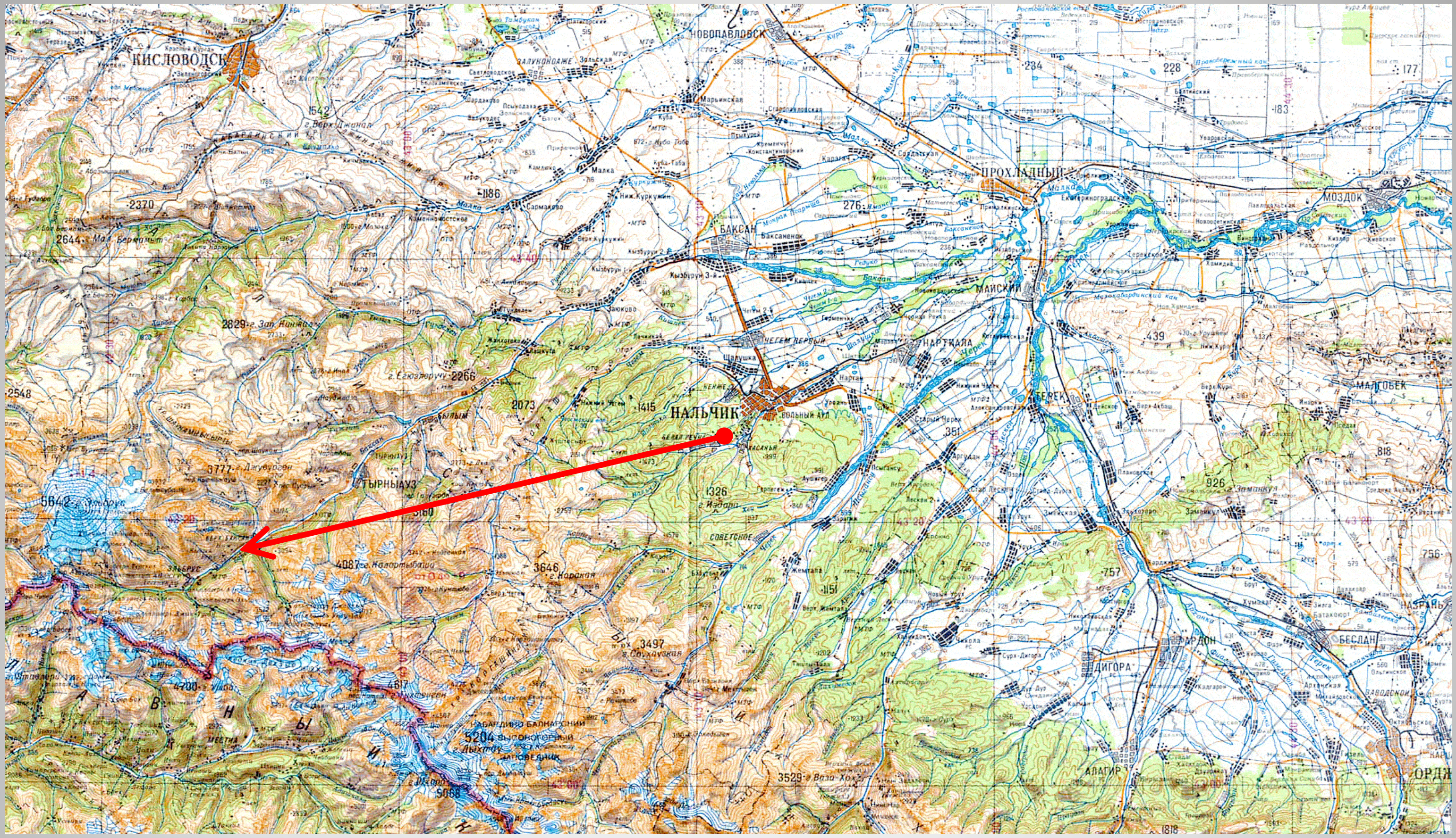



An episode of the thunderstorm on August 5, 2002

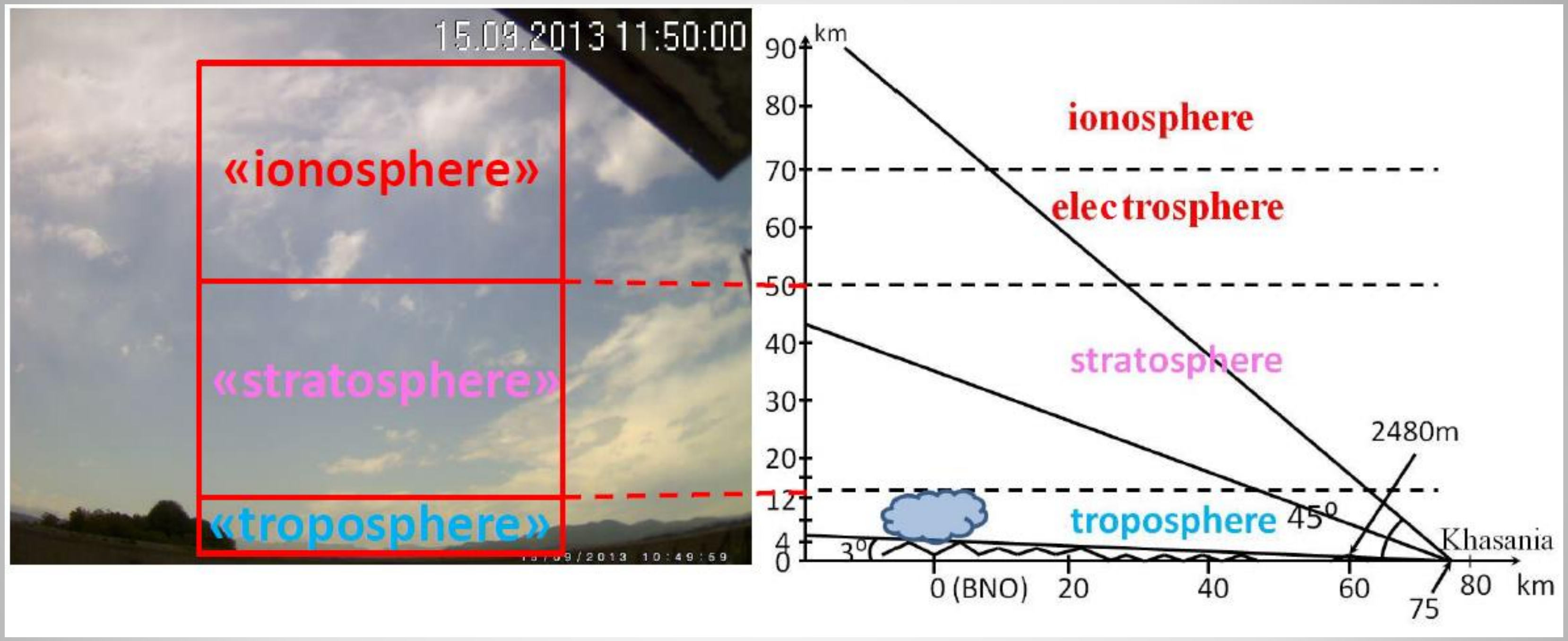
North-Caucasus Geophysical Observatory, Laboratory no. 1 of Shmidt Institute of Physics of the Earth



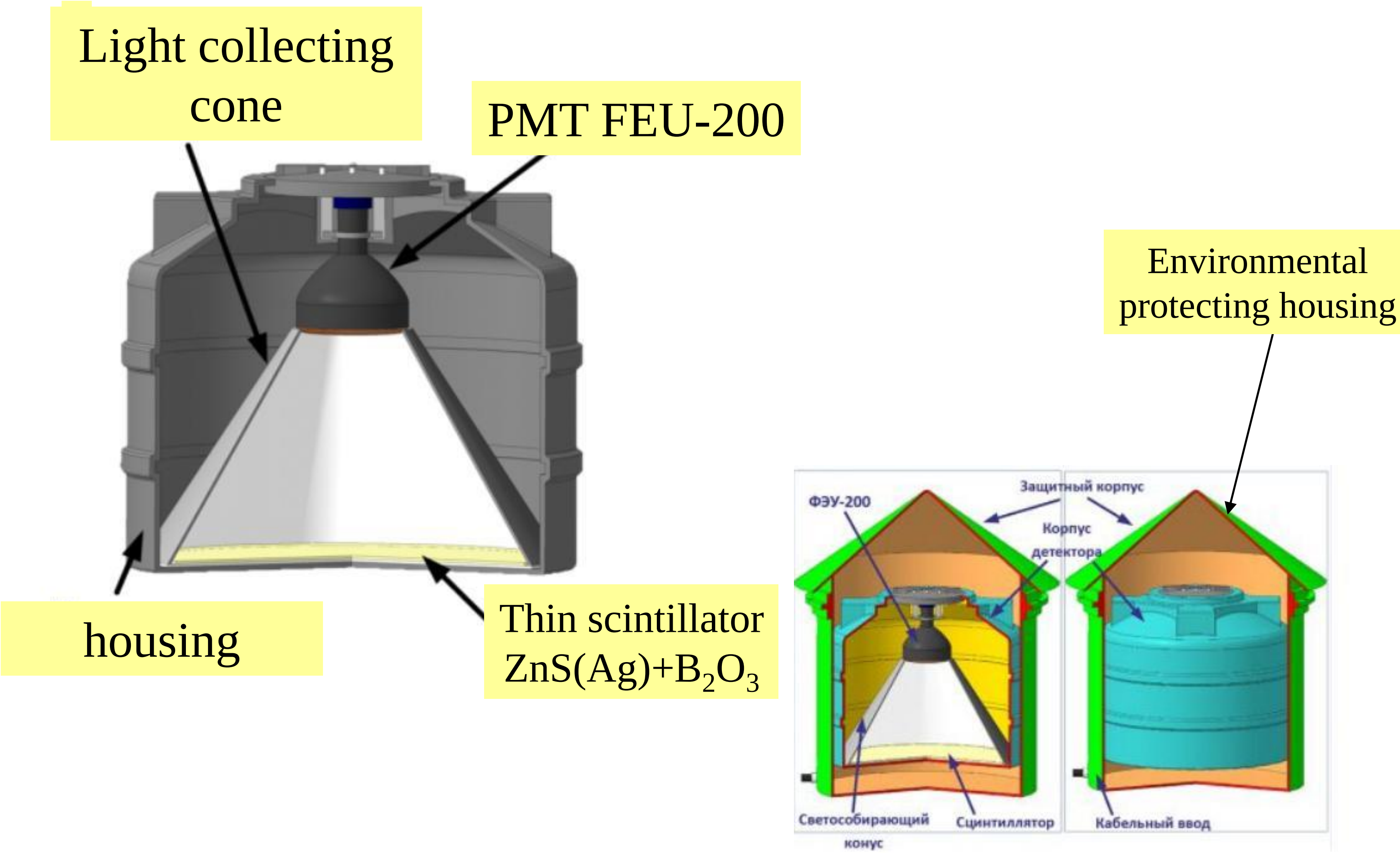

Cross section of the Andyrchi mountain and positions of geophysical laboratories 1 and 2.




Position of the remote video camera relative to the Carpet EAS array



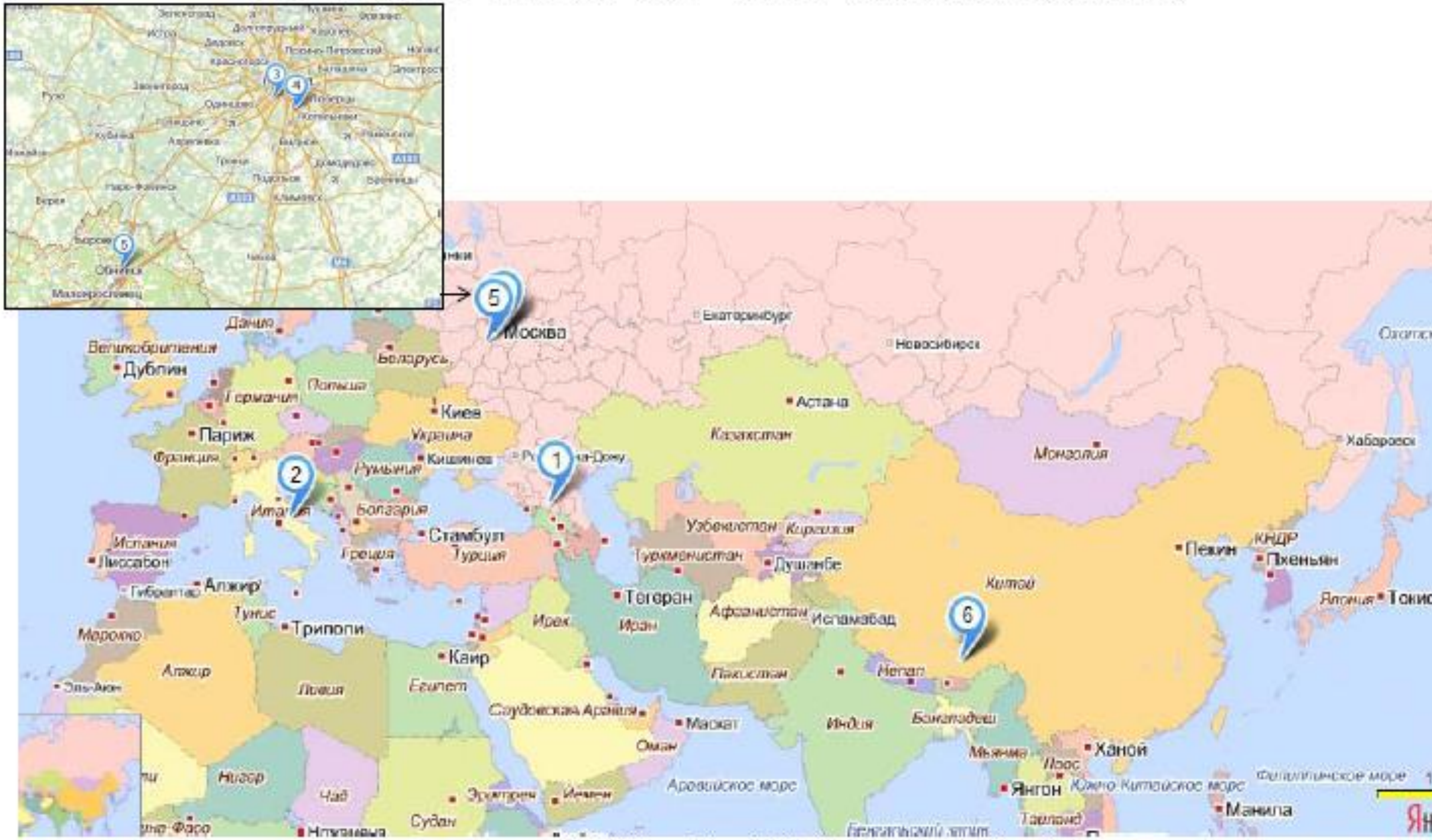

The field of view of the remote video camera and atmospheric regions under analysis




# Конструкция эн-детектора

# Geophysical research

## Global net of en-detectors

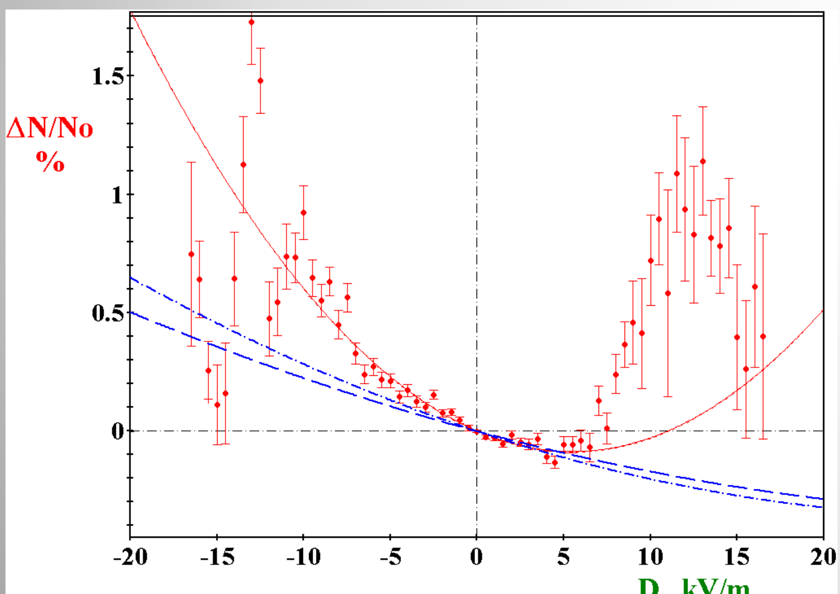


# Results

Correlation the intensity of soft CR component with near-earth electric field as measured and calculated (on the left panel). The difference (not explained by the spectrum transformation in the field near the ground surface) is shown on the right panel

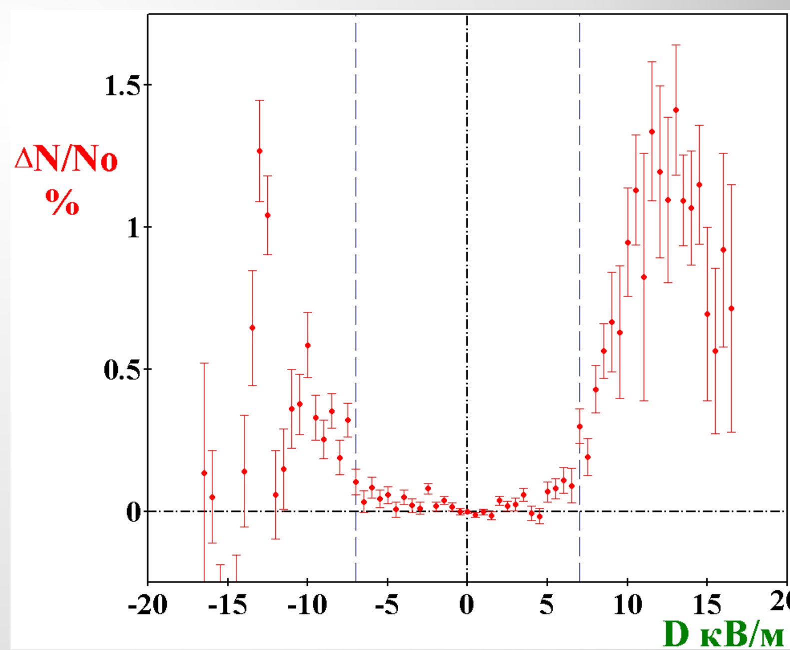
## Accelerated near the ground

Electrons Positrons




## Accelerated in the clouds

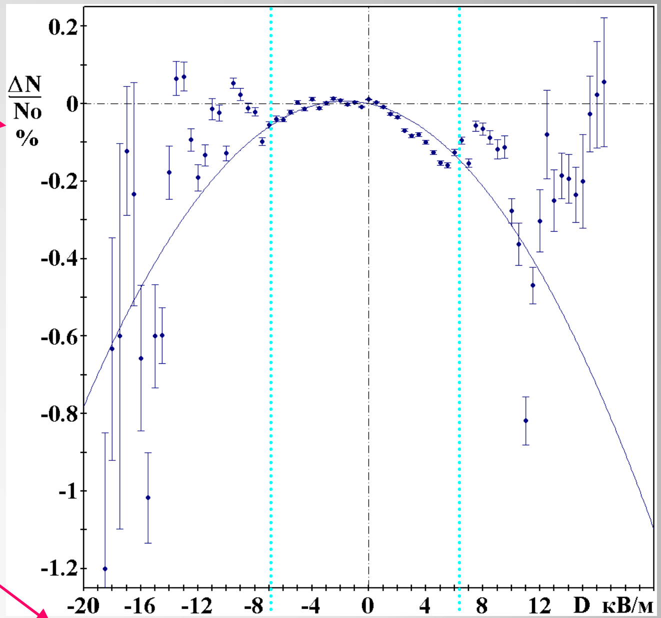
Positrons Electrons

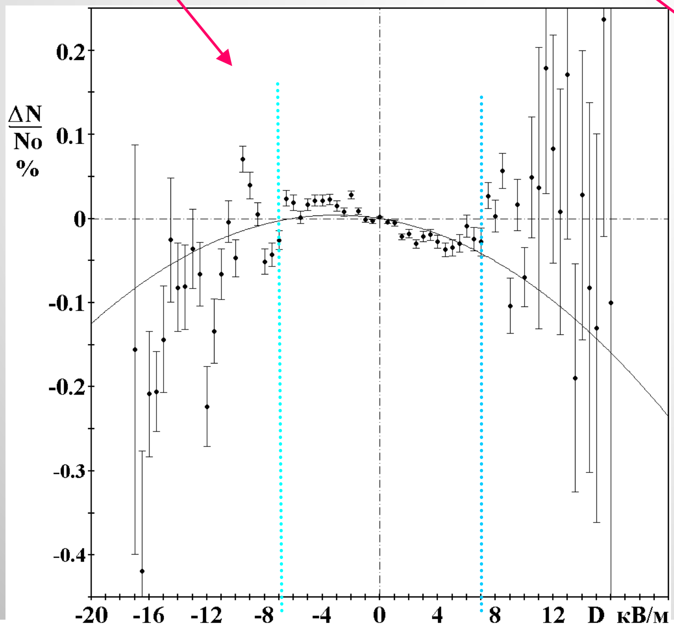


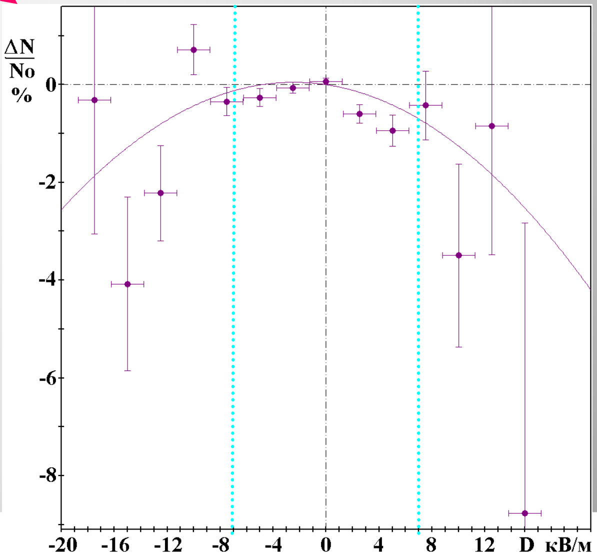
Muons with Eμ > 100 MeV

Stopping muons
(15 < Eμ < 90 MeV)

Muons with Eμ > 1 GeV

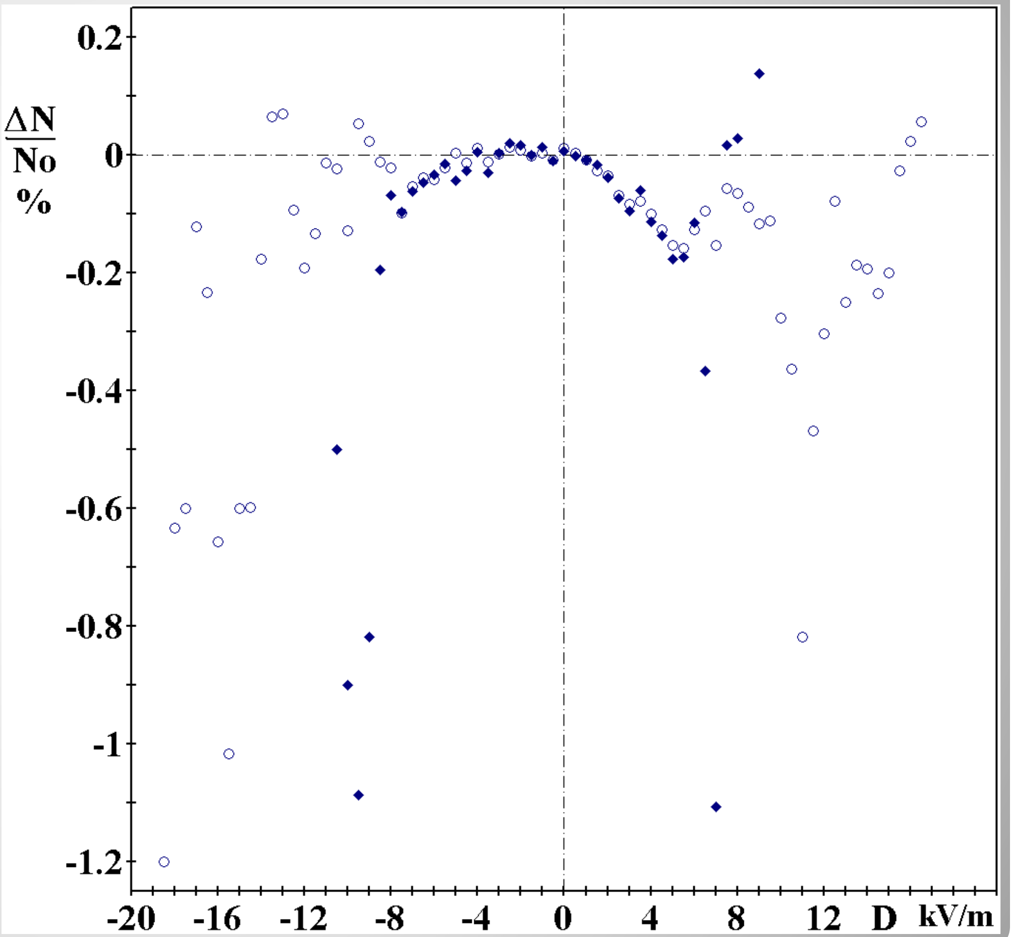


# Muons with Eμ > 100 MэВ, deviation from the mean intensity as a function of near-ground electric field strength (weighted average curve, summation over separate thunderstorms)

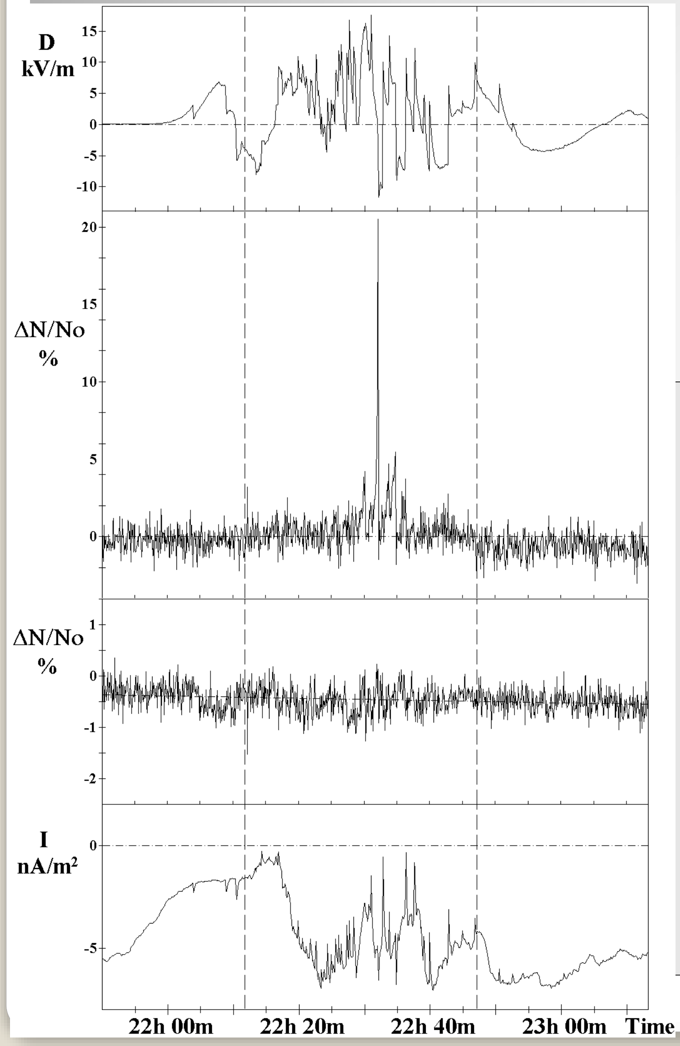
Solid circles correspond to distribution after exclusion of ±300-second periods of active thunderstorm phase.
Variations with large dispersion have no effect on the regular variation with the near-ground field.



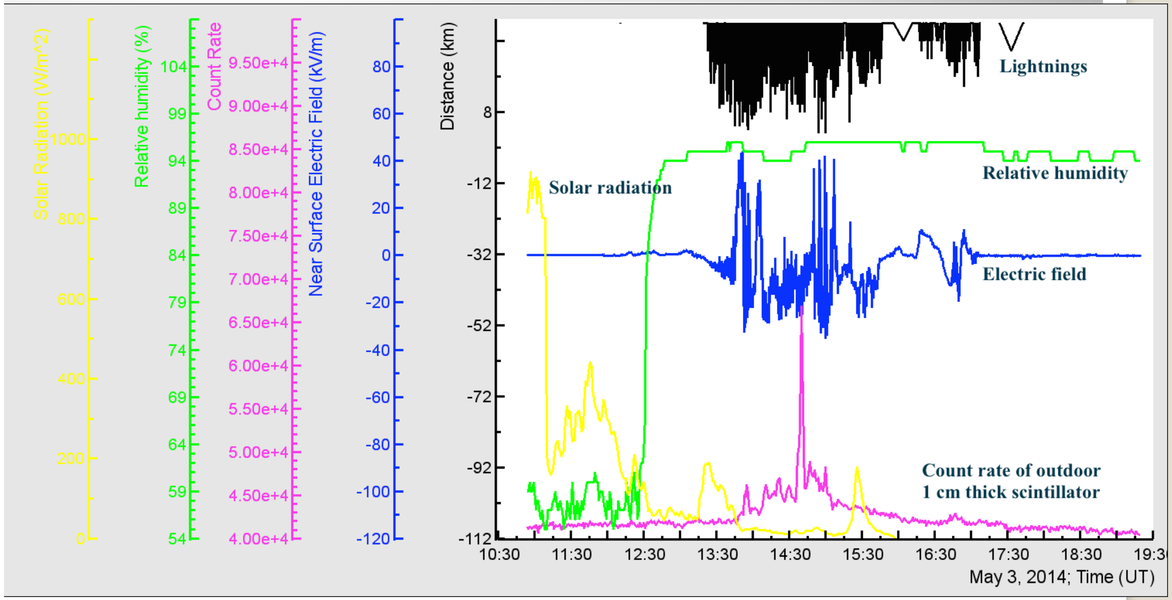
## Weighted mean coefficients of approximations by second-degree polynomials of the intensity – field regression curves for different components

| Component | Energy | Linear coefficient, % per kV/m | Quadratic coefficient, % per $(kV/m)^2$ |
|---|---|---|---|
| Muons | > 1 GeV | – 0.00277 ± 0.00034 | – 0.00045 ± 0.00005 |
| Hard component (muons) | > 100 MeV | – 0.00794 ± 0.0013 | – 0.00235 ± 0.00002 |
| Stopping muons | 20 – 80 MeV | – 0.04124 ± 0.01260 | – 0.00845 ± 0.00201 |

Strong enhancement of the soft component on September 7, 2000, Baksan Valley



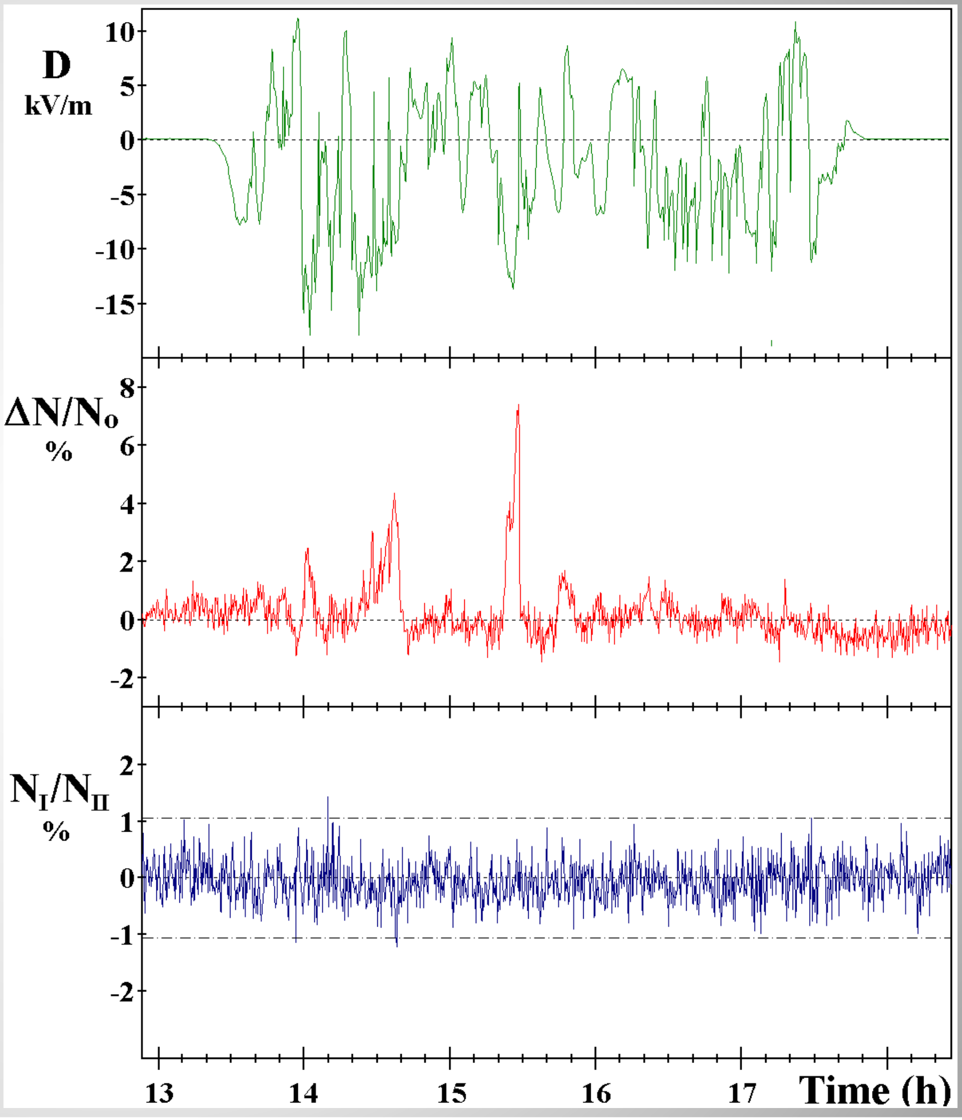

Mt. Aragats experiment in Armenia.
Very similar example of TGE



# Thunderstorm on Sept 26, 2001

Total counting rate of soft component detectors

The ratio of counting rates of two halves of soft component detectors shows purely statistical behavior. Dashed lines correspond to three-sigma level.



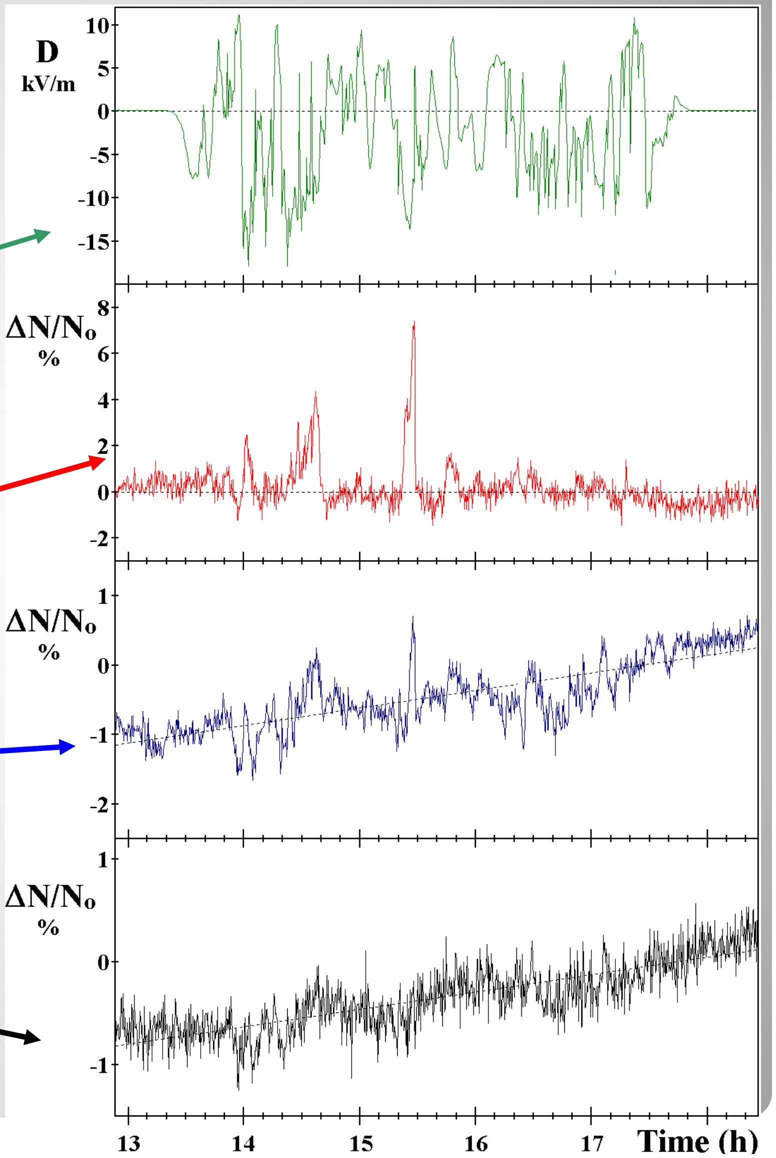
# Thunderstorm on September 26, 2001 (Baksan)

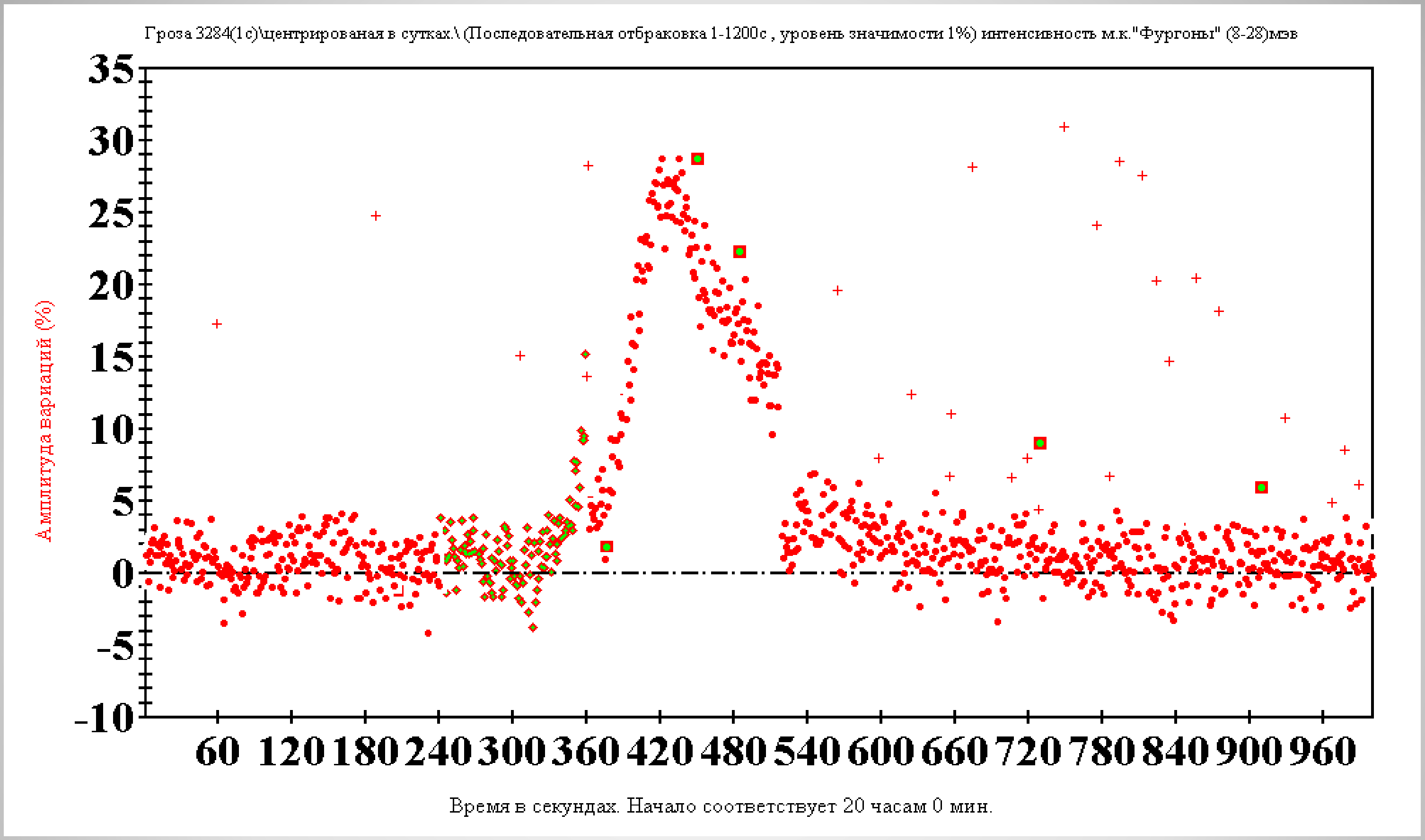
Electric field

Soft component
(10-30 MeV)

Hard component
(> 100 MeV)

Flux of muons (> 1 GeV)

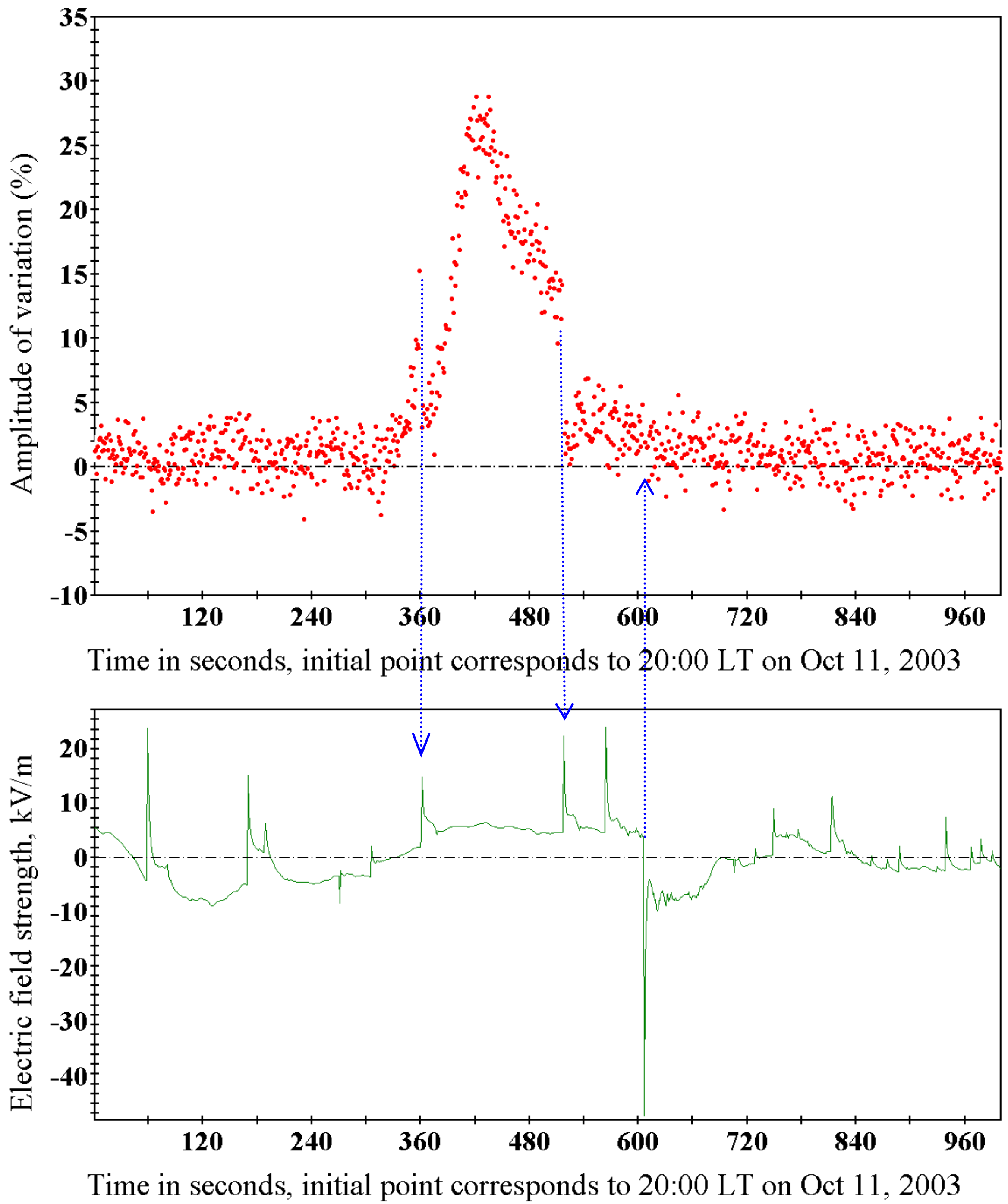




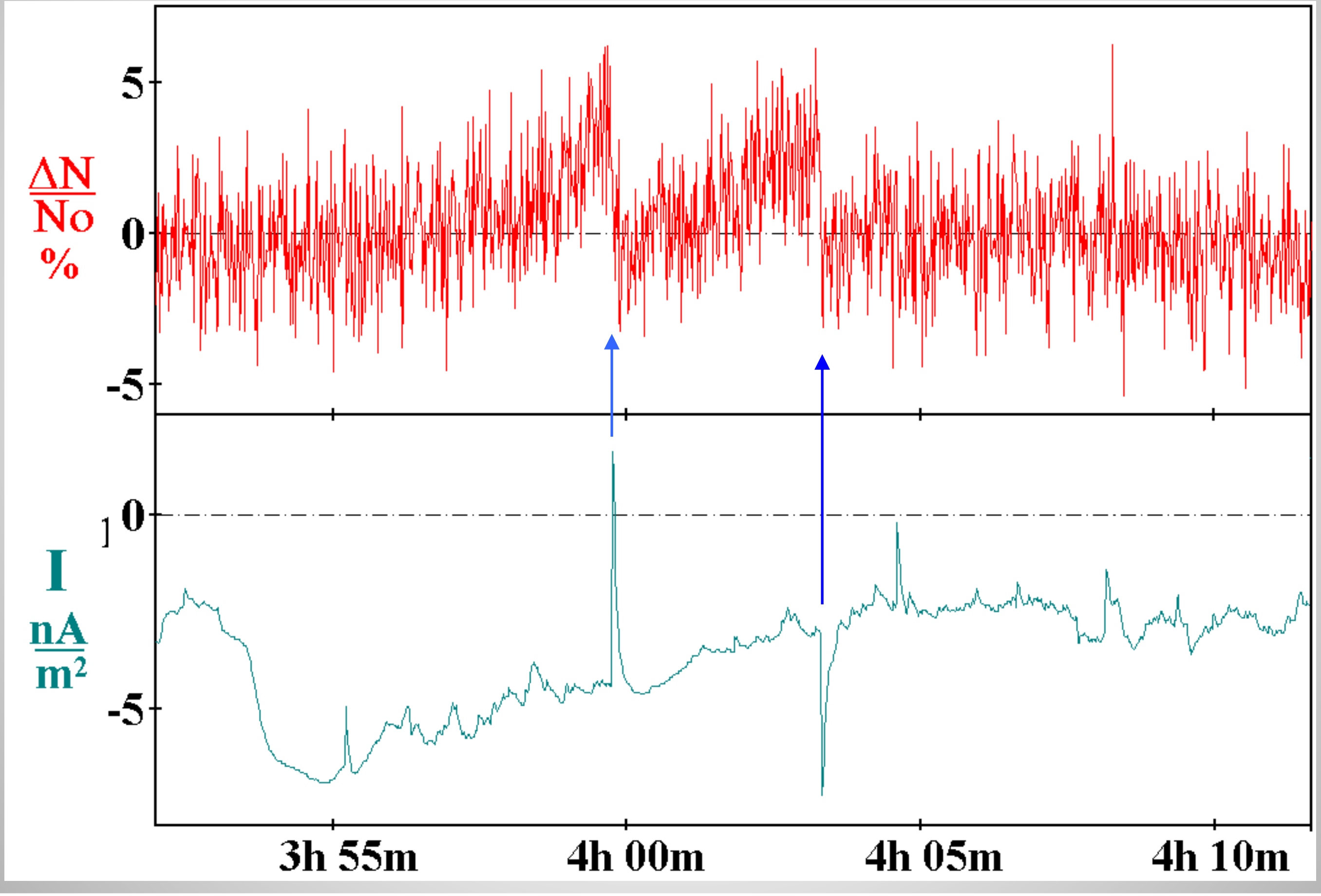

Event on October 11, 2003 before correction for noise and homogeneity

# Record enhancement during thunderstorm on October 11, 2003

Estimates of minimal distance to two lightning strokes exerting strong effect on the intensity are 4.4 and 3.1 km. Other lightning discharges,including very near, give no such an effect.

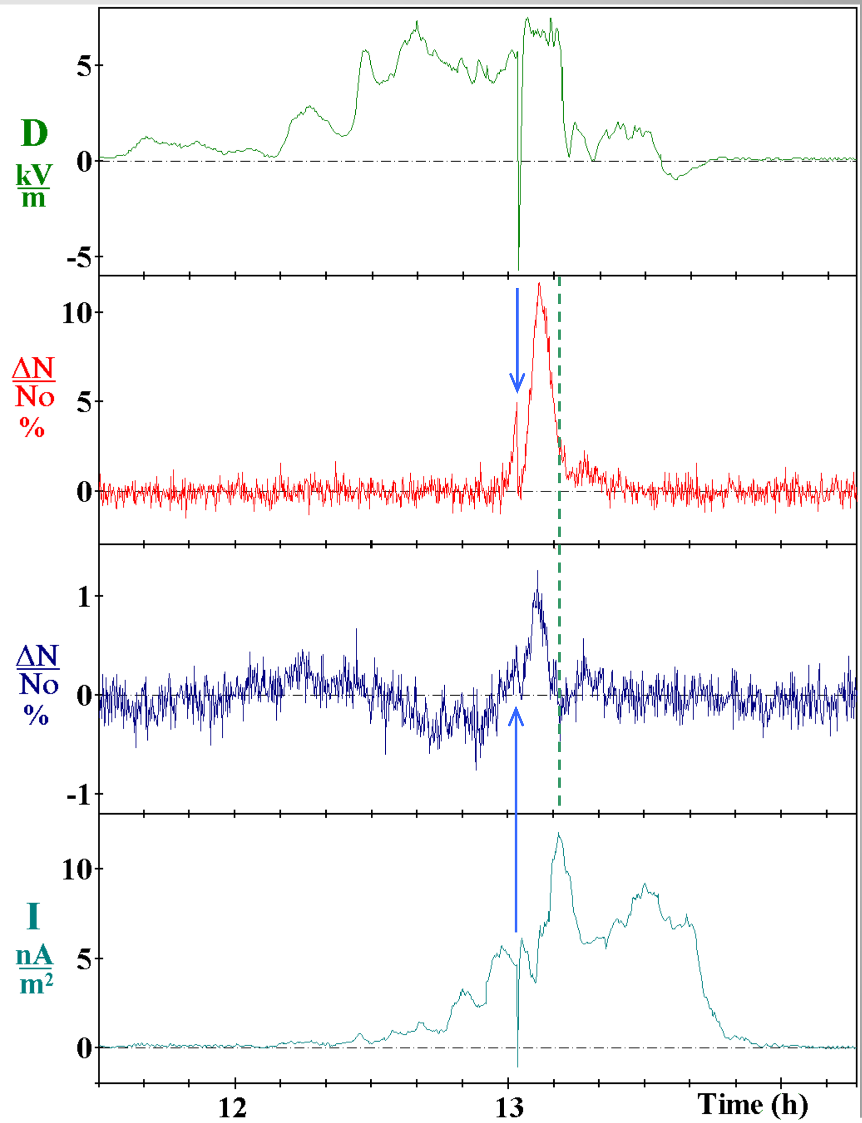


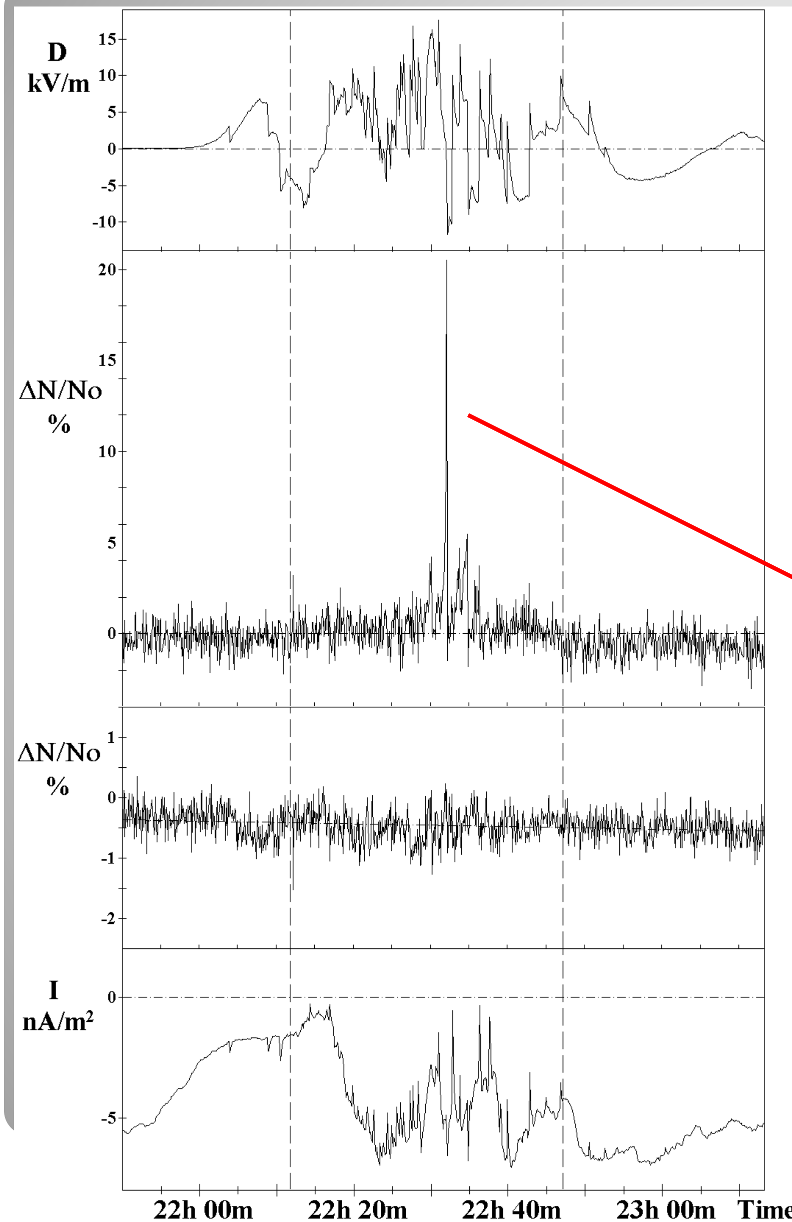
Two lightning discharges of different polarities producing a similar effect in the event on August 1, 2008



Event on September 11, 2005
(averaging 10 s)

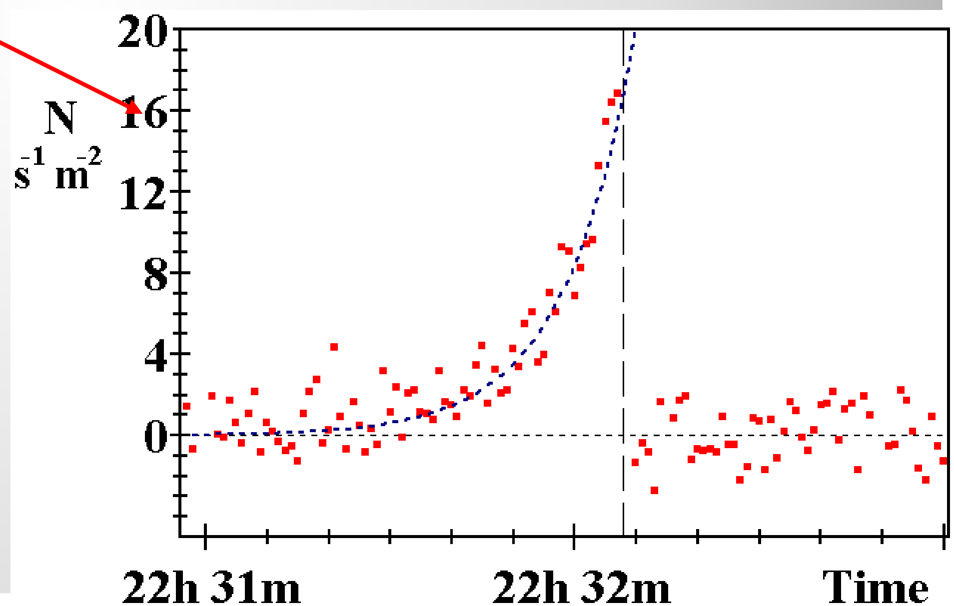
In this event a lightning discharge causes jumps in the intensities of both soft and hard components. Autocorrelation with precipitation electric current. Time delay is 260 s.



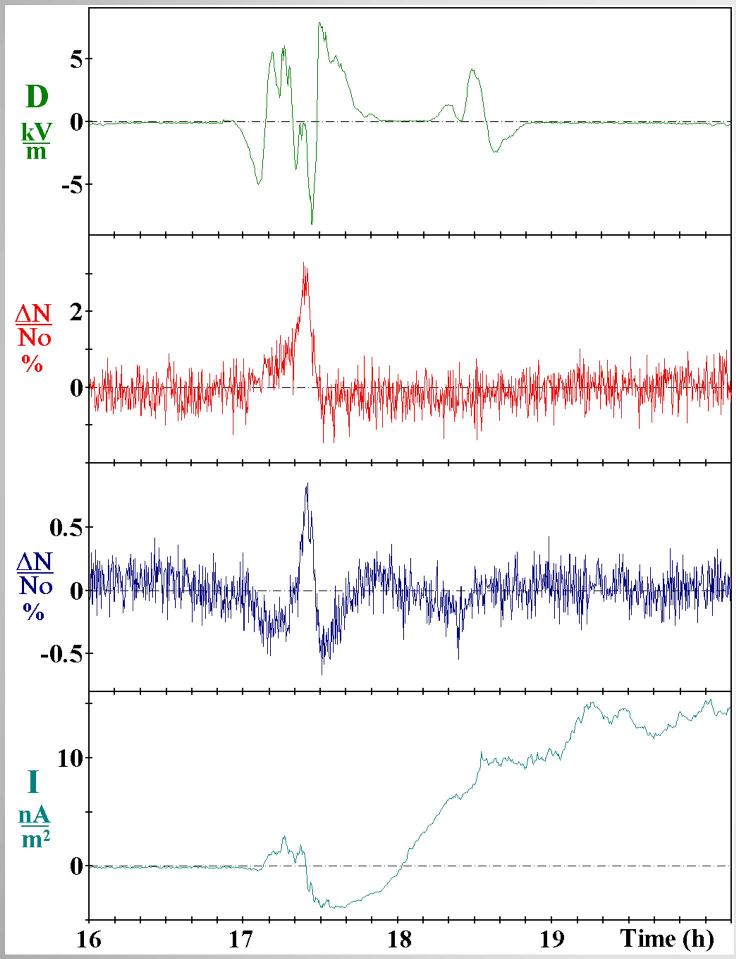


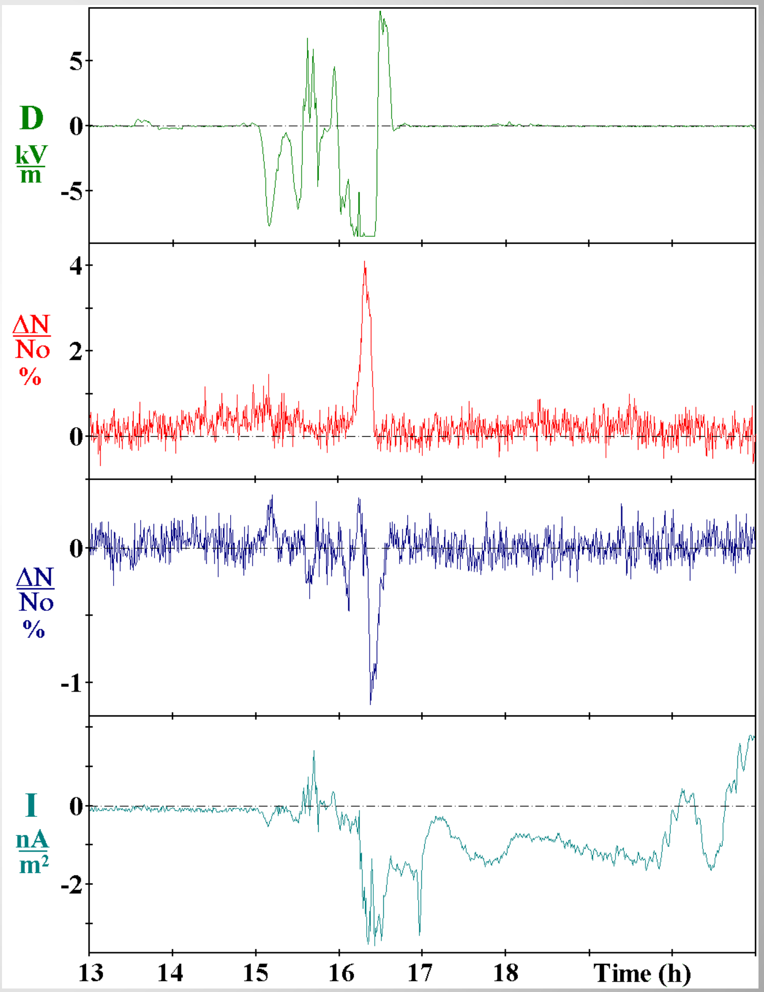

# Sept 7, 2000 event

The largest increase is exponential with high precision and has an abrupt stop at the instant of lightning

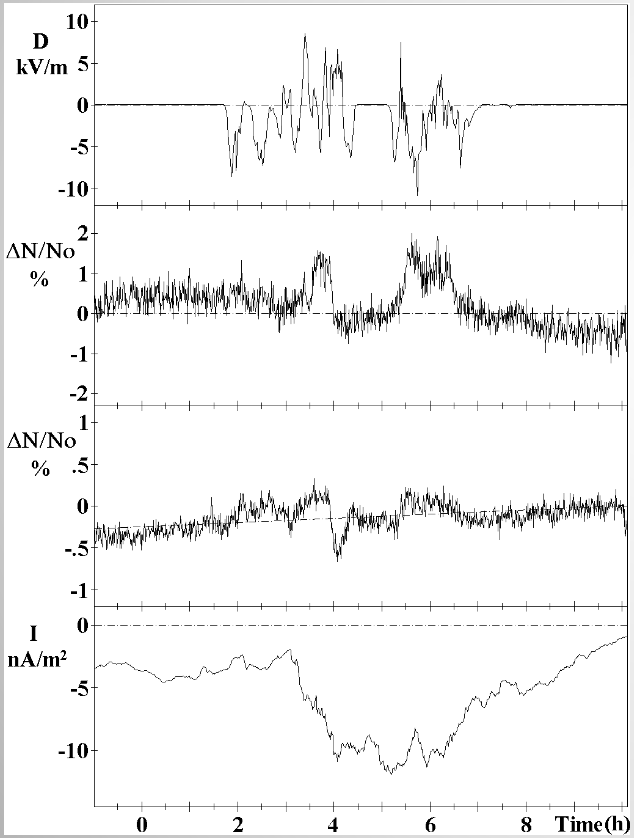


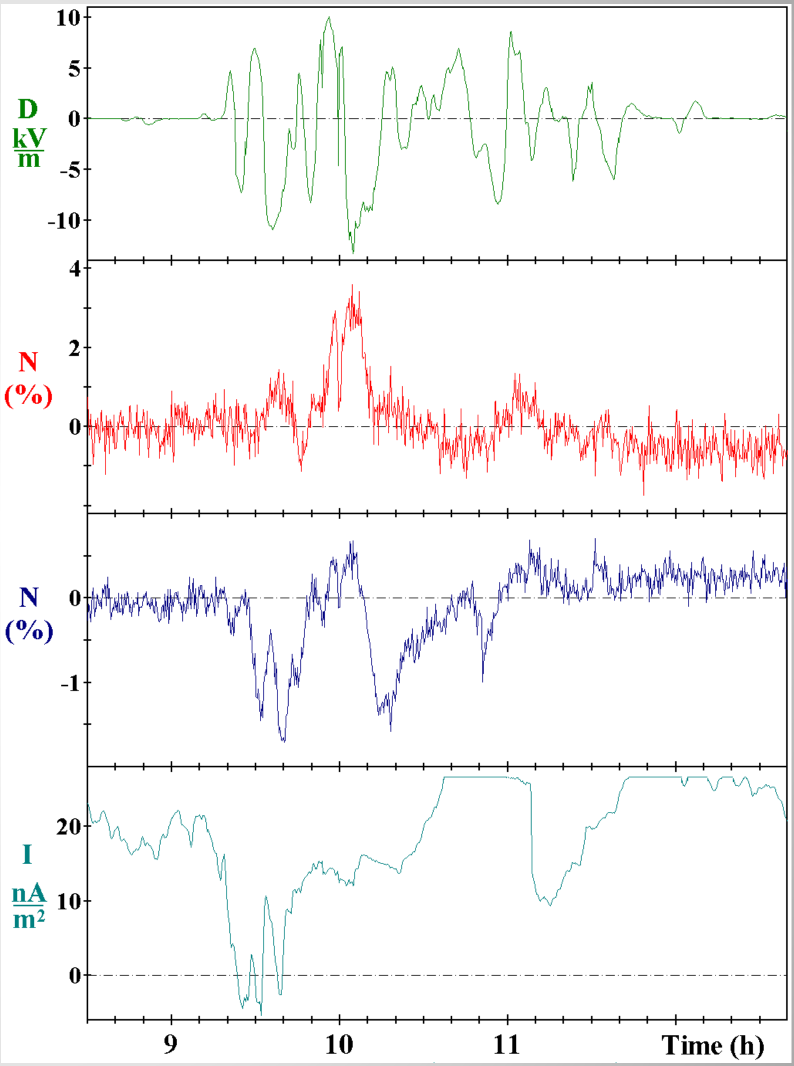
# Events on June 18, 2008 (left, averaged over 15 s) and July 18, 2008 (right, averaged over 30 s)



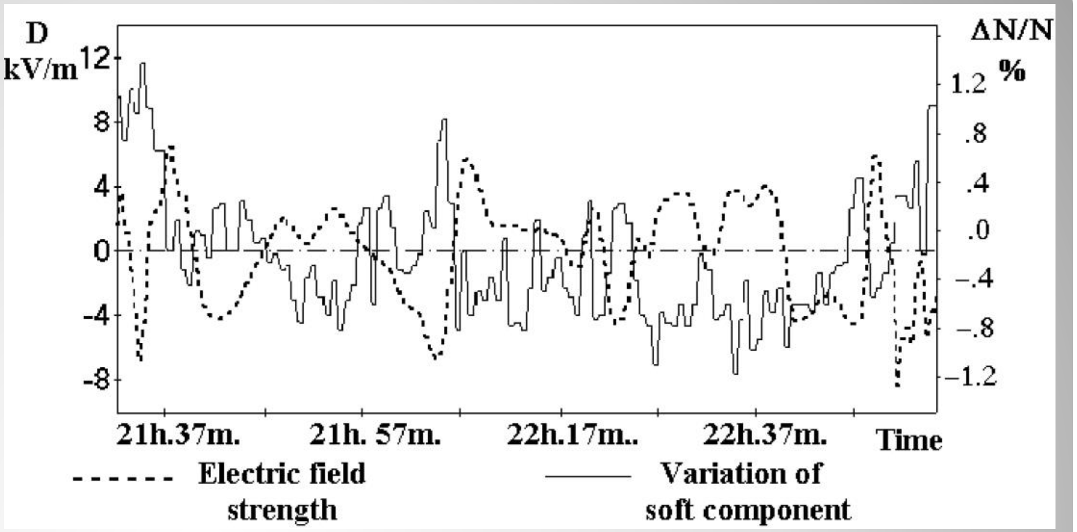



Thunderstorms on
Sept 26, 2000 (1p – 40 s) and
September 6, 2005 (1p – 20 s)

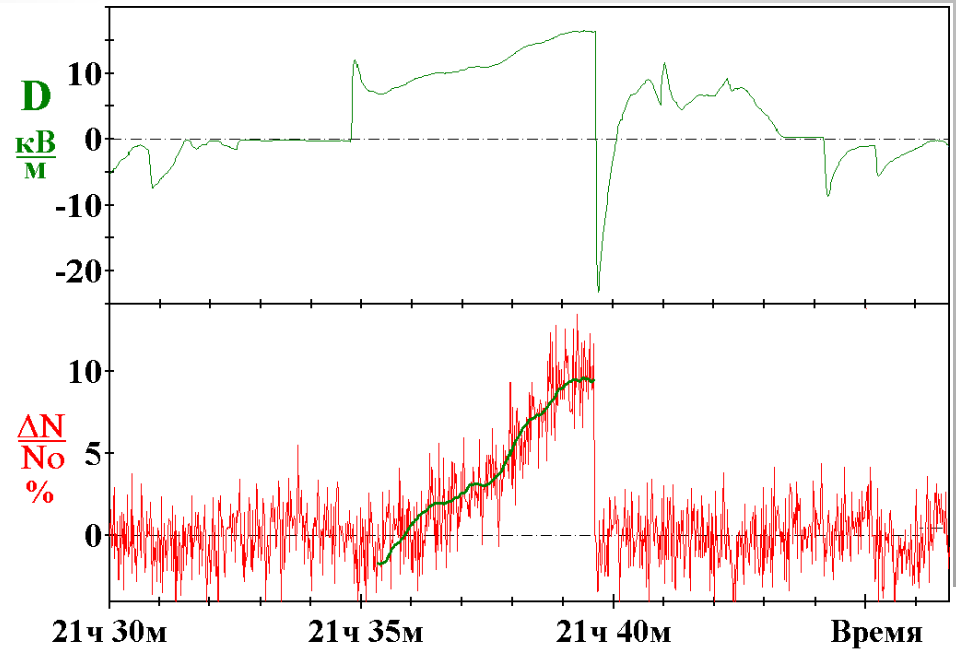


# Correlation of soft component with field




An example of negative correlation of electric field and soft component. Event on September 7, 2000. Bin width is 80 s.




Pre-lightning enhancement.
Event on Sept 3, 2006

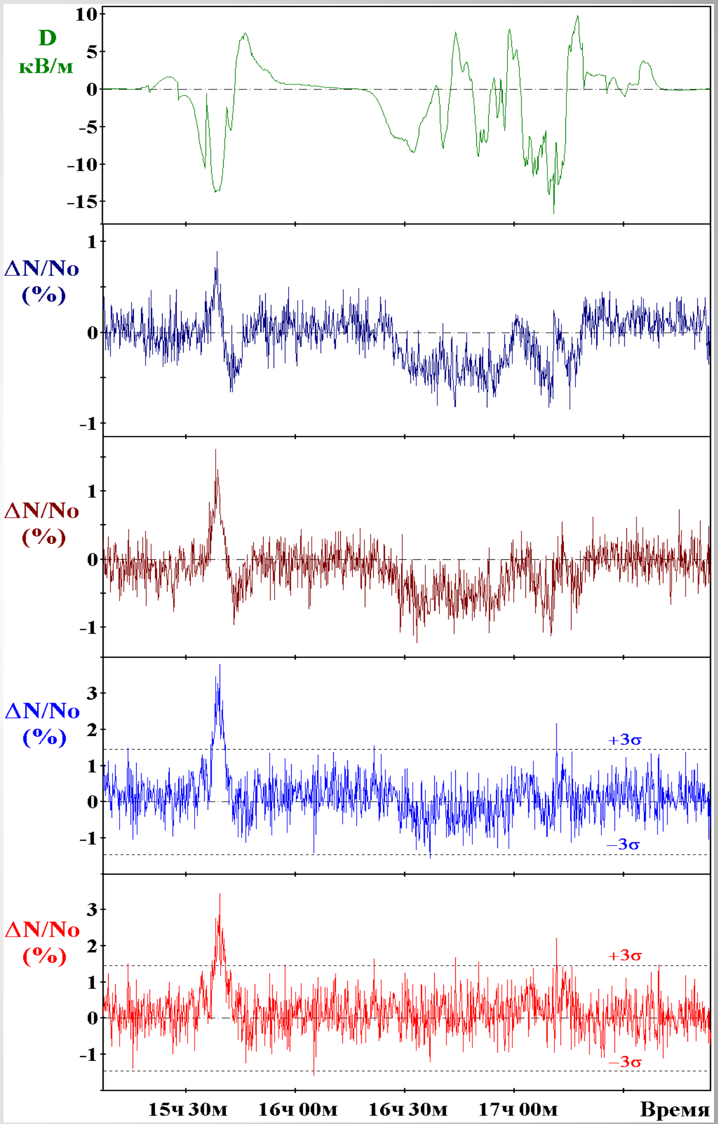
An example of separating independent variations of the hard and soft components during thunderstorm on September 24, 2000

Intensity (E > 100 MeV) (hard component)

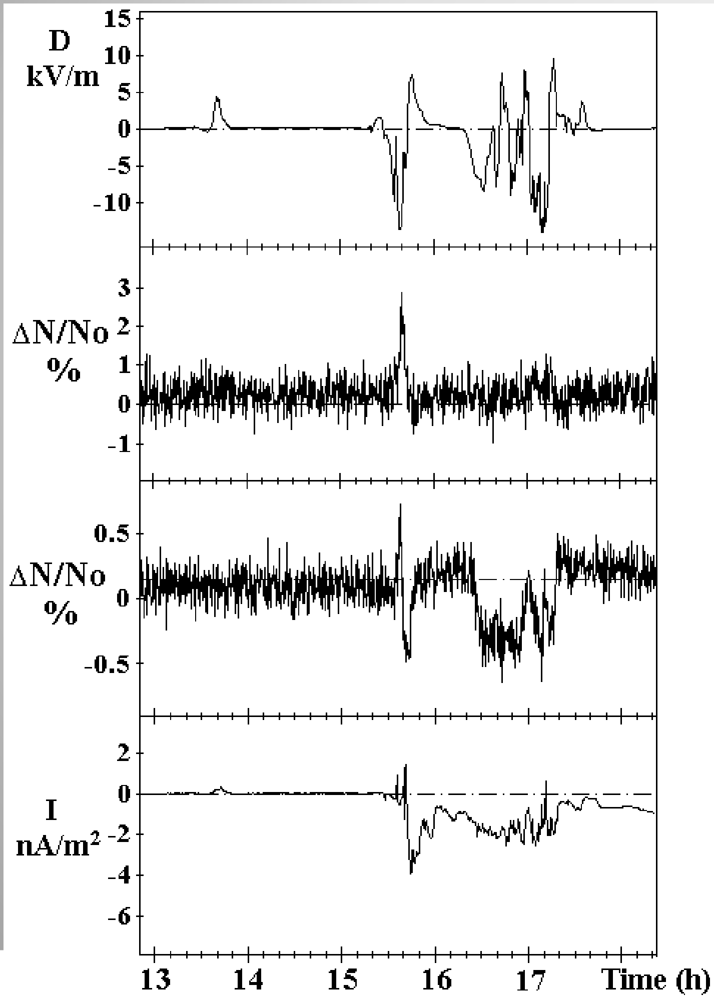
Intensity (E > 10 MeV). Mixed.

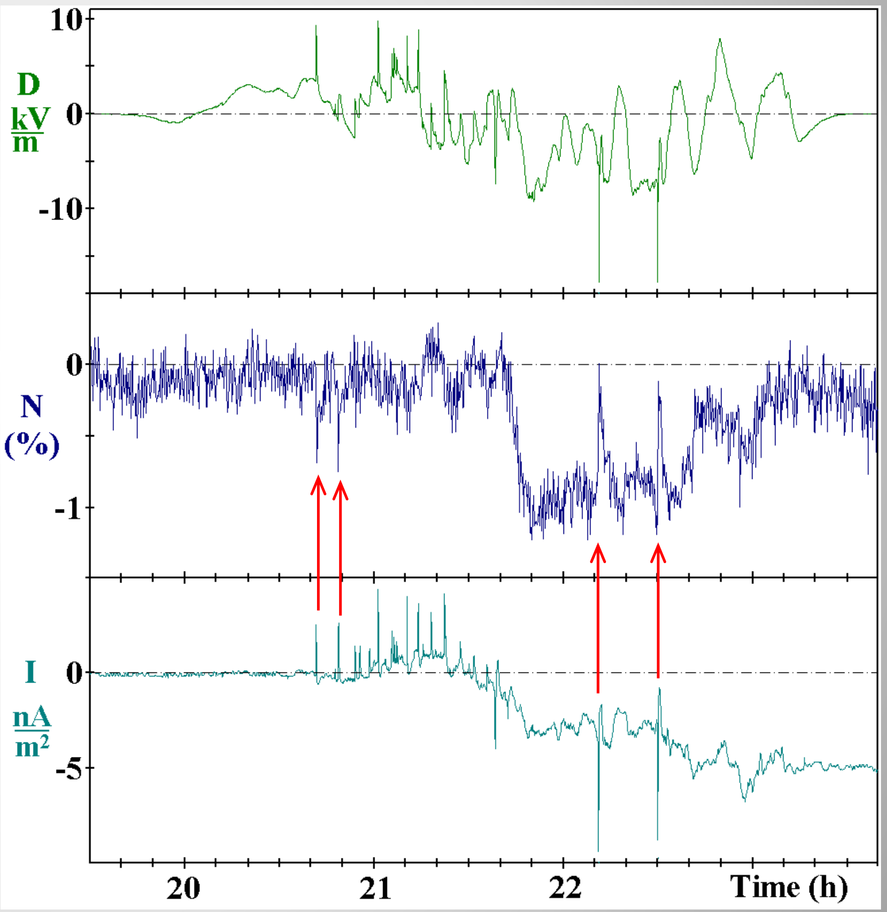
Soft component (10 < E < 30 MeV)

Soft component (10 < E < 30 MeV) (after correction)

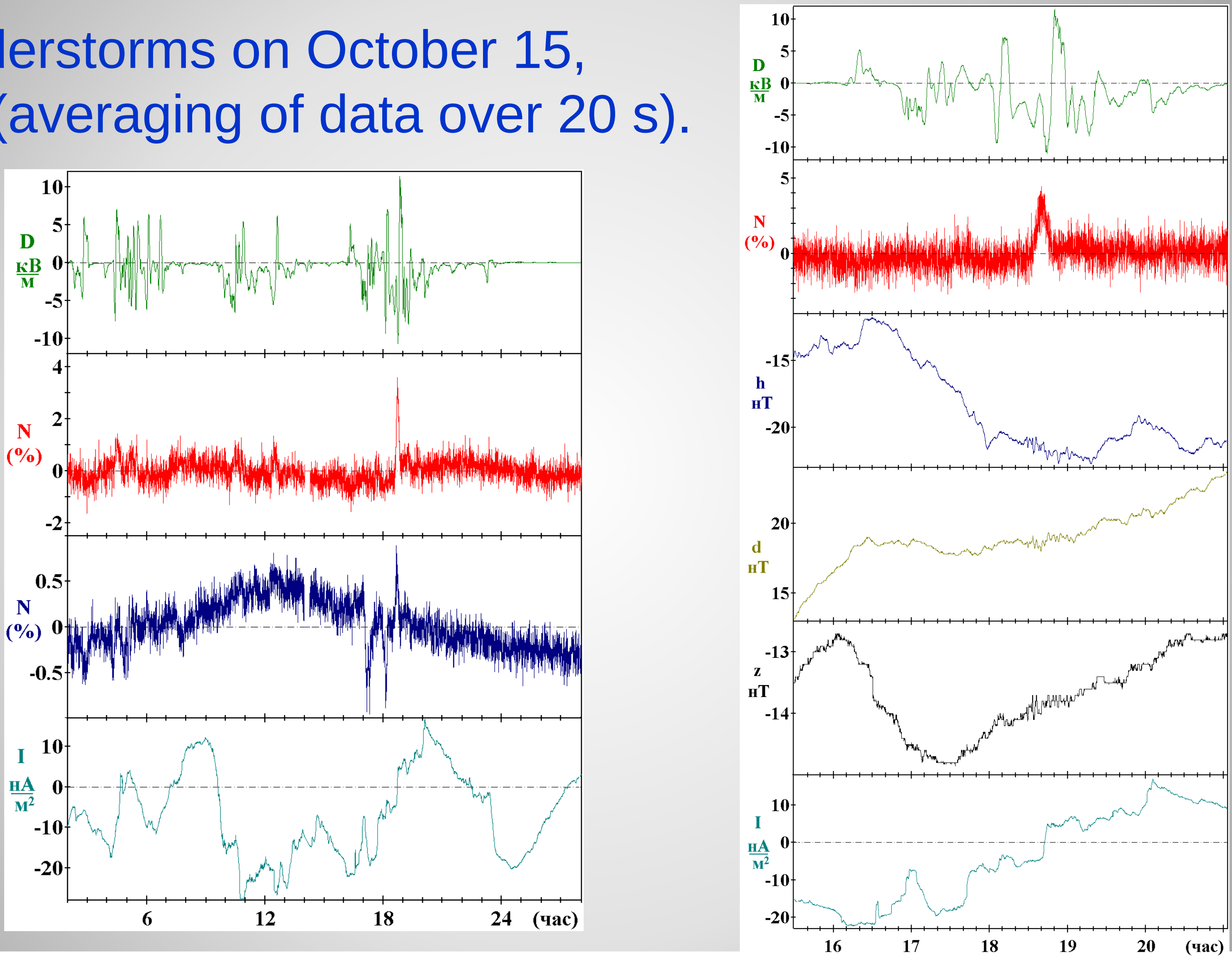


Two strong variations of muons on one day of a year separated by seven years: September 24, 2000 and 2007. In the latter event sharp variations associated with lightning discharges are observed



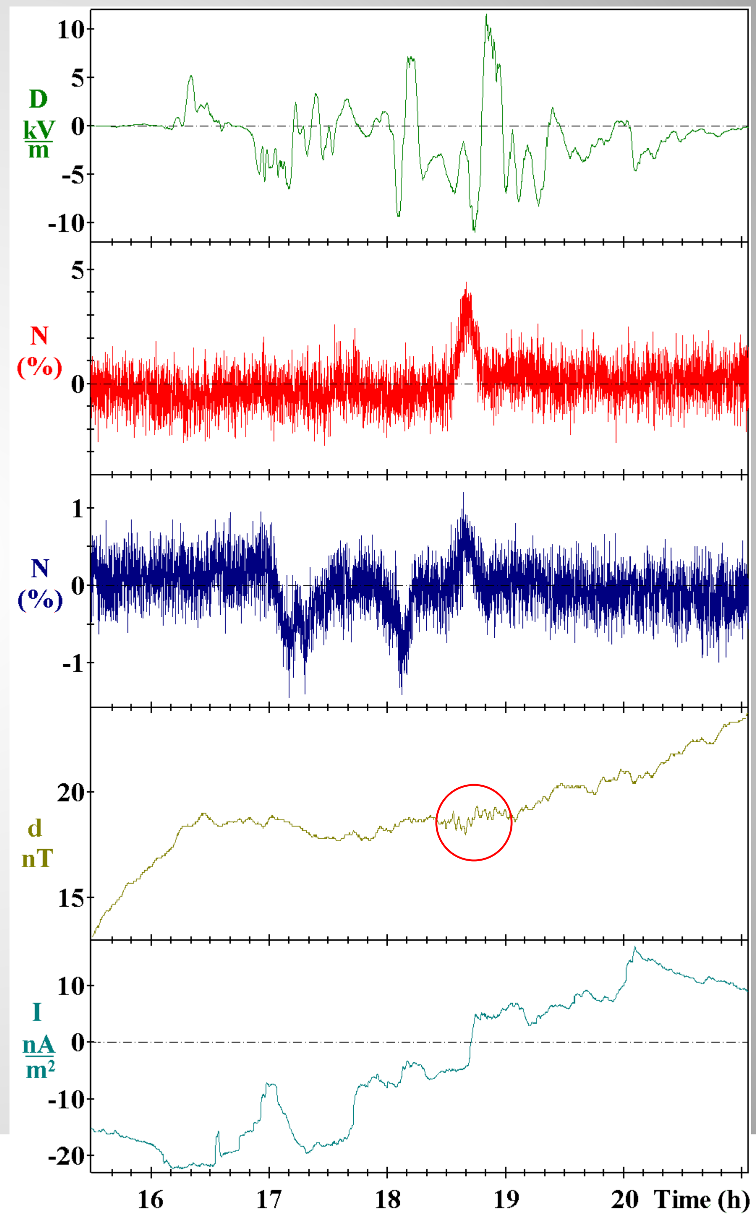
# Thunderstorms on October 15, 2007 (averaging of data over 20 s).



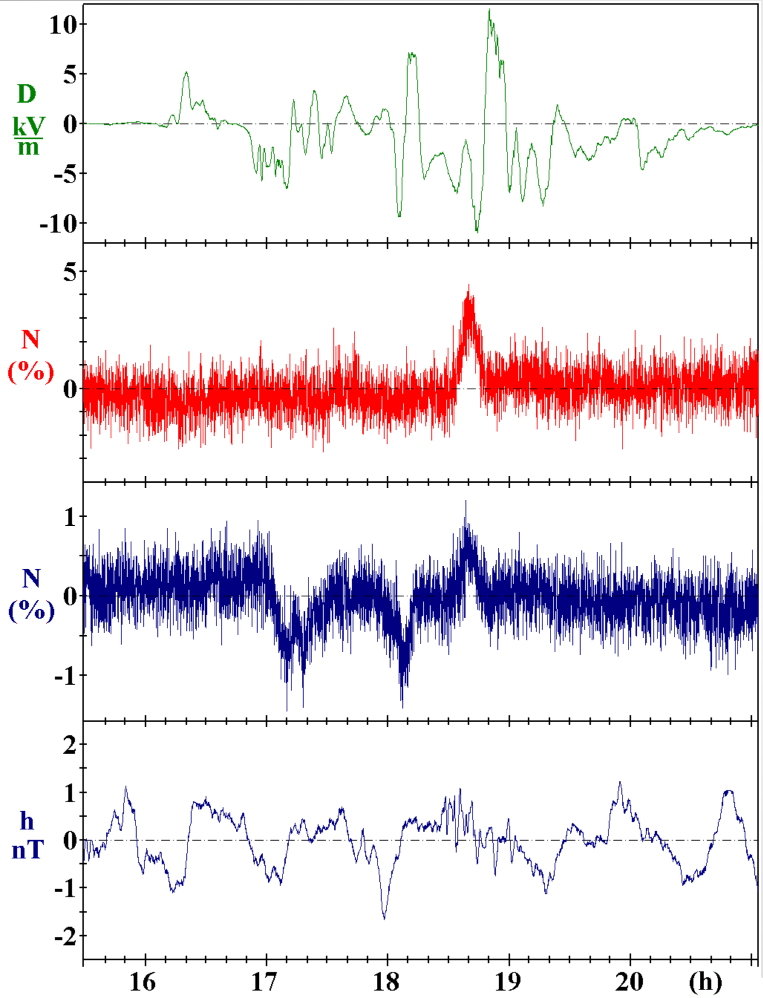
## The event on October 15, 2007

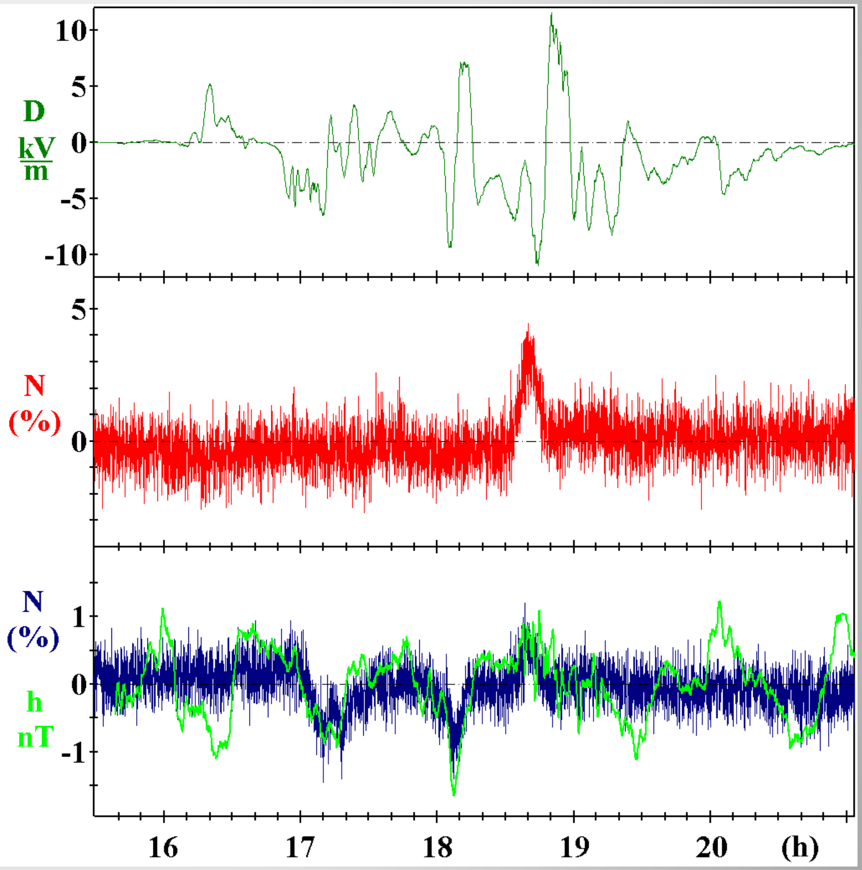
Classification of geomagnetic pulsations (amplitude from some tenth to tens of nT): regular Pc and irregular Pi

| ***Pc*** | ***Period, s*** | ***Pi*** | ***Period, s*** |
|---|---|---|---|
| Pc1 | 0,2 - 5 | Pi 1 | 1 - 40 |
| Pc 2 | 5 -10 | Pi 2 | 40 - 150 |
| Pc 3 | 10 - 45 | Pi 3 | > 150 |
| Pc 4 | 45 - 150 | | |
| Pc 5 | 150 - 600 | | |

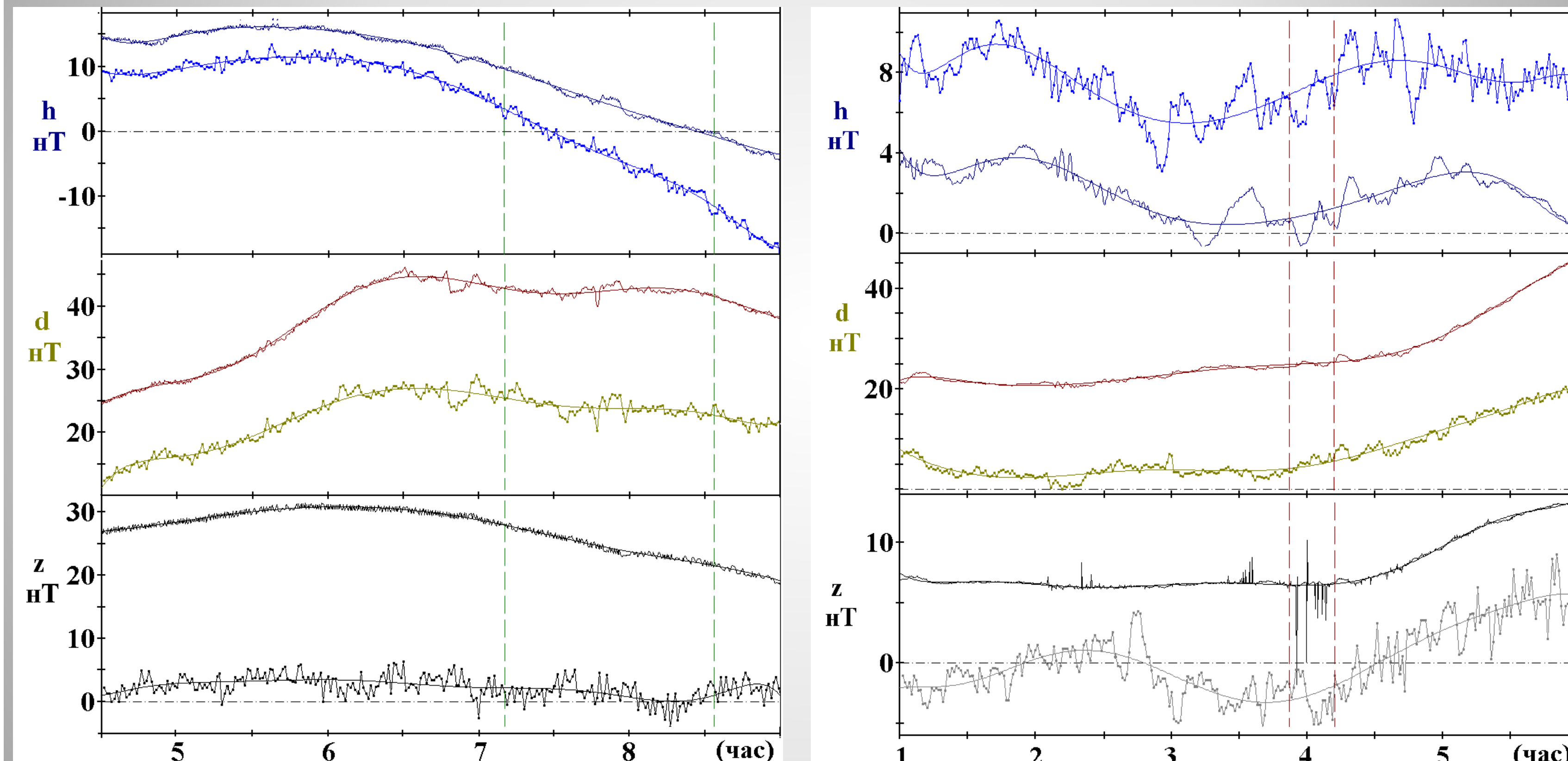


Event on October 15, 2007: complex variation of muons repeats the behavior of h-component of geomagnetic field (daily wave subtracted) with a time delay of 9 min

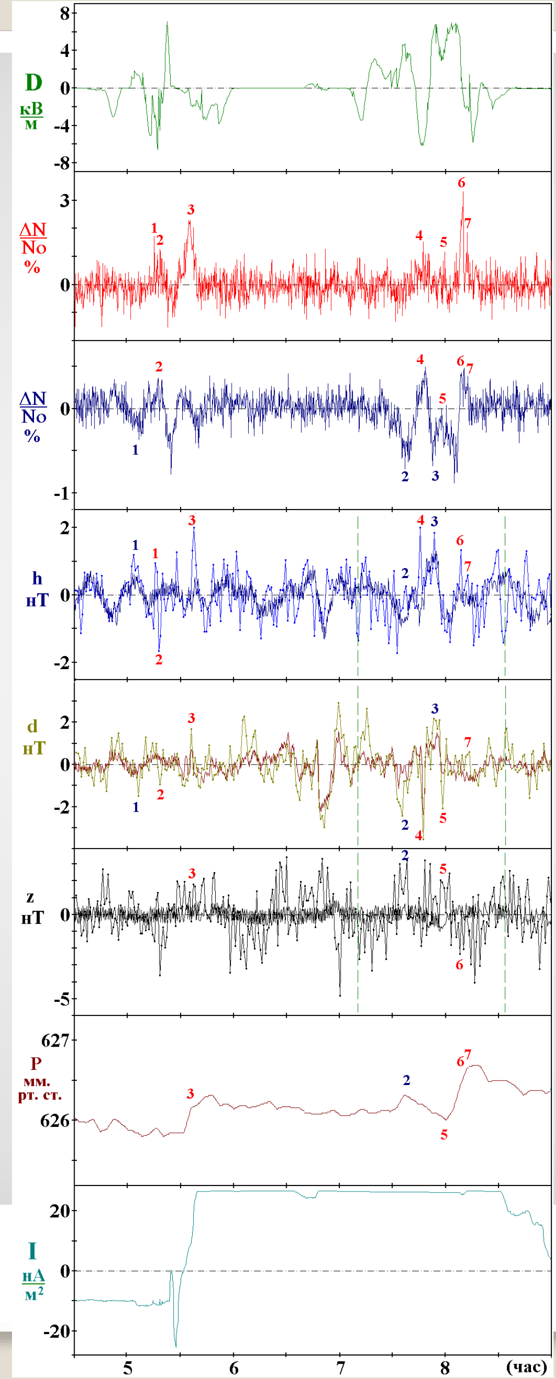


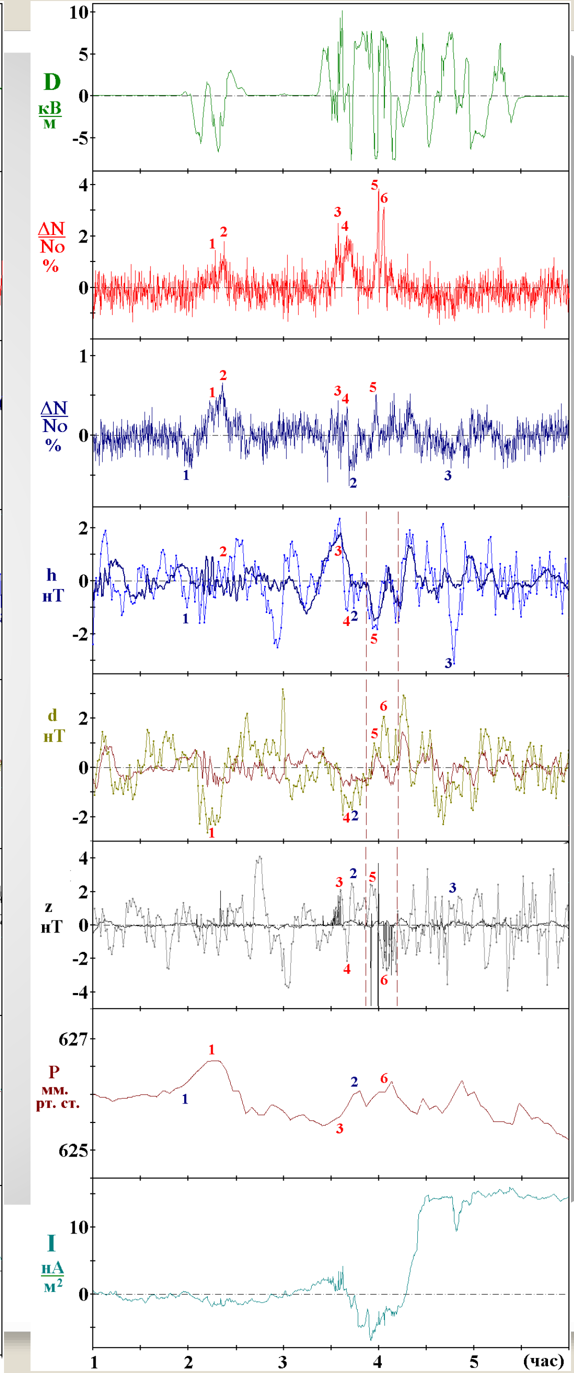



Variations of three components of the geomagnetic field on July 31 and August 1, 2008 according to stations Baksan and Moscow. Interval of averaging is 15 s.



Joint plots of deviations of the magnetic field components from their trends for two stations. Red digits are the numbers of local soft component enhancements that correspond to disturbances of the geomagnetic field measured at the same time in Moscow. Maxima of negative disturbances of the hard component are enumerated by blue digits.



# Examples of bright events (TGEs)

- Pre-lightning enhancements
- Enhancements without lightning effects
- Soft component enhancements without muon effects
- Soft component enhancements with muon disturbances of different sign
- Correlated with near-ground field
- Correlated with precipitation electric current
- Accompanied by geomagnetic pulsations

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy…

Hamlet, Prince of Denmark

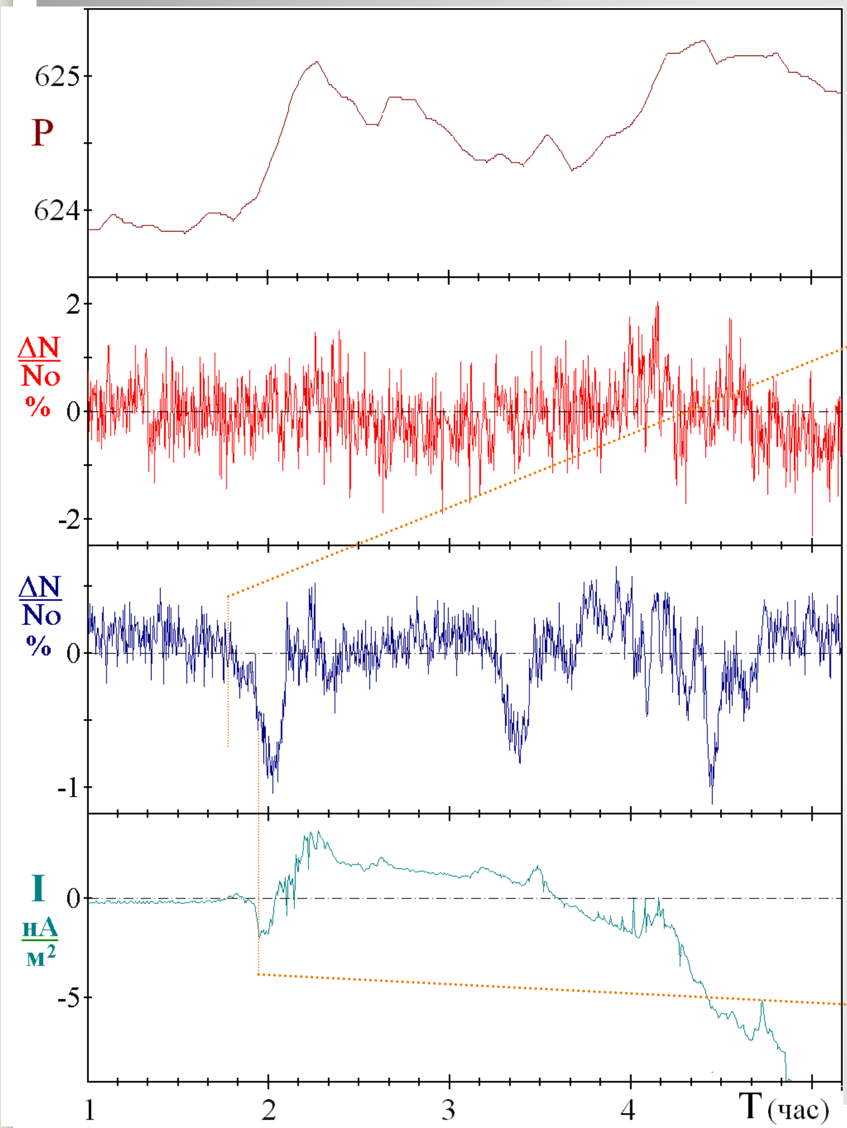
There are more things between cathode and anode
Than are dreamt of in your philosophy…

Gas discharge researcher

These two statements are equally valid when the cathode and anode are between heaven and earth…

# Types of discharges

- Arc discharge large current density at relatively small voltage
- Spark discharge high voltage and strong non-steady current in narrow channels
- Glow discharge current through rarefied gas at high voltage
- Corona discharge feeble current at normal pressure and a strong, highly non-uniform field
- Silent discharge small current density and no luminosity





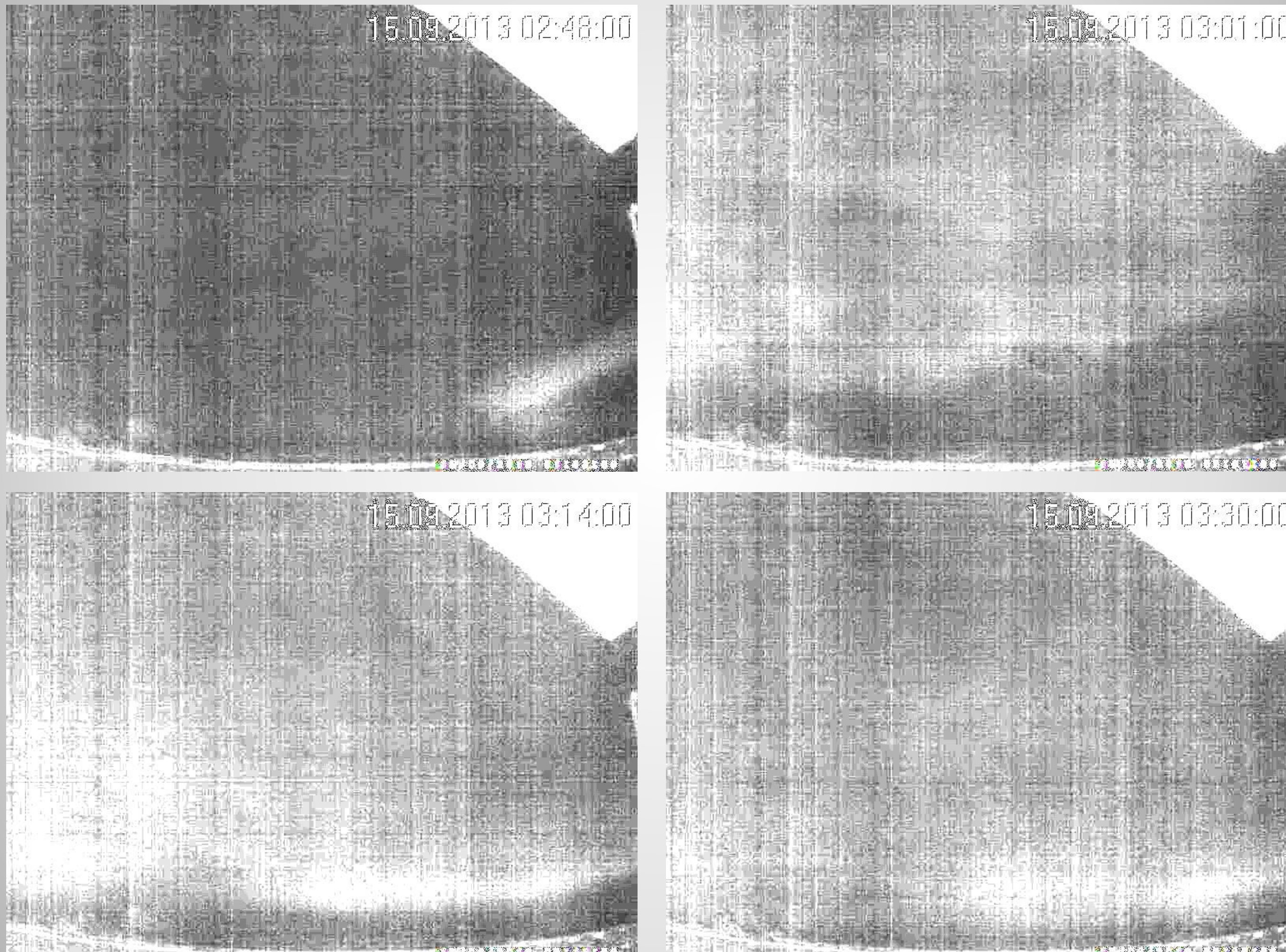
Three snapshots of the sky at a sharp disturbance of the muon flux during thunderstorm on September 15, 2013


15.09.2013 02:48:00
15/09/2013 01:48:09

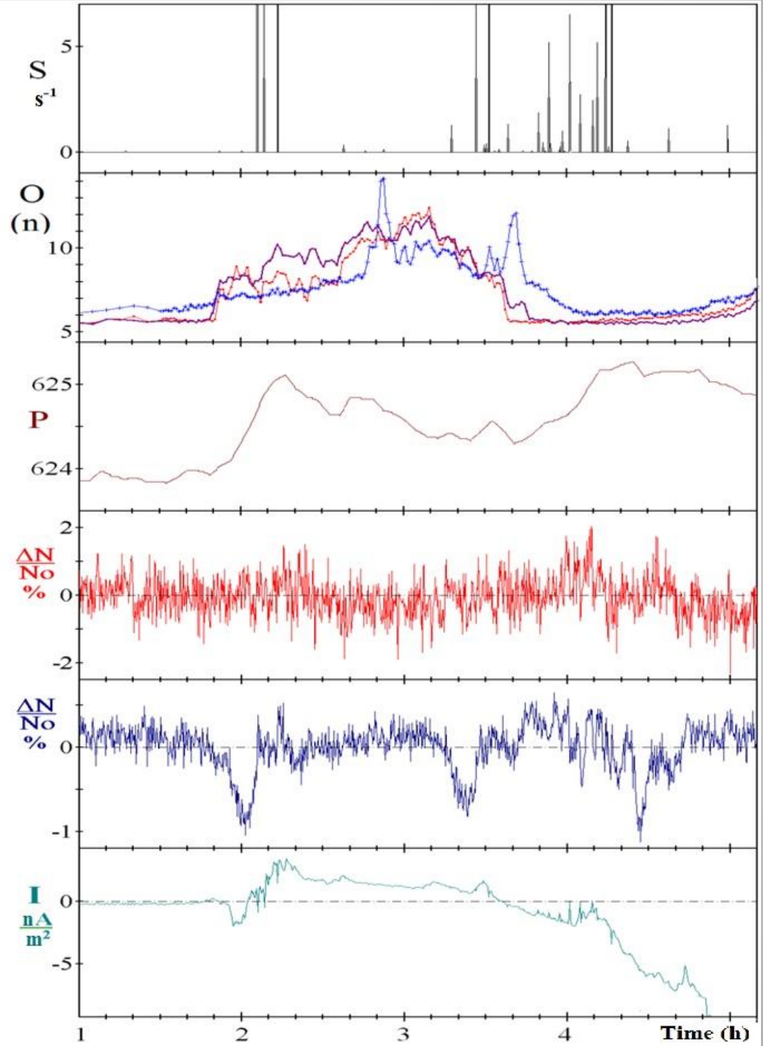

15.09.2013 02:50:00
15/09/2013 01:50:09


15.09.2013 02:56:00
15/09/2013 01:56:09

Thunderstorm event on September 15, 2013. Moments characterizing the dynamics of glow evolution in the atmosphere. Brightness is amplified by a factor of 25.



Thunderstorm event on September 15, 2013. Interval of averaging is 15 s in all cases except for two upper panels. From top to bottom: 1. lightning indicator (arbitrary units proportional to amplitude of electromagnetic noise from lightning discharges), 2. mean brightness of different sky areas on distant camera images (red colour for ionosphere, violet for stratosphere, and blue for troposphere), 3. pressure, 4. variations of the soft component, 5. variations of the hard component, 6. precipitation electric current. Units of optical data in the second panel 10-7 lx (data are presented with one-minute intervals averaged over four adjacent frames).



Thunderstorm on August 31, 2013. Data are averaged over 15 s intervals. From top to bottom:

1. Lightning detector (arbitrary units proportional to the amplitude of lightning electromagnetic signal).

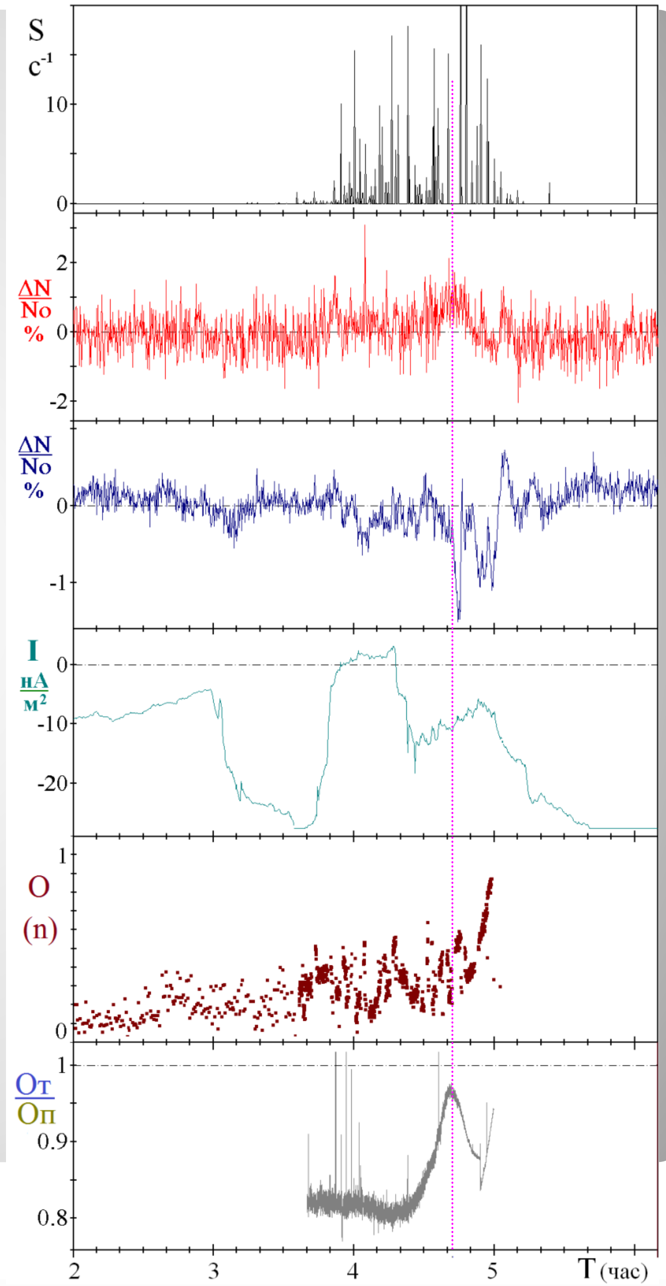
2. Variations of the soft component intensity.

3. Variations of the hard component intensity.

4. Precipitation electric current.

5. Mean illumination of the near video camera (relative units: 1 ~ $10^{-7}$ lx), the data are averaged over 4 s intervals.

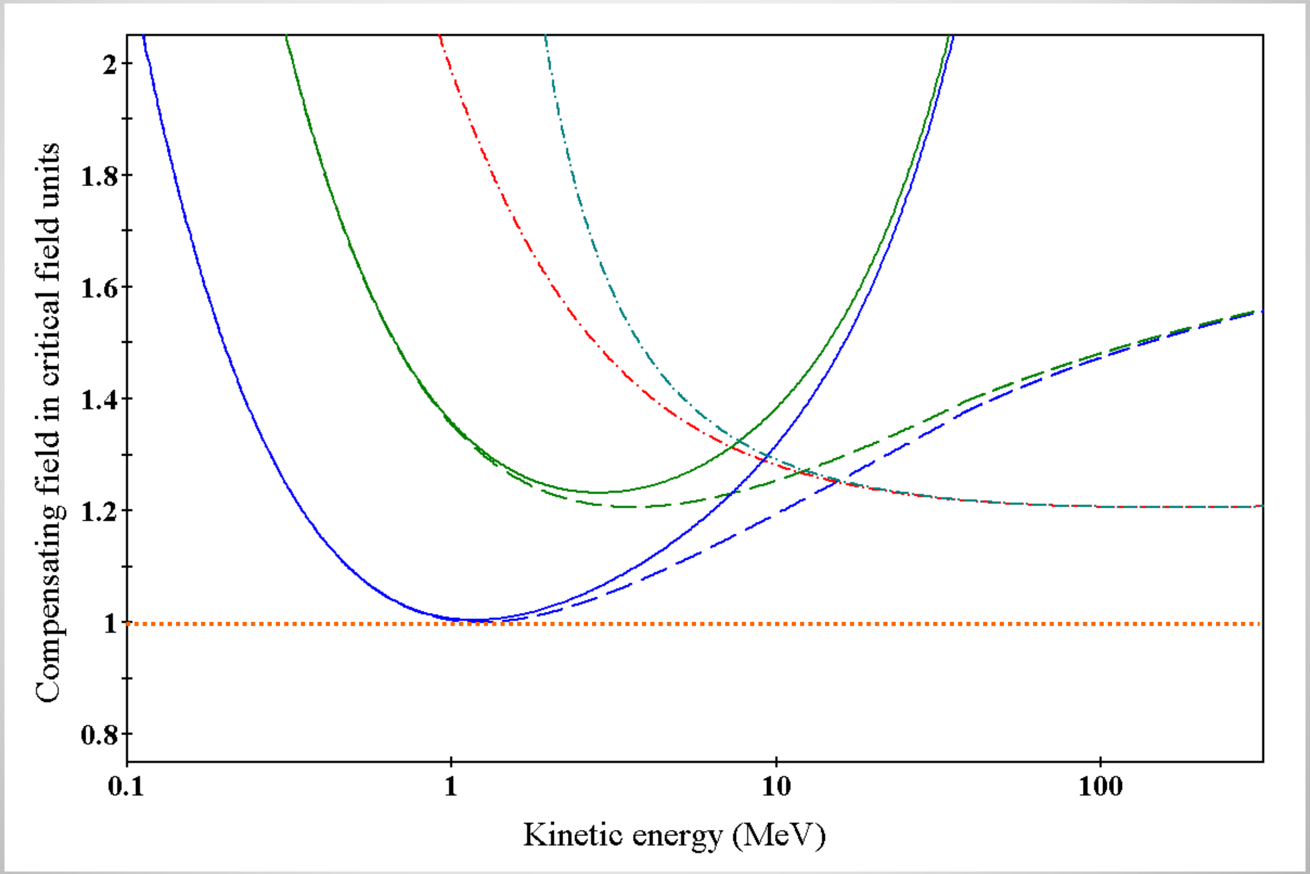
6. The ratio of the brightness in the troposphere region to the average brightness over the matrix for the remote camera, one-second values.



# Interpretation

Critical field by different authors: 216 (Gurevich), 270 (Elensky), 275 (Khaerdinov), 284 (Dwyer) kV/m

# Admissible regions for runaway and feedback particles

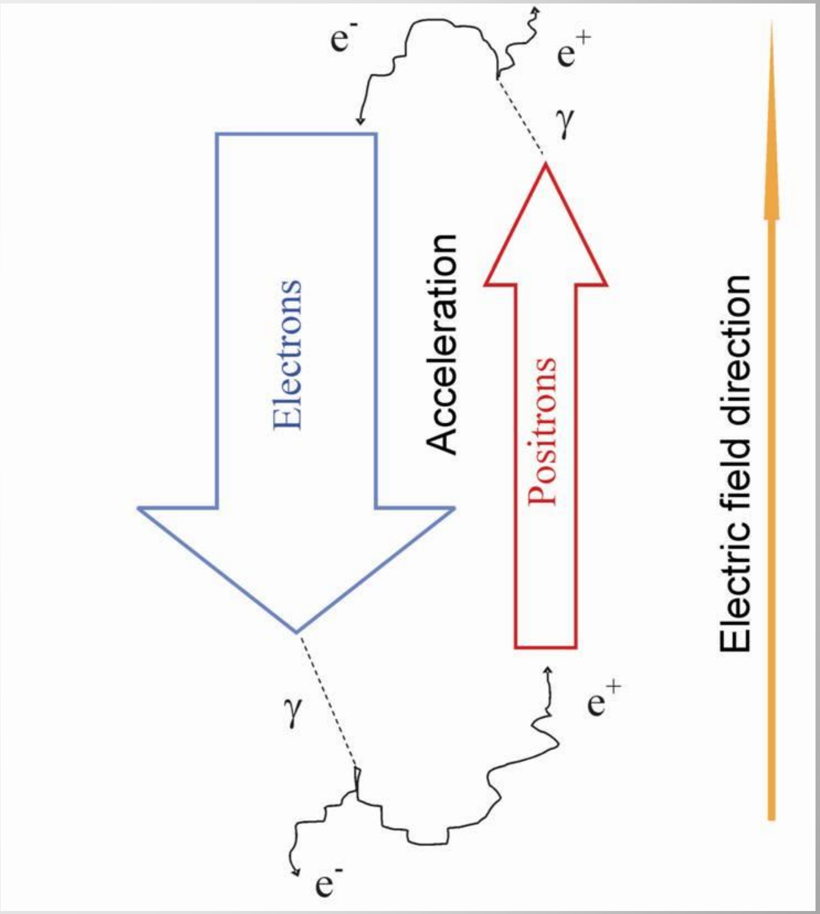


# A model of particle generation in thunderclouds. Secondary CR are seed particles and the electric field is a reservoir of energy

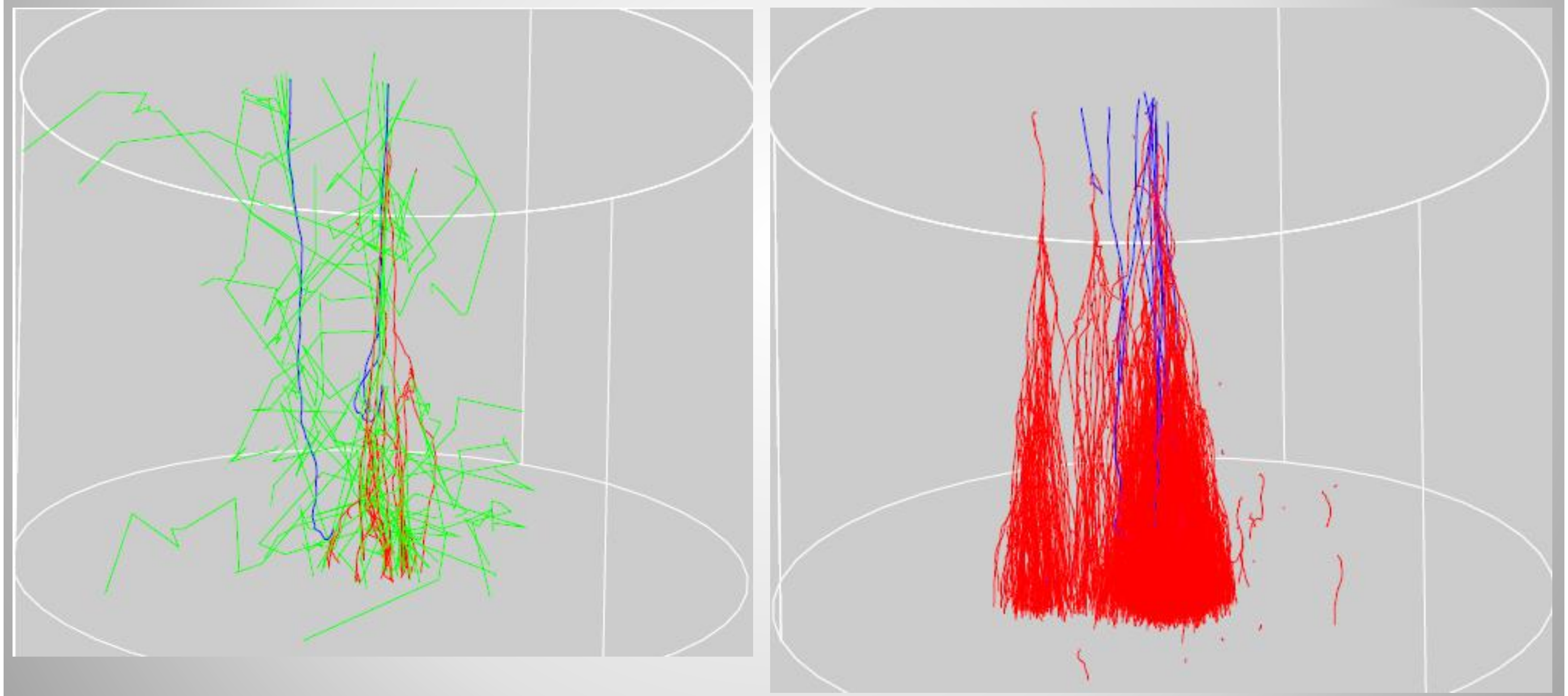
Under stable conditions and at sufficient strength (D) and extension (from x0 to x1) of the field the intensity of particles increases exponentially ($K$ is the probability of one cycle, and $\tau$ is its duration):

$$I(\varepsilon_{SC}, t) = I(\varepsilon_{SC}, t_0)\exp\left\{\frac{t - t_0}{T_D}\right\},$$

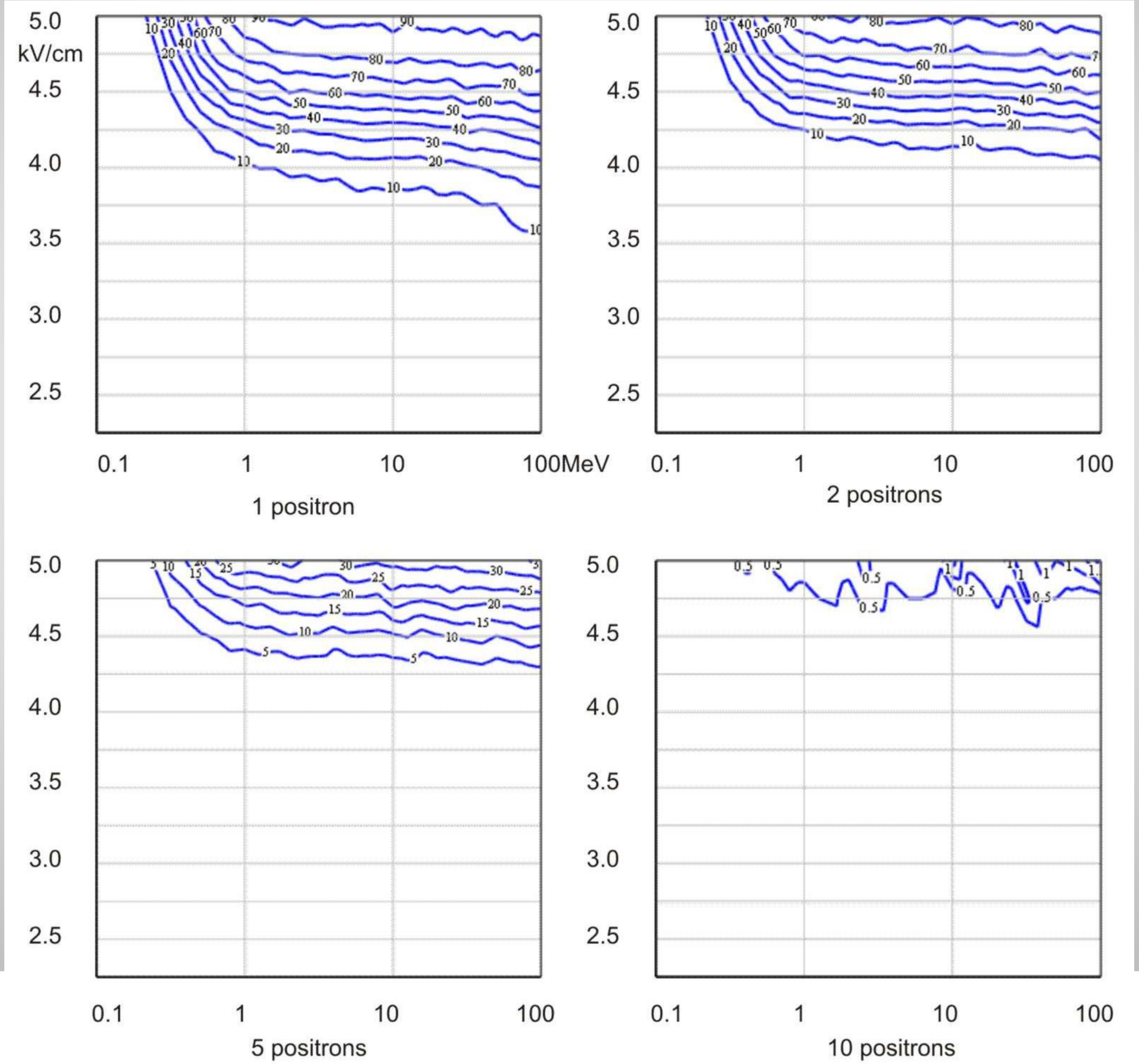
$$T_D = \frac{\tau}{K^2(D, x0, x1)}$$



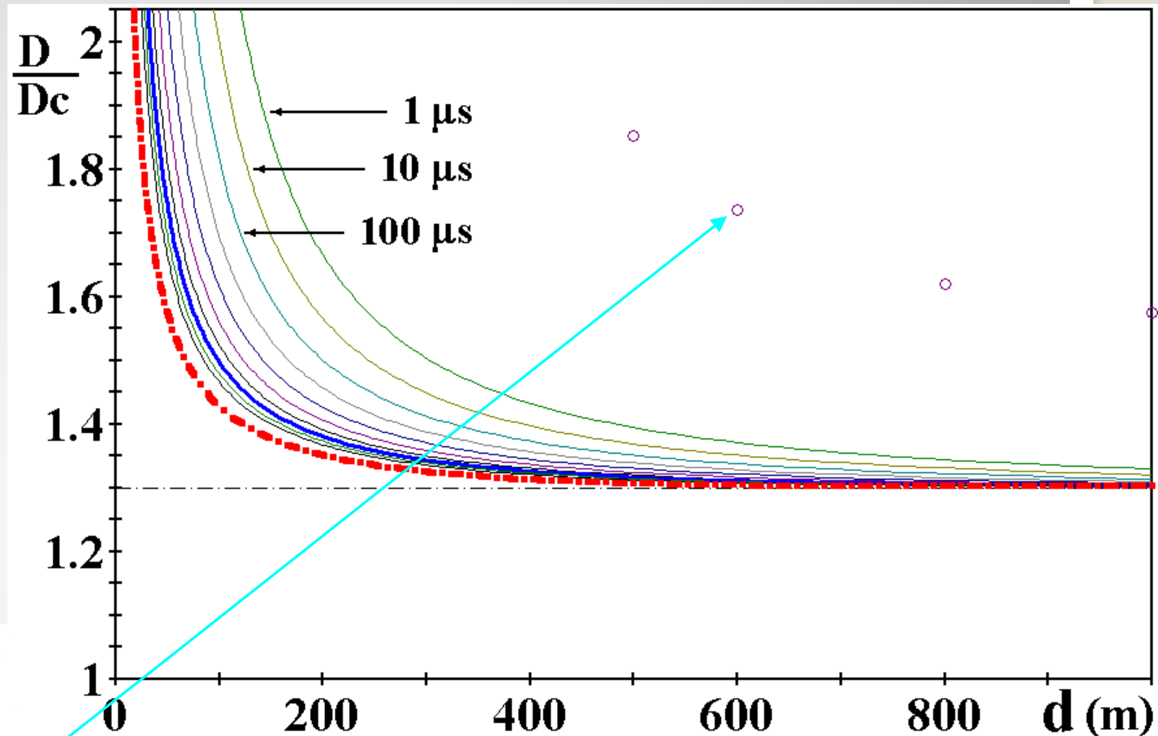
Cascades of particles generated by a single electron:
20 MeV in the field of 3.75 kV/m and 80 MeV in the field of 4.75 kV/m

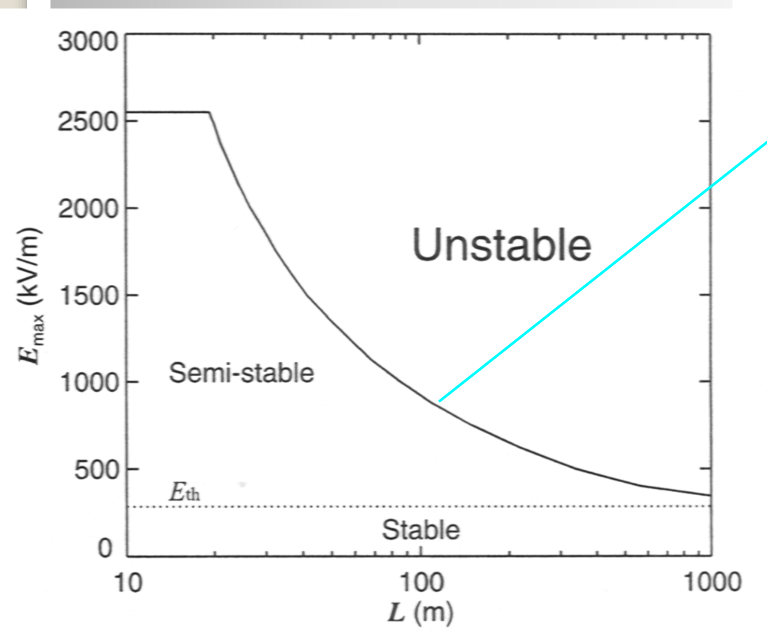


Equal probability lines for generation of 1, 2, 5 and10 positrons in the field of various strength for electrons with different energies



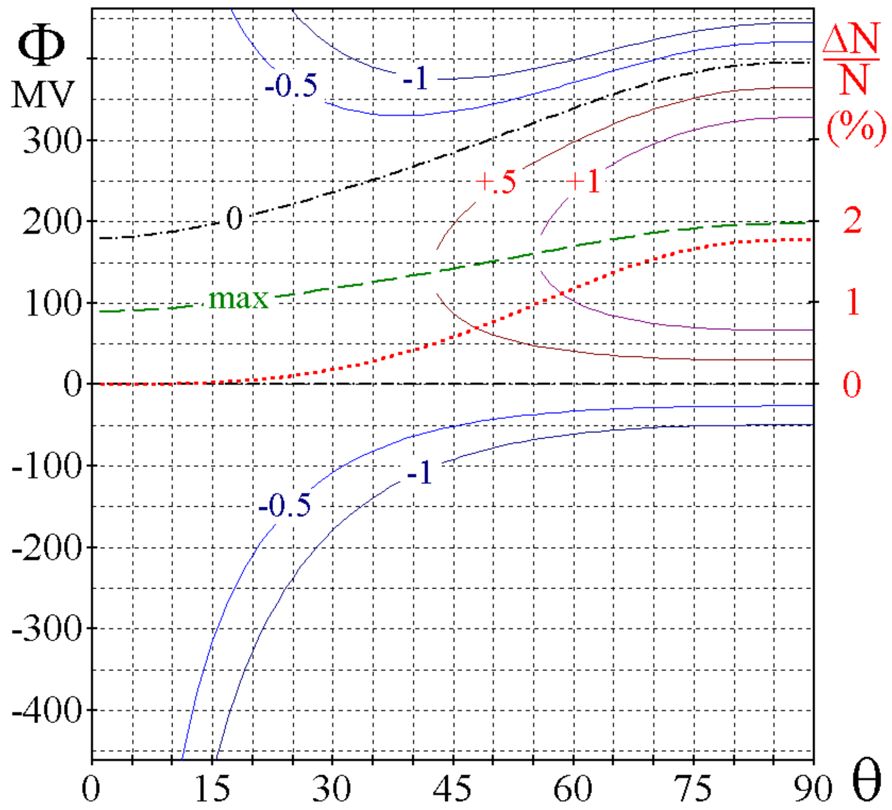
Field strength versus field extension for particle generation process with different rise time.

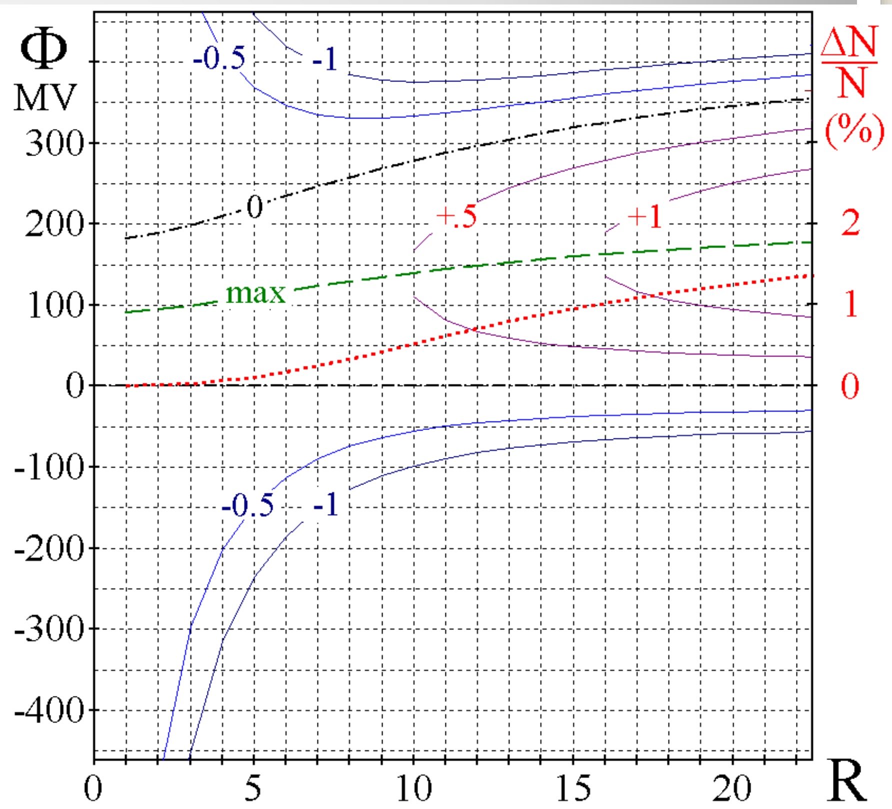



Fundamental limit on electrostatic field in air calculated by J.R. Dwyer. Monte Carlo simulation (Geophys. Res. Lett., 30, 2055 (2003)) at a pressure of 1 atm.

# Interconnection of potential difference between levels of generation and observation, size of thundercloud, and amplitude of muon disturbance



# Geophysical research with thermal neutrons

- Seasonal variations
- Moon tidal waves
- Neutrons in thunderstorms
- Forbush effect and environmental neutrons
- Barometric pumping effect for neutrons
- Earth free oscillations in neutrons

PRL **114,** 125003 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

# Decrease of Atmospheric Neutron Counts Observed during Thunderstorms

V. Alekseenko,[1] F. Arneodo,[2] G. Bruno,[3,*] A. Di Giovanni,[2] W. Fulgione,[3,4] D. Gromushkin,[5] O. Shchegolev,[6] Yu. Stenkin,[5,6] V. Stepanov,[6] V. Sulakov,[7] and I. Yashin[5]

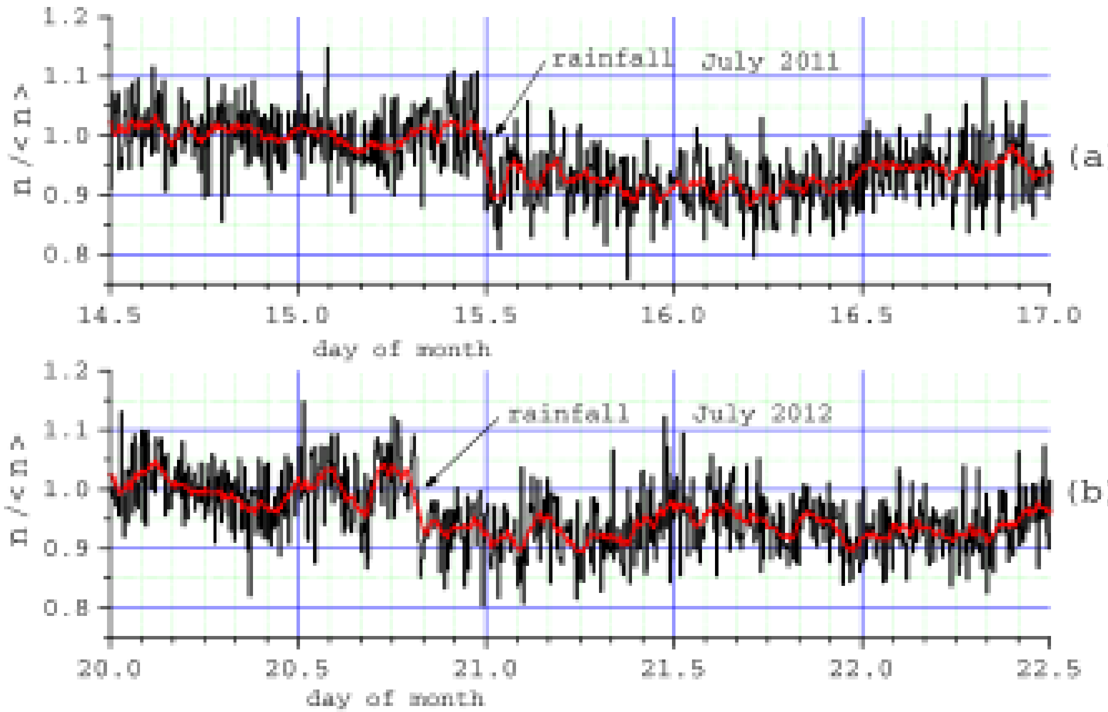



FIG. 5 (color online). Neutron counting rate as a function of the time for two different rainfalls [panels (a) and (b)]. Pressure corrected data.

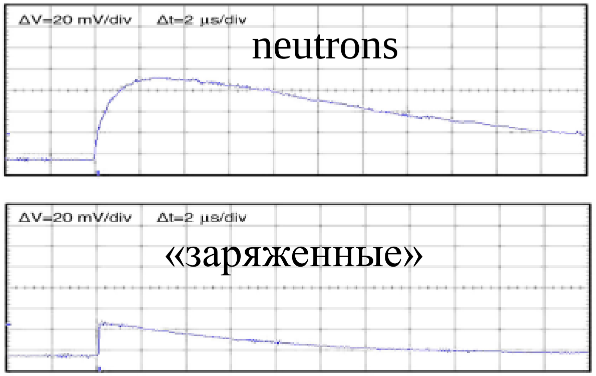



FIG. 2 (color online). Pulse induced by neutron capture ("neutrons," top panel) and background "sharp" pulse (bottom panel).

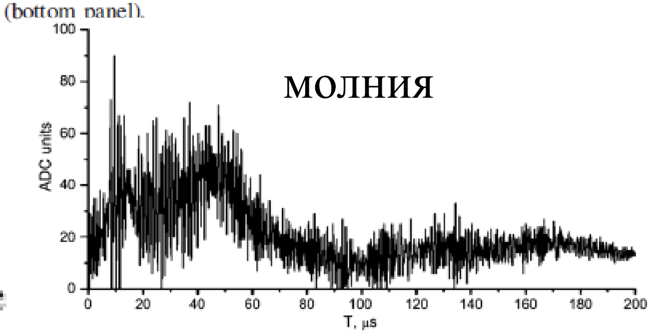


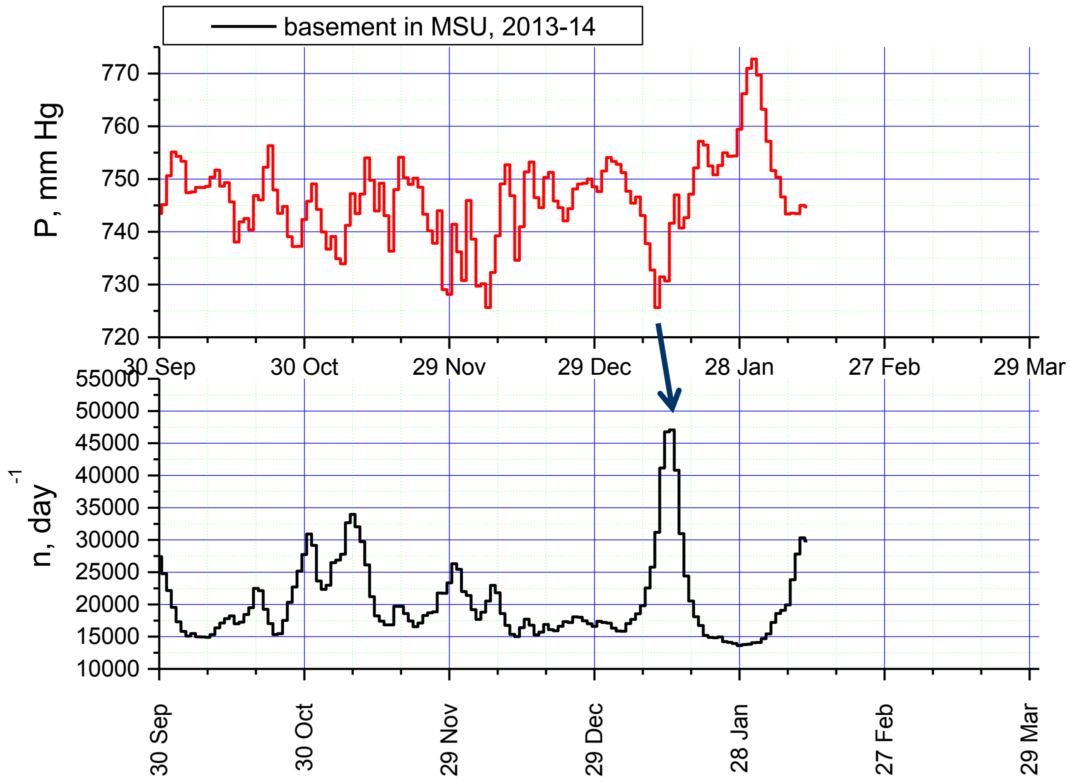

FIG. 3. Noise pulse shape produced by lightning.

<u>Вывод</u>: нет избытка нейтронов, но иногда есть понижение из-за дождевой воды

# Report at TAUP-2015:

**"Barometric pumping effect for radon-due neutron flux in underground laboratories"**

*Yu. V. Stenkin, V.V. Alekseenko, D.M. Gromushkin, O.B. Shchegolev and V P. Sulakov*




2-days delayed anti correlation is observed between air pressure and neutrons underground.
This effect for underground gases is known as *Barometric pumping effect*

It works only for pressure decrease

# Вывод

- Мониторинг разных компонент космических лучей с привлечением других типов данных (приземное электрическое поле, оптические и магнитные наблюдения) позволяет наблюдать уже известные и открывать новые эффекты, важные для динамики грозовой атмосферы