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Muonography of the Earth's atmosphere and near-terrestrial space

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Introduction

Muonography is the method (technique) of investigations of various objects by means of the muon flux.

Analogies: ***radiography, electronography, neutronography, protonography***, etc.

Two main fields of investigations by means of ***muonography***:

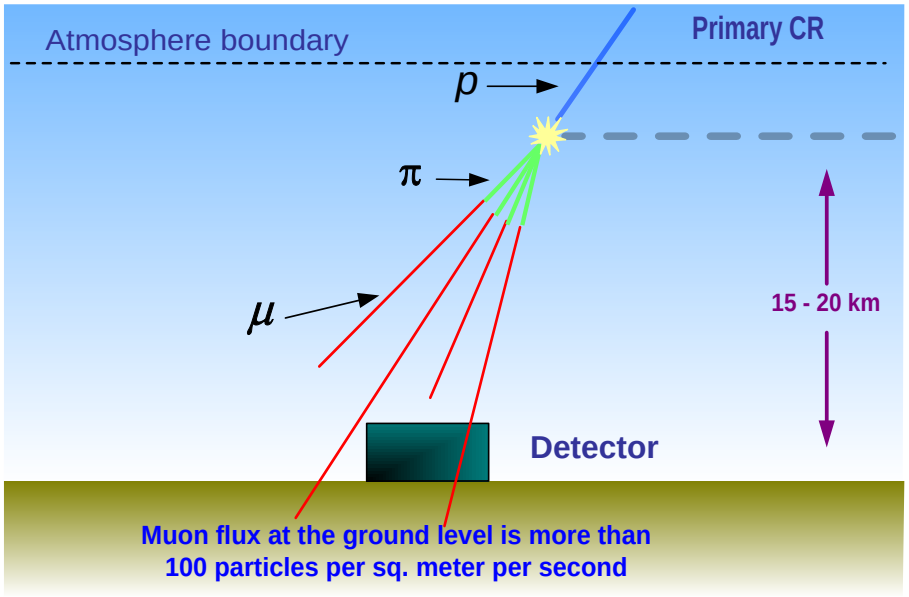
- Heliosphere and magnetosphere of the Earth due to close **connection of muon and primary cosmic ray trajectories;**
- Earth's atmosphere and various objects on the Earth due to a high **penetrating ability of muons.**

The goal is to give a basic idea of the muonography and its applications.

Content

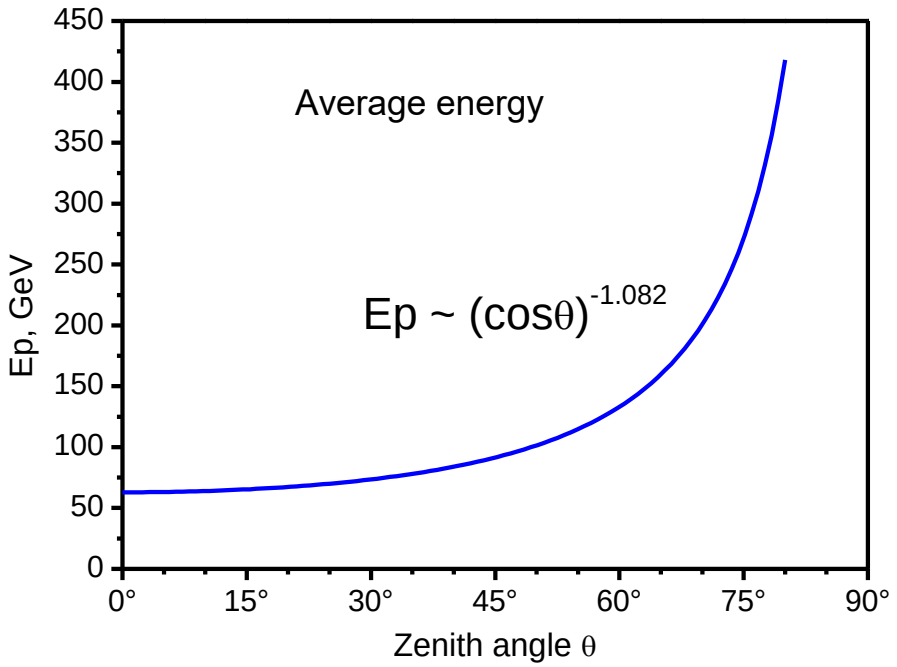
Muons in cosmic rays

Muons in the atmosphere are produced mainly in decays of **pions** and **kaons**, which in their turn are produced in primary cosmic ray interactions with nuclei of atoms of the atmosphere. The ratio of energies E_0/E_μ is about 10.



Scheme of muon generation

Dependence of this energy on zenith angle



Average muon energy at the Earth's ground

$\langle E_\mu \rangle$ = 4 GeV

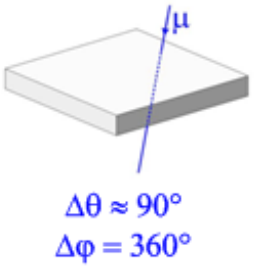
Average energy of primary protons

$\langle E_p \rangle$ = 50-60 GeV

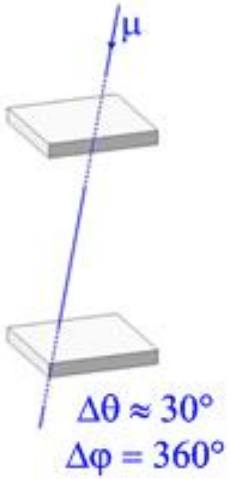
Average energy of muons in near horizontal flux ≈ 70 GeV, and corresponding primary proton energies ≈ 700 GeV.

Different types of muon detectors

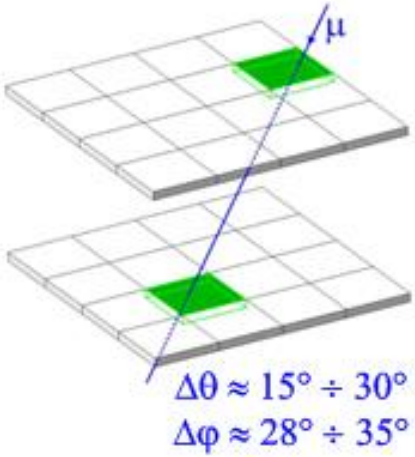
Muon detector



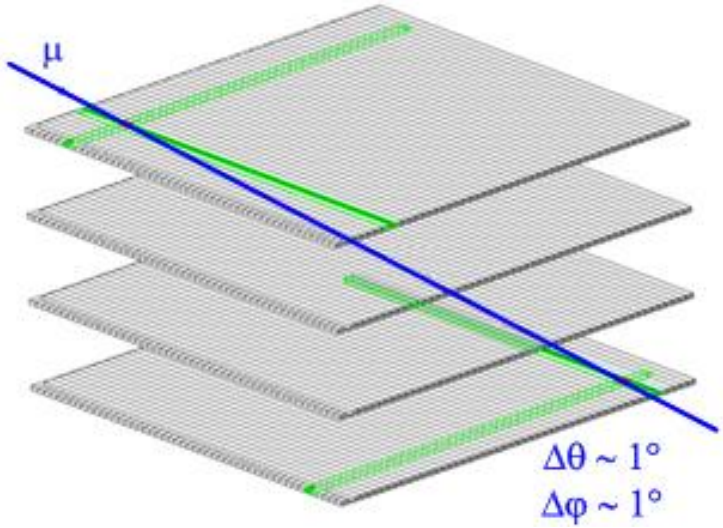
Muon telescope



Multidirectional muon telescope



Muon hodoscope

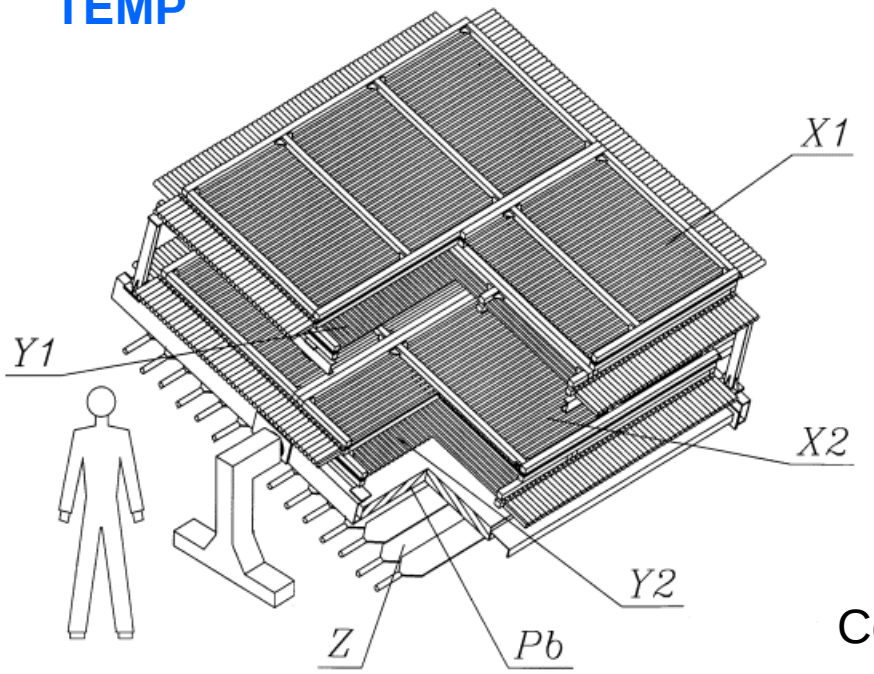


The main feature of muon hodocope is track reconstruction of each muon with high spatial and angular accuracy

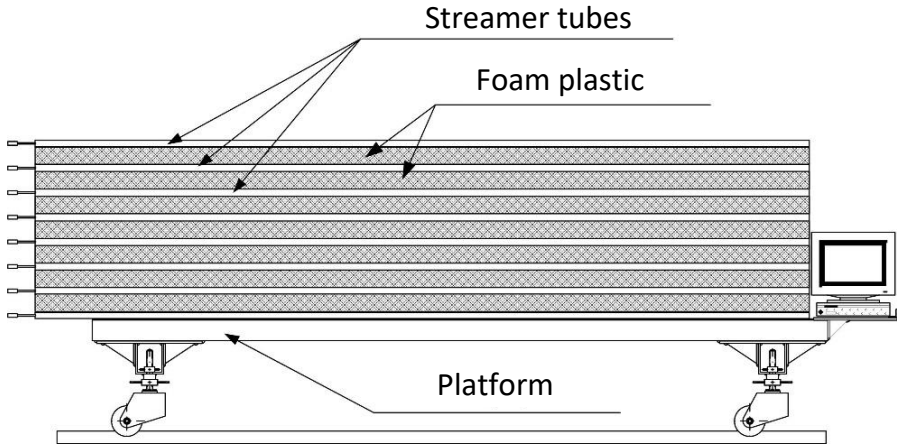
A **hodoscope** from the Greek "hodos" for way or path, and "skopos" an observer

Muon hodoscopes for muonography

TEMP



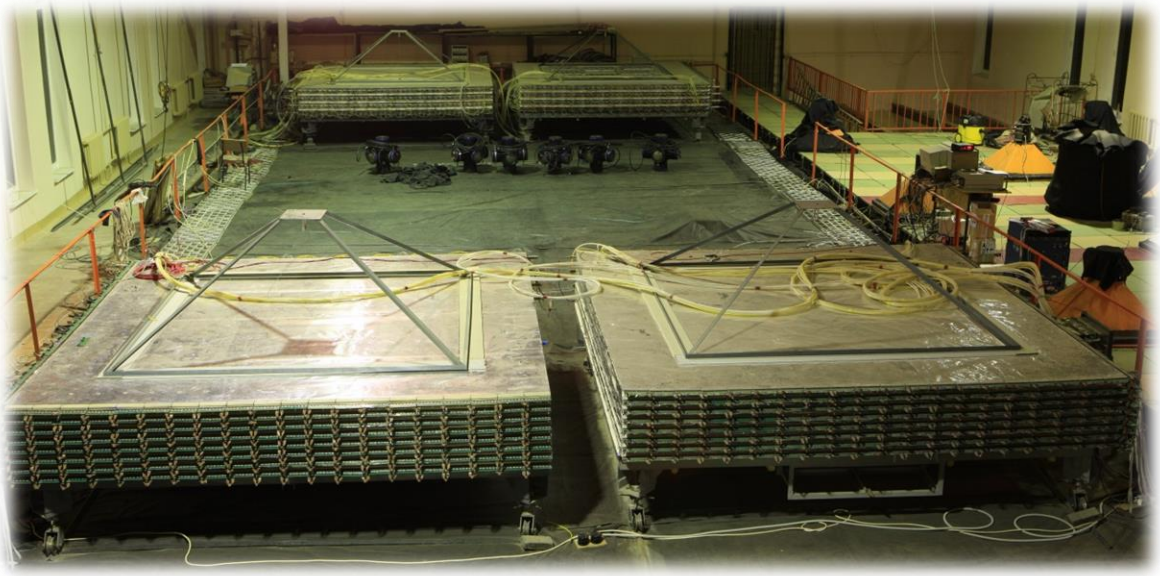
URAGAN



	TEMP	URAGAN
Coordinate planes	2	8
Area, m^2	9	11.5
Angular accuracy, °	2	0.8
Counting rate, s^{-1}	550	1400
Efficiency of registration, %	90	99

The first muon hodoscope TEMP was constructed in 1995 in MEPhI, 2 coordinate planes only . More perfect MH consisting of 8 coordinate planes was constructed also in MEPhI in 2005-2006. A similar MH also consists of 8 coordinate planes and was constructed in Mexico in 2014.

Muon hodoscope URAGAN



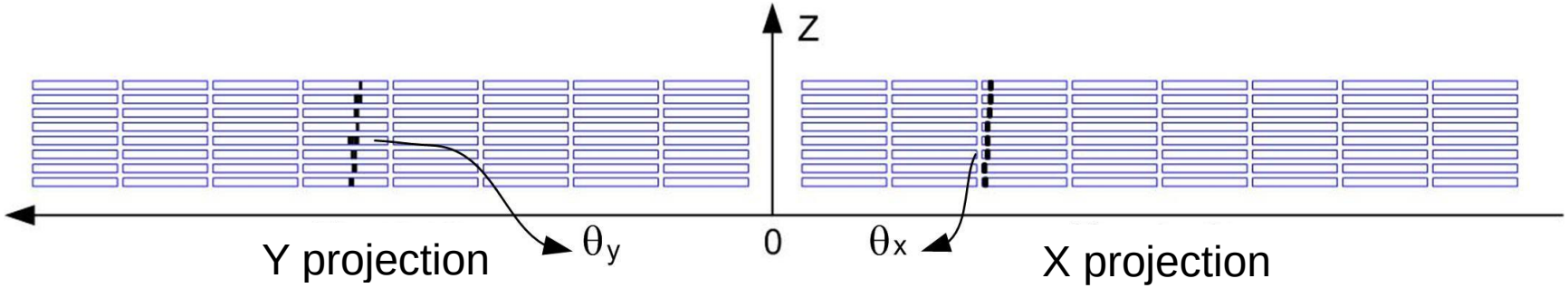
Muon hodoscope URAGAN consists of 4 supermodules. The total area is 45 sq. m. The supermodule provides high spatial and angular accuracy of muon track registration (1 cm and 1°, correspondingly) in a wide range of zenith angles: from 0° to 80°.

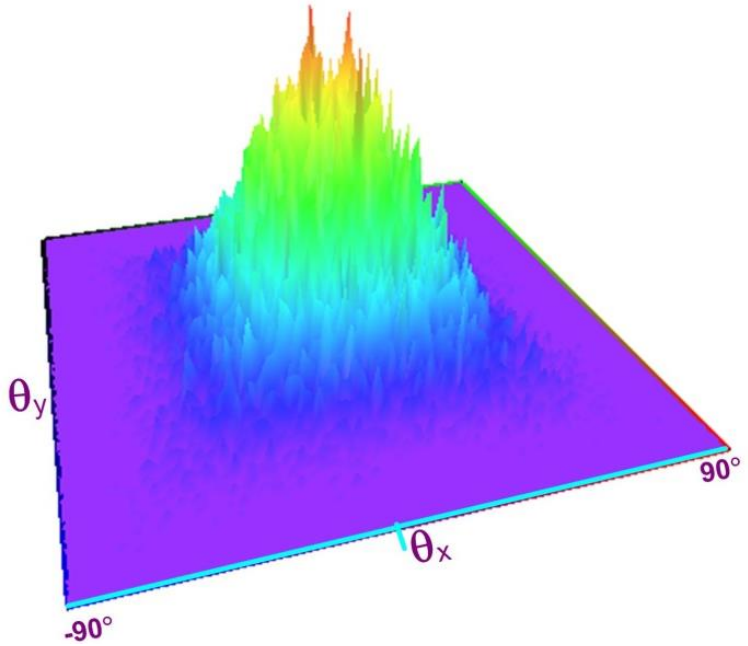
Capabilities :

- **Integral mode:** measurements of the variations of total muon flux.
- **Hodoscopic mode** provides simultaneous measurements of muon flux coming from various directions of the celestial hemisphere.
- **Matrix method for storing information is used:**
  - zenith-angular dependence; azimuthal dependence; muon flux anisotropy.

Matrix method of registration

The arrival direction of each muon is determined in real-time. Each event is added in the appropriate cell of the two-dimensional matrix of projection angles having the size of 2 by 2 degrees.



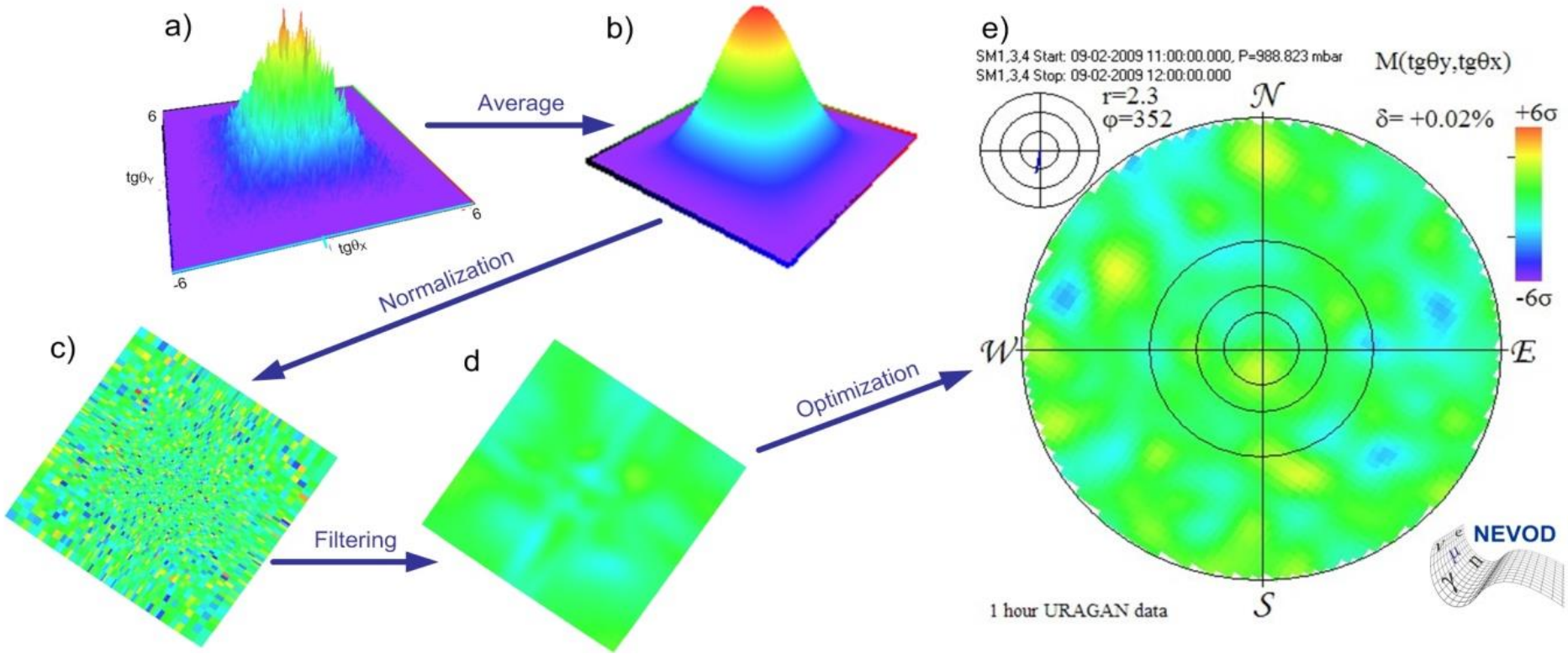


Maximum corresponds to the vertical direction.

Every minute one SM of the URAGAN registers about **80,000 muons**. The matrices averaged over the data of three supermodules obtained during **one hour** expositions are used. The statistical reliability of every such matrix is about **15 million events**. Statistical error is of ~ 0.1% (for 10 minute interval).

From muon matrix to muonography

To separate small deviation in muon flux from basic muon flux the muonography technique is used. To get muonographs we do the following manipulations:

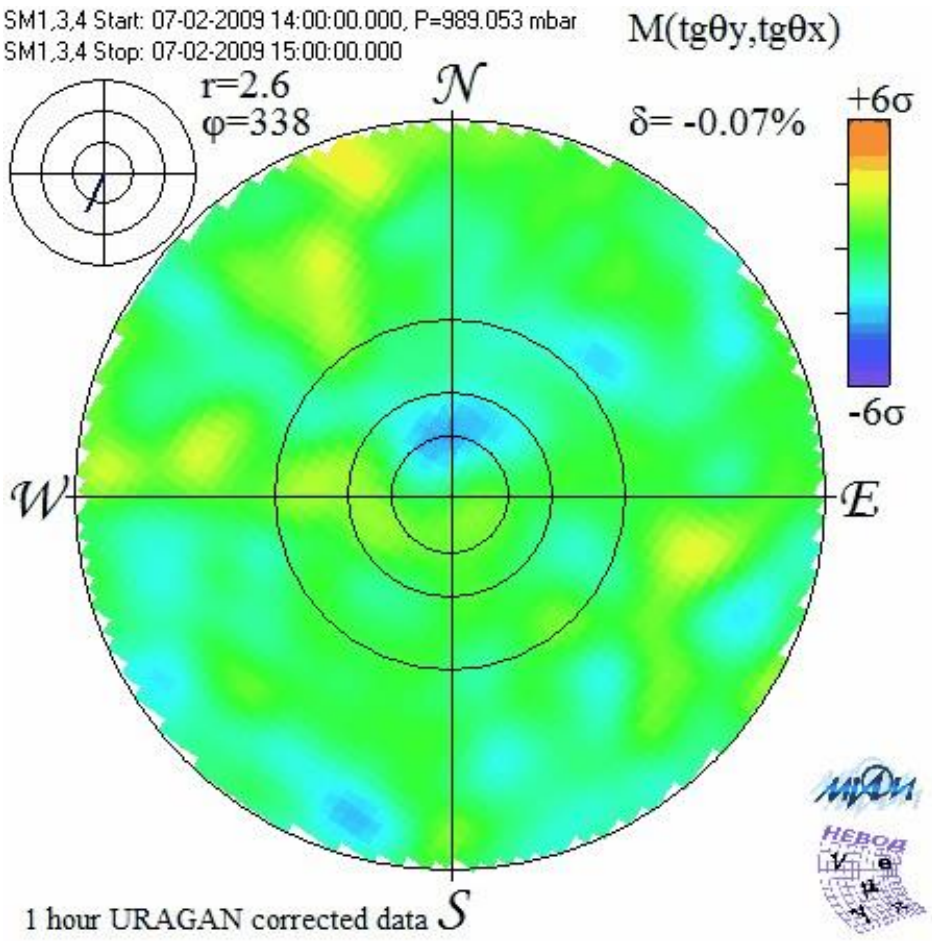


Color shows the deviation from the average in sigma (red color – excess of muons, blue color – deficit of muons)

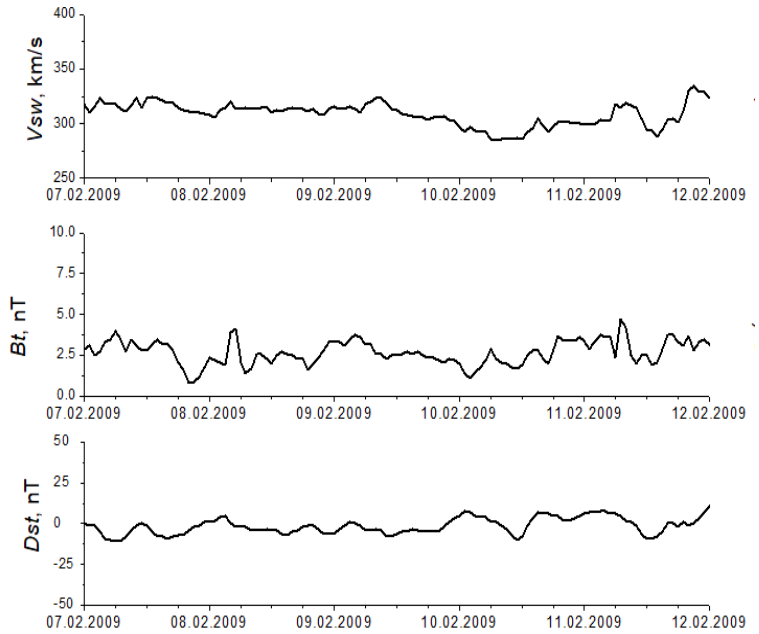
Such muonographs allow to study the dynamics of two-dimensional muon flux variations.

Dynamics of muonographs in laboratory system in a quiet period

June25_Presentation_12_BarbashinaN_Anim_1.gif



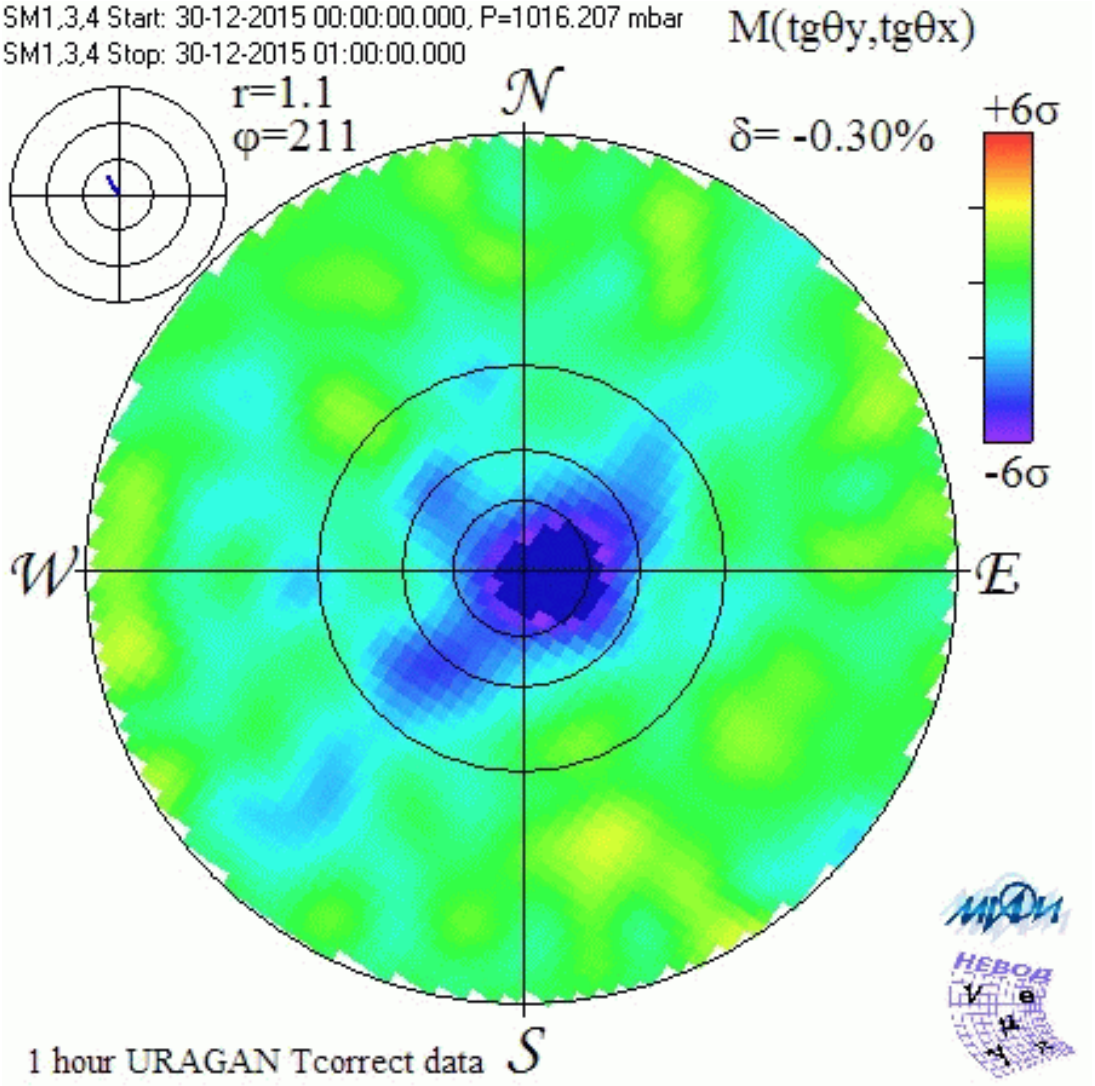
No serious deviations

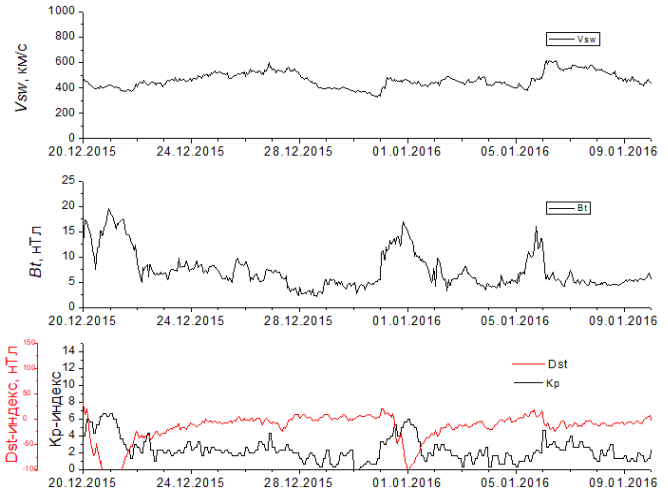


Parameters
of near terrestrial space:

$\langle V_{SW} \rangle$ ~ 325 km/s;
$\langle B_{max} \rangle$ = 4.5 nT;
$\langle Dst \rangle$=2.5 nT;

Dynamics of muonographs of heliospheric disturbance in laboratory system during FD of 30 January 2015





Parameters
of near terrestrial space:

$\langle V_{SW} \rangle$ ~ 460 km/s;
$\langle B_{max} \rangle$ = 16.9 nT;
$\langle Dst \rangle$ = - 100 nT;

Large changes in the angular distribution of the flux of muons

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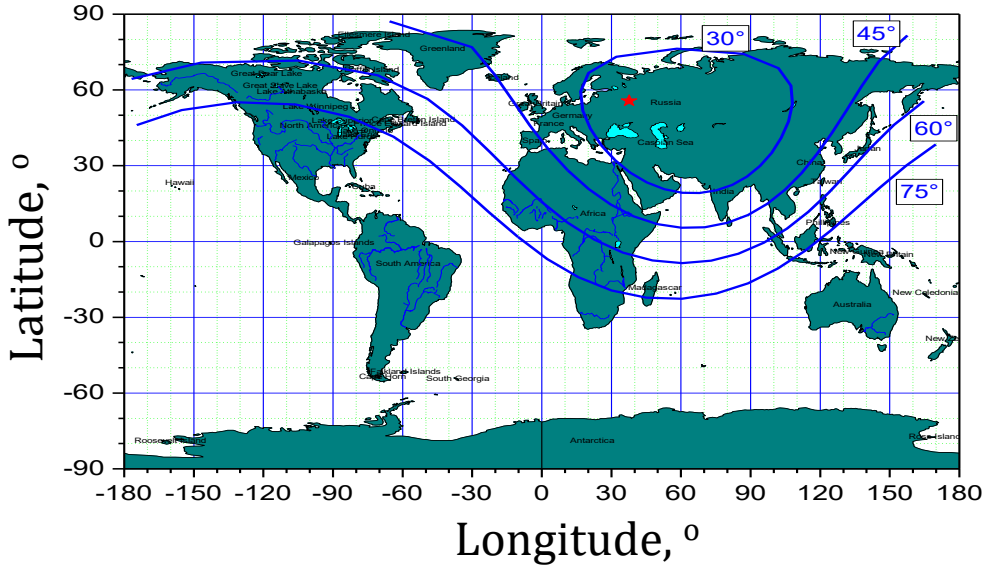
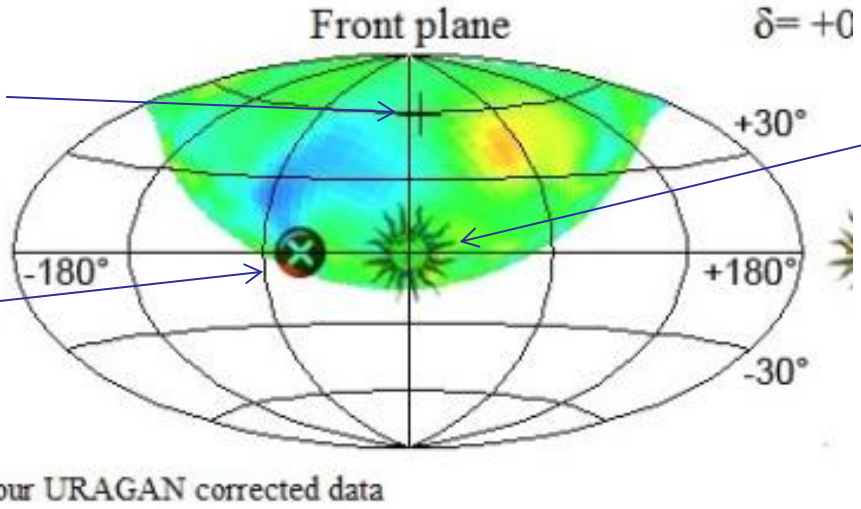
Asymptotic directions of cosmic ray protons for zenith angles of detected muons 30°, 45°, 60° и 75° by URAGAN



By using asymptotic directions it is possible to translate muonographs obtained in laboratory system to geocentric solar ecliptic system

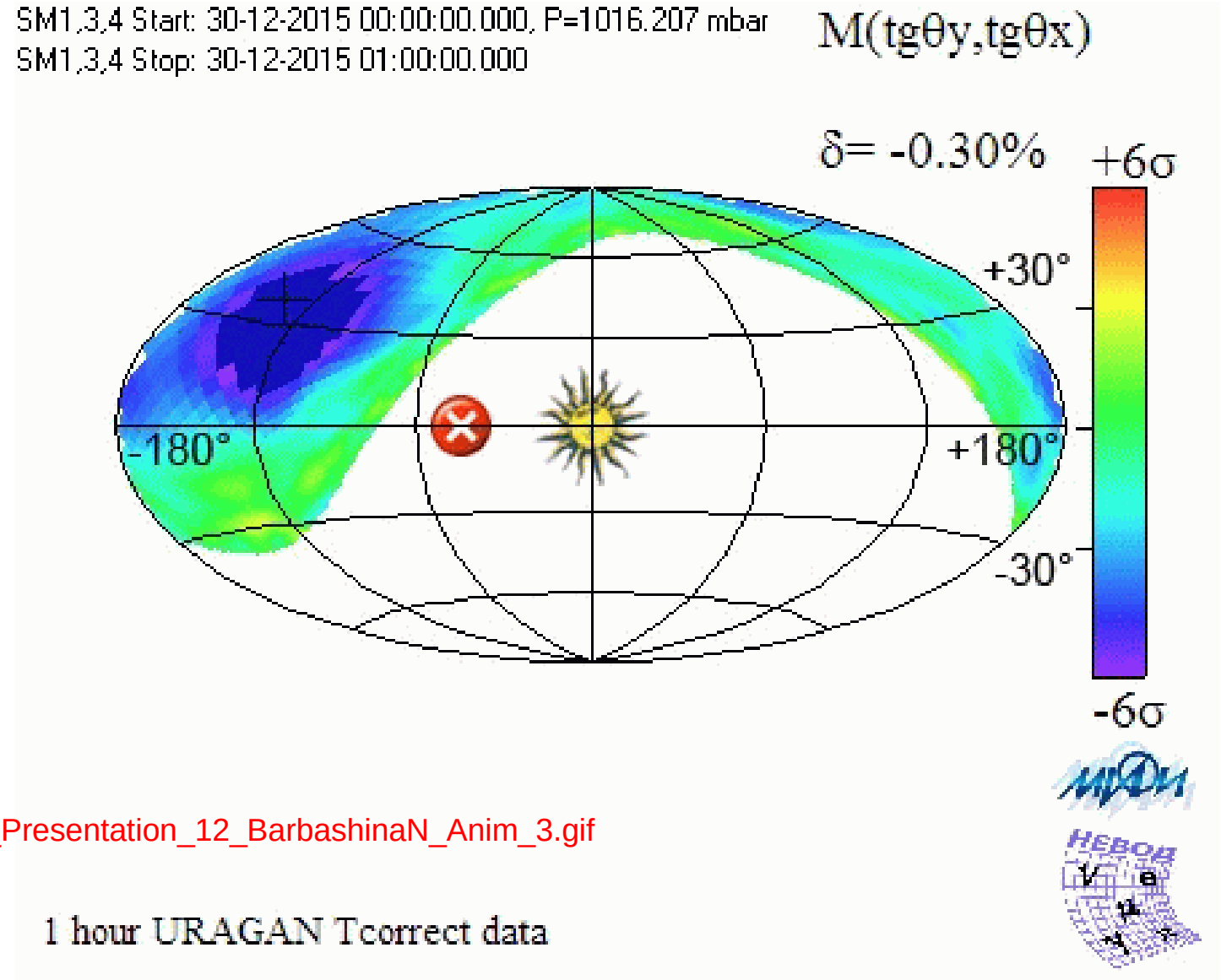
The cross is the vertical direction of the hodoscope,

The direction of the magnetic field line



The Sun

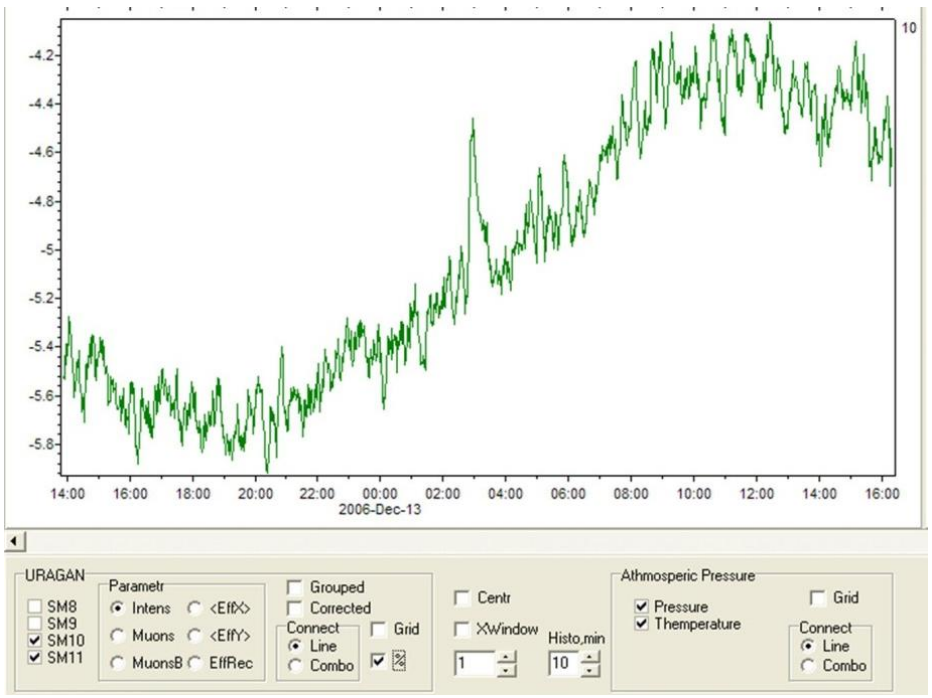
Dynamics of muonographs of heliospheric disturbance in GSE system during FD of 30 January 2015



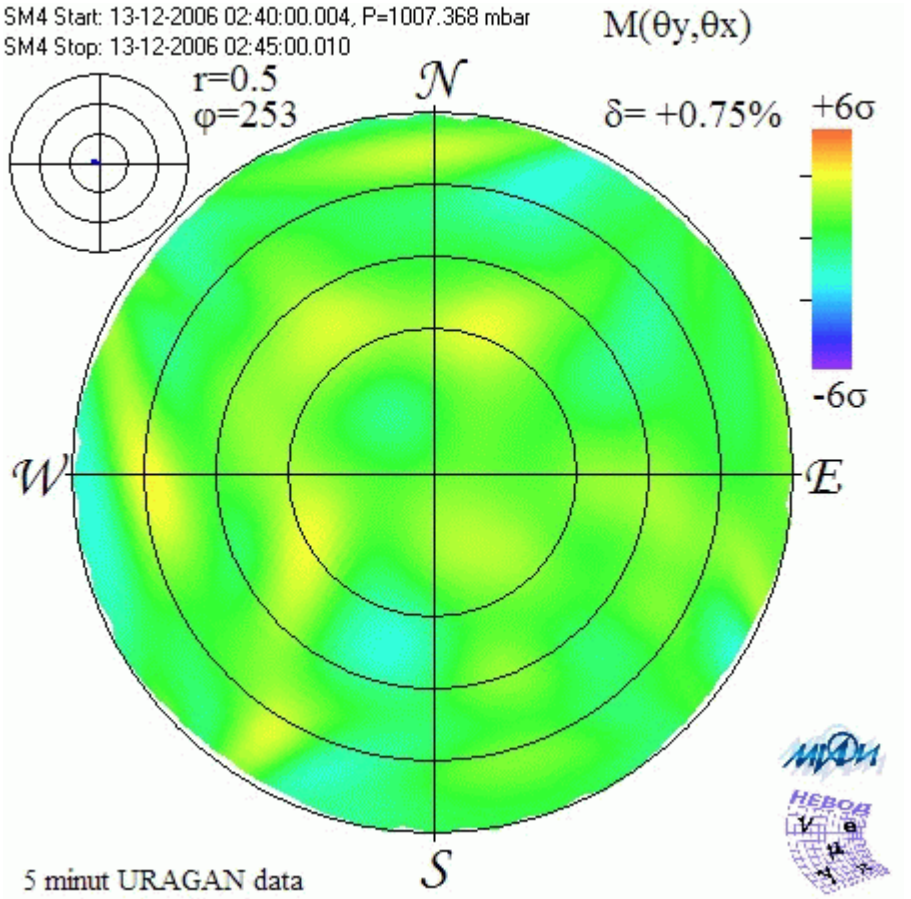
June25_Presentation_12_BarbashinaN_Anim_3.gif

GLE #70 of December 13, 2006

This was very interesting event and muonographs allow to see angular distribution during the increase of muon flux in laboratory system.



The integral counting rate gives only the time and amplitude of the increase



Muonographs allow to see the directions of these changes

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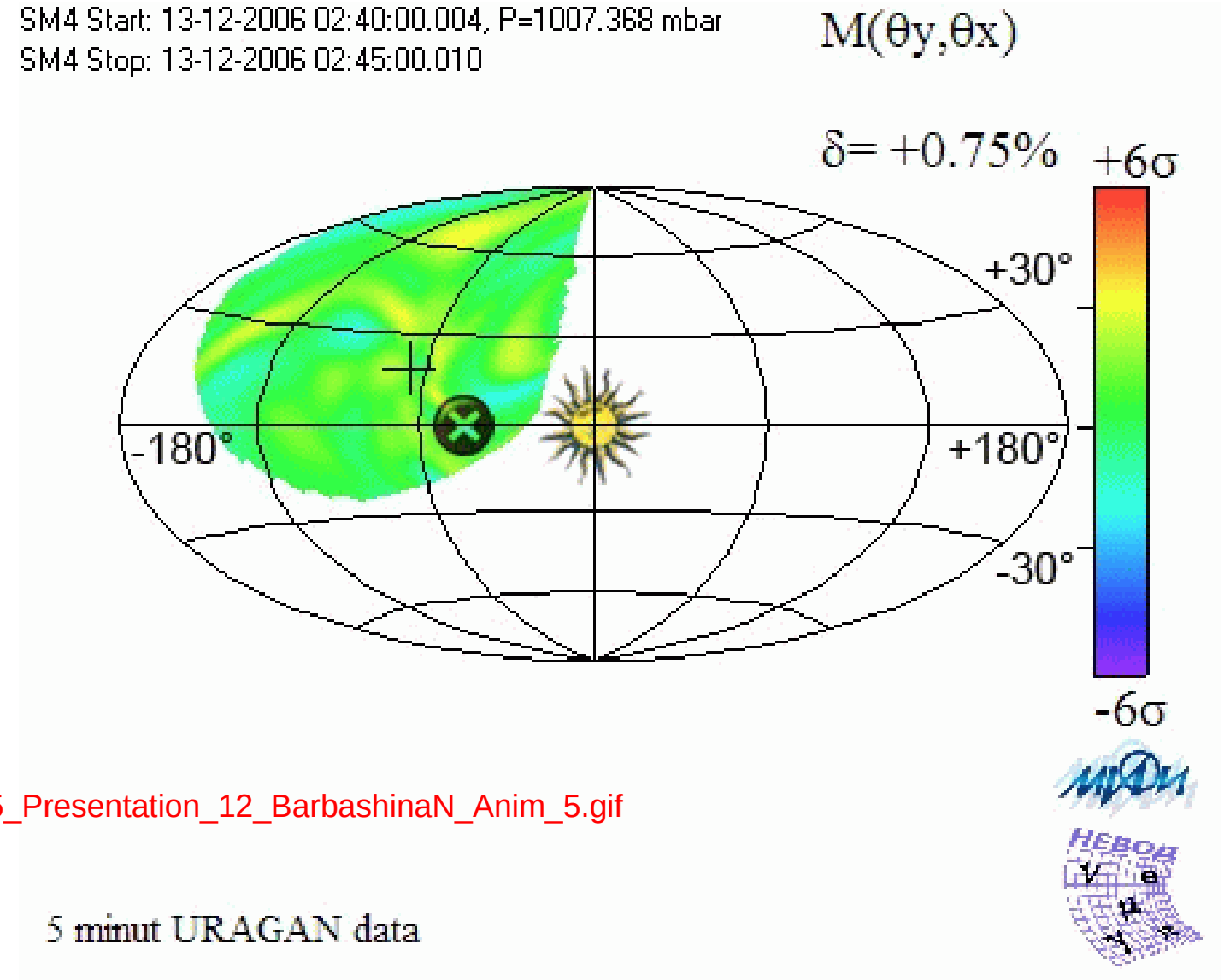
GLE #70 of December 13, 2006 in GSE



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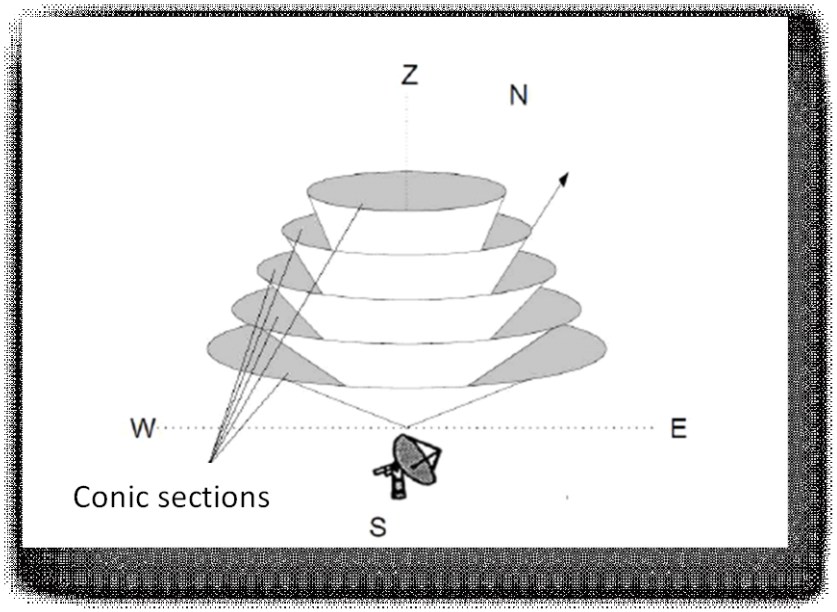
Maximum muon flux is seen in the direction near to magnetic field line

Muonography of atmospheric processes

Thunderstorms are a clear manifestation of non-stationary processes in the atmosphere. For calibration of muonography method, independent information about thunderstorms from Doppler weather radar DMRL-C is used.

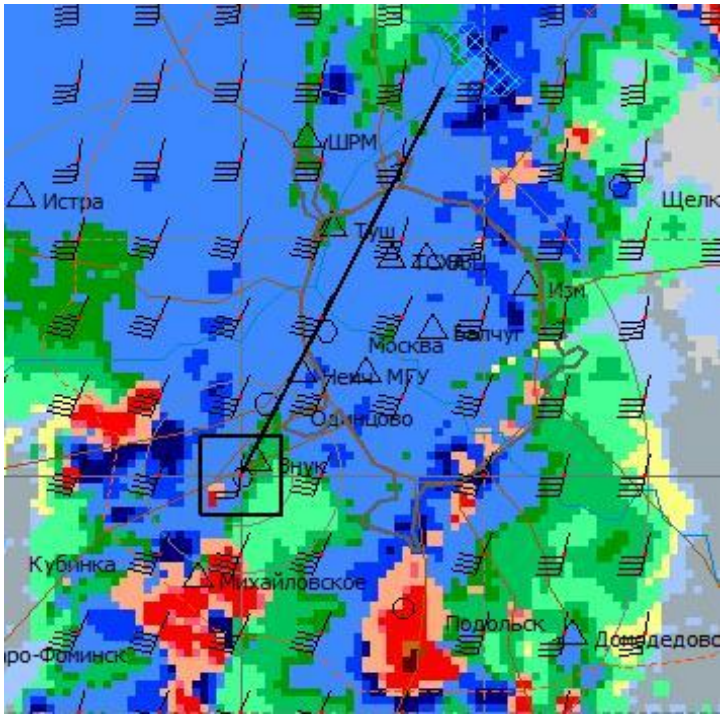
Doppler weather radar DMRL-C

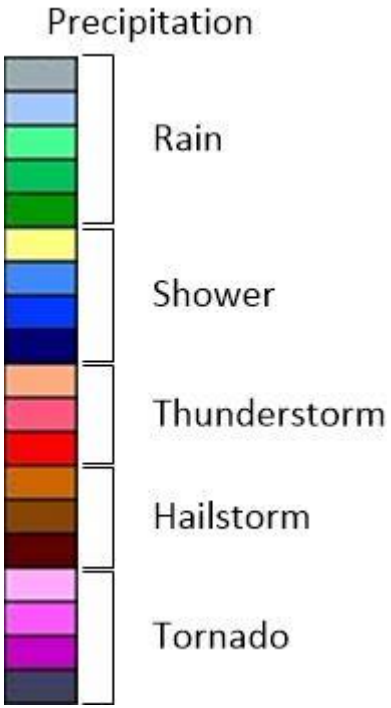


Radio locator determines the radio beam reflectivity from various hydrometeors (droplets, snowflakes, etc.). Instrumental range of radio beam is 250 km, maximum detection height is 20 km.

DMRL-C data

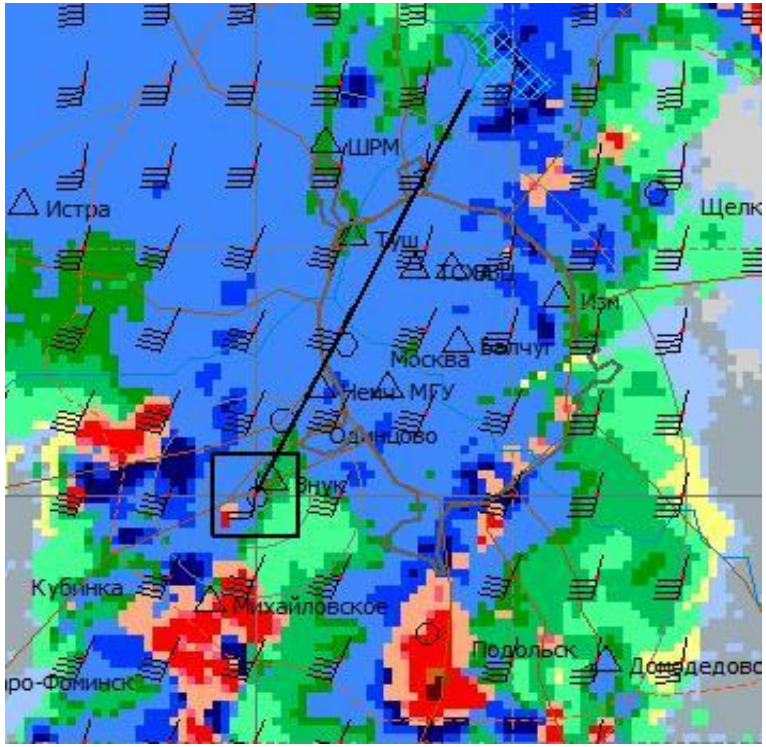
Radio locator data represent 3-dimensional maps of radar scanning (map of phenomena). Resolution of maps is 1×1 km^2.

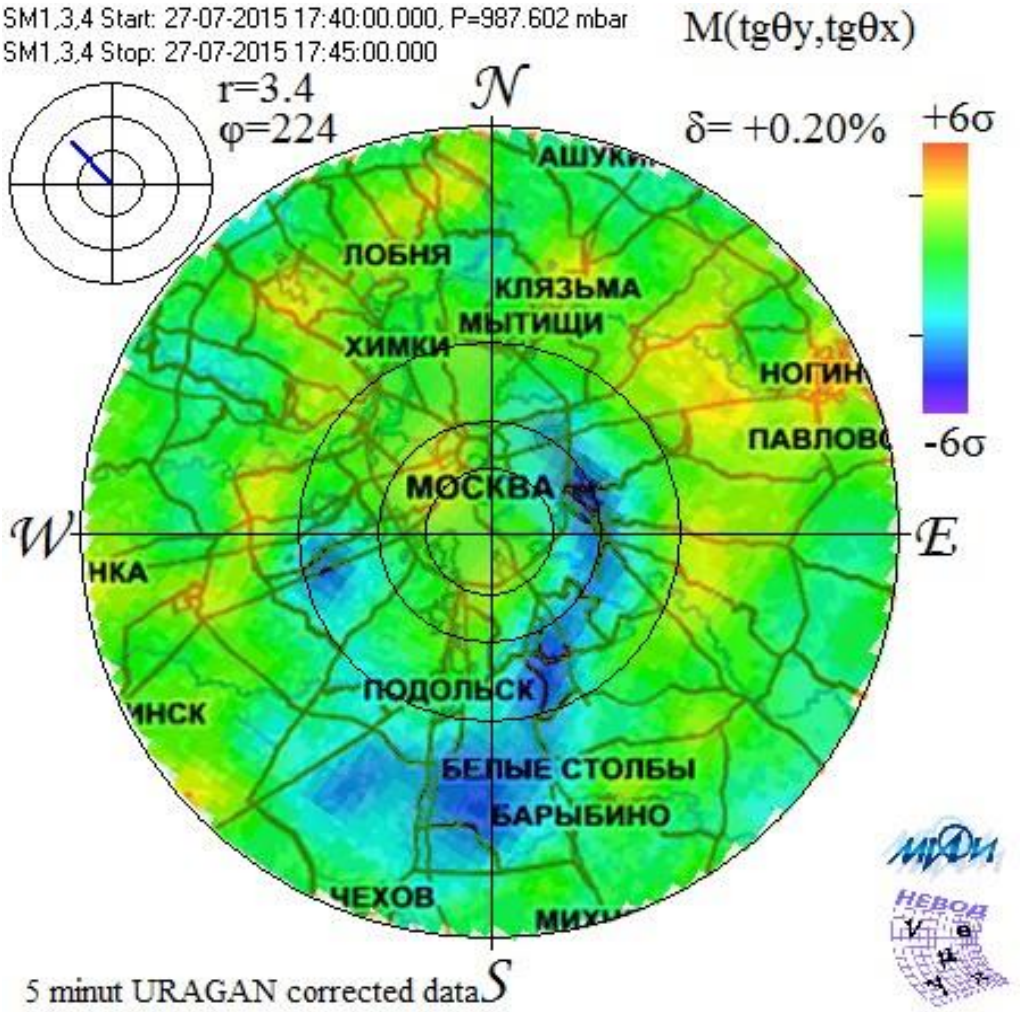




Example of thunderstorm event on July 27, 2015 on the map of meteolocator. Black square represents the locator position, inclined vertical line points the direction of air mass movement. Red color corresponds thunderstorm.

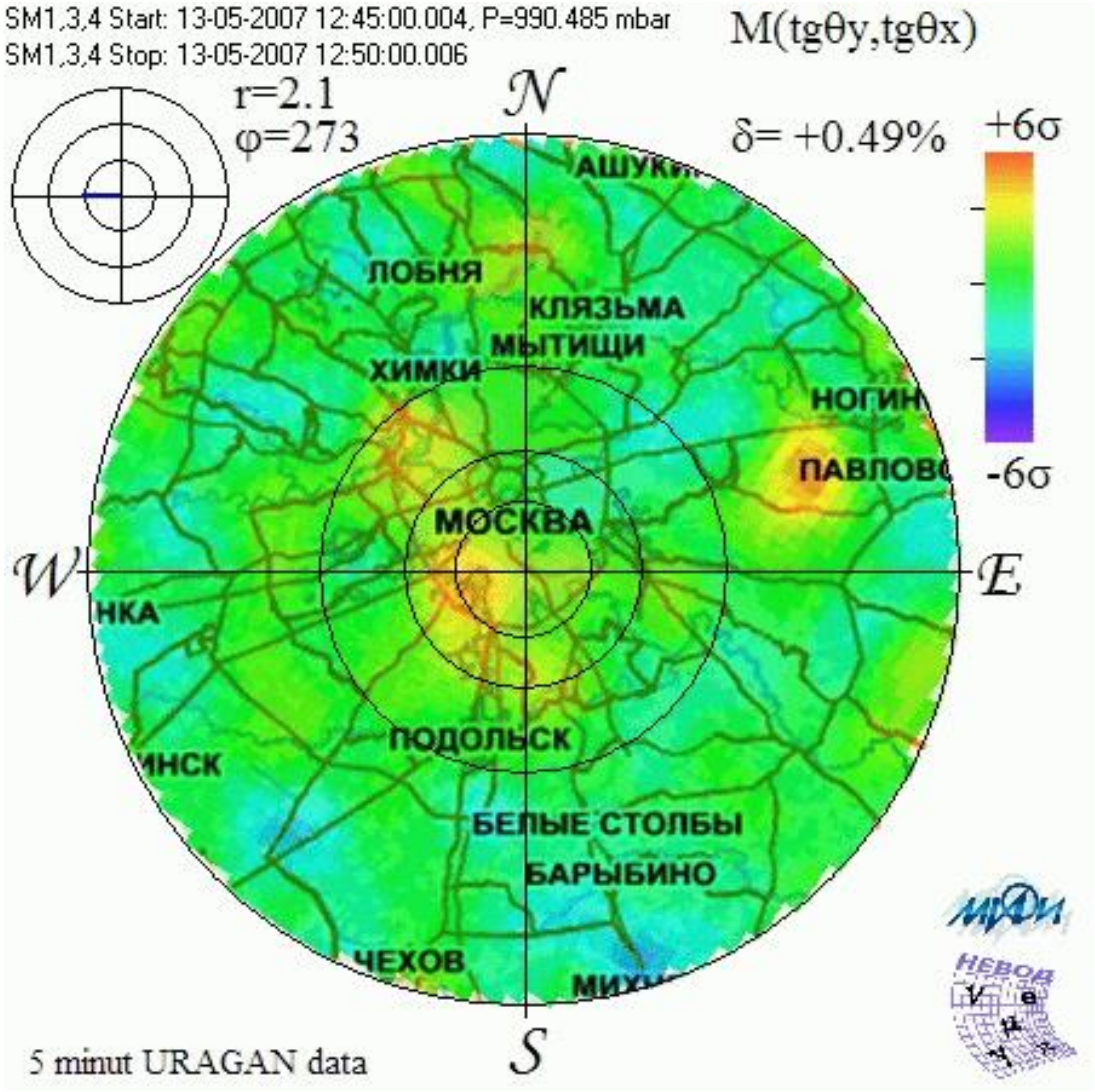
Comparison of Doppler maps and muonographs





This example shows that the area of thunderstorm corresponds to minimum muon flux.

Dynamics of muonographs of atmospheric disturbances



This example shows changes of muonographs during thunderstorm in time.

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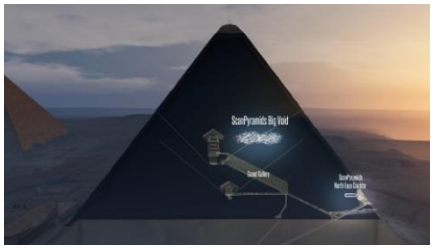
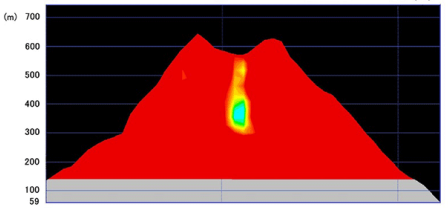
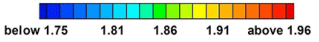
For more details see talk Kachur Alexandra on Friday, 28 June, Session 5B

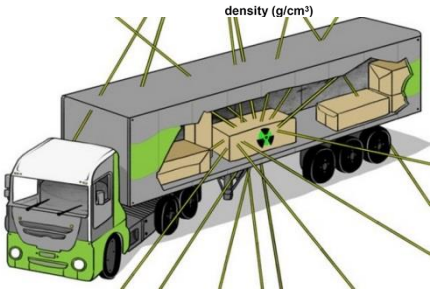
Muonography of Earth's objects (muon tomography)

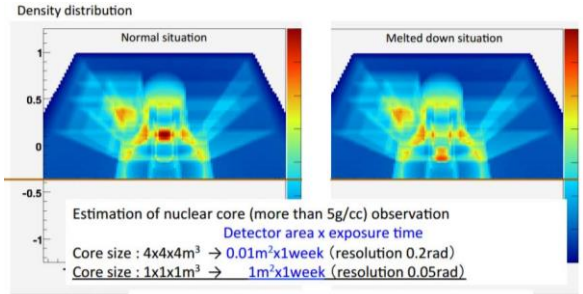
- Study of the structure of Egyptian (Cheops, Chephren, etc.) and Mexican (Teotihuacan) pyramids.
- Mapping of the internal structure of volcanoes (Vesuvius, Stromboli, Etna and Puy de Dome, Satsuma-Ivojima) for the magma level estimations.
- Prevention of forbidden transportation of heavy materials.
- Muonography of the location of nuclear fuel in emergency reactors of the NPP (Fukushima-1).
- Muonography of particle detectors.







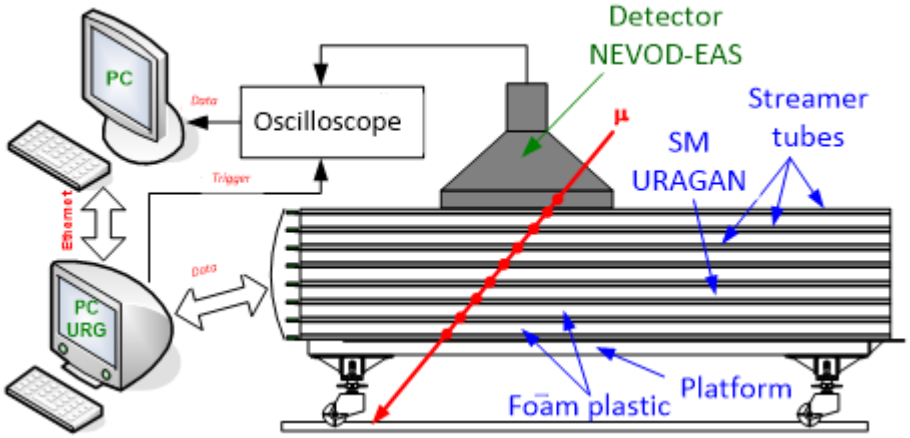




Several 10 m² Films needed for this application

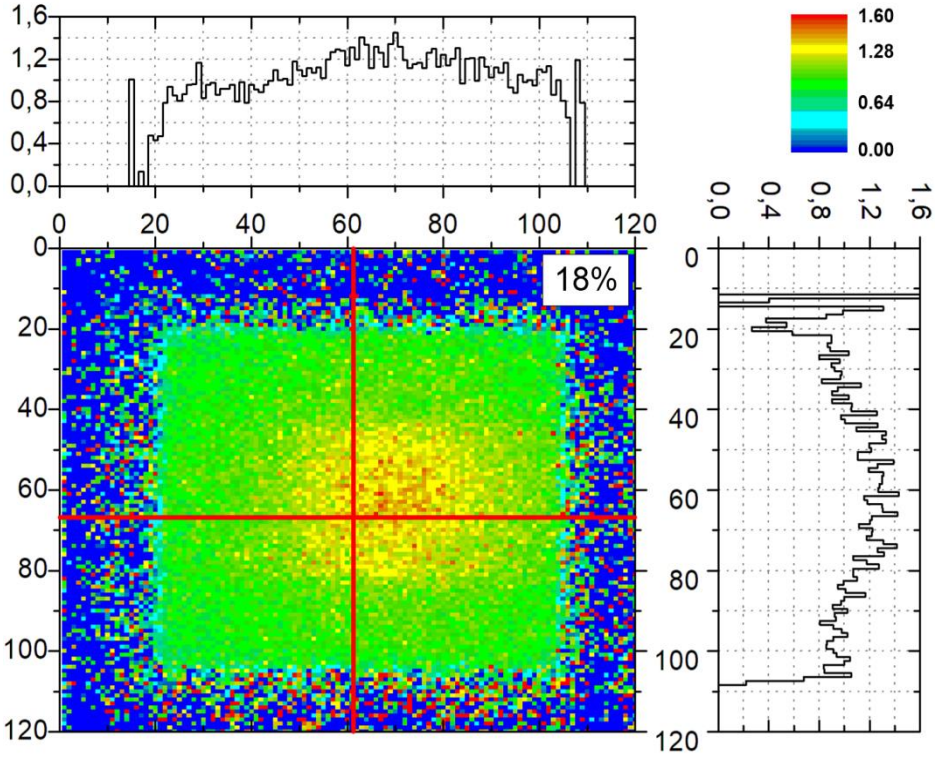
The muonography of particle detectors (non-uniformity of the scintillation counter light collection)

Scheme of measurements



Color corresponds to **relative counter response** to the passage of single muon through the cell with dimensions of 1×1 cm^2.

The muonography of the counter response



Yellow region corresponds to the passage of muons through the PMT

Conclusion

1. Muon hodoscope technique and method of muonography allow to implement a new approach to investigations of heliospheric, magnetospheric and atmospheric disturbances, and to study the structure of various objects.

2. Results of observations with the help of muonography in the real-time mode can be found at:

   in the atmosphere
   http://nevod.mephi.ru/English/sample2.php

   and in the heliosphere
   http://nevod.mephi.ru/English/sample3.php

Thank you very much!