Muonography – a new method of investigations of the 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

- Cosmic ray muons
- From muon detector to muon hodoscopes
- Muonography of heliosphere and magnetosphere
- Muonography of atmosphere and Earth’s objects
- Conclusion
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 $E_0/E_\mu$ is about 10.

![Scheme of muon generation](image1)

**Average energy of muons in near horizontal flux** $\approx 70$ GeV, and corresponding primary proton energies $\approx 700$ GeV.

**Dependence of this energy on zenith angle**

Average muon energy at the Earth's ground

$$<E_\mu> = 4 \text{ GeV}$$

Average energy of primary protons

$$<E_p> = 50-60 \text{ GeV}$$
Different types of muon detectors

- Muon detector
- Muon telescope
- Multidirectional muon telescope
- Muon hodoscope

The main feature of muon hodoscope is track reconstruction of each muon.

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

Petrukhin A.A., Barbashina N.S., Borog V.V. et al. **Muonography - a new method of investigation of the Heliosphere** // 40th COSPAR Scientific Assembly. August 2014, D2.3-32-14
Muon hodoscopes for muonography

**TEMP**

**URAGAN**

<table>
<thead>
<tr>
<th>Coordinate planes</th>
<th>TEMP</th>
<th>URAGAN</th>
</tr>
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<tbody>
<tr>
<td></td>
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<td>8</td>
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<table>
<thead>
<tr>
<th>Area, m²</th>
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<th>URAGAN</th>
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<td>11.5</td>
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<table>
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<th>Angular accuracy, °</th>
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<th>URAGAN</th>
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<td>0.8</td>
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<table>
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<tr>
<th>Counting rate, s⁻¹</th>
<th>TEMP</th>
<th>URAGAN</th>
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<td>550</td>
<td>1400</td>
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<th>Efficiency of registration, %</th>
<th>TEMP</th>
<th>URAGAN</th>
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<tr>
<td></td>
<td>90</td>
<td>99</td>
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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.
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.

Matrix method of registration

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

**Color shows the deviation from the average in sigma**

Such muonographies allow to study the dynamics of two-dimensional muon flux variations.
Dynamics muonography in laboratory system in a quiet period

Parameters of near terrestrial space:

- $\langle V_{SW}\rangle \sim 325$ km/s;
- $\langle B_{max}\rangle = 4.5$ nT;
- $\langle Dst\rangle = 2.5$ nT;
Dynamics of muonography of heliospheric disturbance in laboratory system during FD of 30 January 2015

Parameters of near terrestrial space:

\[ \langle V_{SW} \rangle \sim 460 \text{ km/s}; \]
\[ \langle B_{max} \rangle = 16.9 \text{ nT}; \]
\[ \langle Dst \rangle = -100 \text{ nT}; \]
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 muonography 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

Front plane

1 hour URAGAN corrected data
Dynamics of muonography of heliospheric disturbance in GSE system during FD of 30 January 2015

SM1.3.4 Start: 30-12-2015 00:00:00.000, P=1016.207 mbar
SM1.3.4 Stop: 30-12-2015 01:00:00.000

\( M(\theta_y, \theta_x) \)

\[ \delta = -0.30\% \]

1 hour URAGAN Tcorrect data
GLE #70 of December 13, 2006

This was very interesting event and muonography allows 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

Muonography allows to see the directions of these changes
GLE #70 of December 13, 2006 in GSE

Maximum muon flux is seen in the direction of the magnetic field line.
**Vector of relative anisotropy**

For a quantitative estimation of these changes, the local anisotropy vector is used.

- **Local anisotropy vector** is the sum of unit vectors of muon tracks, normalized to the number of events. The vector can be expanded in directions to the geographic South ($A_S$) and East ($A_E$).

- For the study of deviations from the average anisotropy vector direction, the **relative anisotropy vector** $r$ and its projections $r_S$ and $r_E$ to the South and East are used.

  $$
  r = A - \langle A \rangle
  $$

  $$
  r_S = A_S - \langle A_S \rangle \quad \text{and} \quad r_E = A_E - \langle A_E \rangle
  $$

- The $r_S$ and $r_E$ quantities are convenient for the study of the azimuthal muon flux anisotropy variations during the FD.

- Horizontal projection of this vector $\vec{r}$:

  $$
  r_h = \sqrt{(r_S)^2 + (r_E)^2}
  $$

  indicates to what extent the deformation of the angular distribution of the particle flux occurred.
Long-term variations of the flux of muons

Experimental data of the muon hodoscope URAGAN for the 11-year period from 2007 to 2017.

The upper panel represents the counting rate taking into account barometric effect (black curve) and temperature effect (red curve).

The three panels below give dependences of three projections of relative anisotropy vectors on time.

Minimal values of these projections are observed during minimal solar activity in 2009 year. Maximal values of these projections are observed during maximum solar activity in 2012 and 2015-2016.
Comparison of temporal (average during month) changes of $r_h$ and heliosphere and magnetosphere activities
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 $1 \times 1$ 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 muonographies

This example shows that the area of thunderstorm corresponds to minimum muon flux.
Dynamics of muonography of atmospheric disturbances
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.
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 $1 \times 1$ cm$^2$.

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
   - and in the heliosphere
Thank you very much!
Disturbances of the primary spectrum (shaded region) influences the detector response (green region).

The energies of primary particles responsible for changes in the muon flux during heliospheric disturbances are significantly less than the average energies responsible for the production of the total muon flux.

$J_p(E)$ – differential intensity of primary particles.

$P(E, \theta)$ – detector collection function.

$G(E, \theta)$ – detector response function.

$\Delta J_p / J_p \sim R^{-1}$  

[L. Dorman, 1963]

### Median and average primary energies for different zenith angle intervals

<table>
<thead>
<tr>
<th>Zenith angles</th>
<th>$E_{0.5}$, GeV</th>
<th>$E_{\text{mean}}$, GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-17 °</td>
<td>13.55</td>
<td>16.05</td>
</tr>
<tr>
<td>17-26 °</td>
<td>14.33</td>
<td>16.93</td>
</tr>
<tr>
<td>26-34 °</td>
<td>16.19</td>
<td>18.96</td>
</tr>
<tr>
<td>34-44 °</td>
<td>18.36</td>
<td>21.22</td>
</tr>
<tr>
<td>44-70 °</td>
<td>24.13</td>
<td>26.88</td>
</tr>
</tbody>
</table>

[E. Yakovleva, 2009]