Present status of muon diagnostics

I I Yashin1, N V Ampilogov1, I I Astapov1, N S Barbashina1, V V Borog1, A N Dmitrieva1, R P Kokoulin1, K G Kompaniets1, G Mannocchi2, A S Mikhailenko1, A A Petrukhin1, O Saavedra3, V V Shutenko1, G Trinchero2, E I Yakovleva1

1 National Research Nuclear University MEPhI, 115409, Moscow, Russia
2 Istituto di Fisica dello Spazio Interplanetario, INAF, 10133, Torino, Italy
3 Dipartimento di Fisica dell’ Universita di Torino, 10125, Torino, Italy

E-mail: iiyashin@mephi.ru

Abstract. Muon diagnostics is a technique of remote monitoring of various dynamic processes in the heliosphere, the magnetosphere and the atmosphere of the Earth based on the analysis of spatial-angular and temporal variations of muon flux simultaneously detected from all directions of the upper hemisphere. The developed approaches to data analysis and results of the study of various terrestrial and extra-terrestrial processes detected by means of a wide aperture URAGAN muon hodoscope are discussed.

1. Introduction
The ground level flux of cosmic ray muons generated by interactions of primary cosmic rays in the upper atmosphere is sensitive to both atmospheric and extra-atmospheric phenomena. Therefore the use of high energy primary cosmic rays and produced by them secondary muons as a penetrating probes gives possibility to explore processes both in the heliosphere and in the atmosphere. The solution of this task by means of real time analysis of spatial-angular variations of muon flux at the Earth's surface caused by these reasons is the object of muon diagnostics. The main objective of muon diagnostics is the early recognition and forecasting of the development of destructive phenomena of atmospheric and extra-atmospheric origin. This problem has not been solved yet, despite of enormous amount of data related to our space environment obtained with world-wide net of ground based stations (neutron monitors and muon telescopes) and space-born apparatus. One of the main reasons of this is a scarcity of information about heliosphere conditions between the Mercury's and the Earth's orbits. New possibilities are opened with the use of muon hodoscopes [1, 2]. Since muons (in contrast to neutrons) keep primary particle direction, the opportunity to measure primary cosmic ray variations from various directions appears. Moreover, muon hodoscope allows to detect muons simultaneously from any direction of upper hemisphere and form "muon images" of the disturbed regions.

2. Muon hodoscope URAGAN
The muon hodoscope URAGAN (55.7° N, 37.7° E, 173 m altitude a.s.l.) is currently operating in MEPhI (Moscow) [3] and represents four eight-layer assemblies-supermodules on the basis of streamer tubes (1 cm² cross-section, 3.5 m length) with external two-coordinate data readout. It has 46 m² total area, sufficient to provide high statistics: more than 5000 muons per second. The supermodule (SM) response contains information about muon track in X- and Y-projections. More detailed description of muon...
hodoscope URAGAN can be found elsewhere [3, 4]. Two projected angles are reconstructed in real time mode and are accumulated in 2D-directional matrices. Sequence of such matrices represents the filming of the upper hemisphere in “muon light”. To study muon flux variations, for every cell of the angular matrix the average number of muons (estimated during preceding 24 hours and corrected for atmospheric pressure and temperature [5]) is subtracted, and results are divided by standard deviations. Obtained data array is a “muon snapshot” of the upper hemisphere with 1-minute exposure. The size of angular cells in URAGAN matrix data was chosen as 2°×2° (in projected zenith angles). As a quantitative characteristics of angular flux variations, the local anisotropy vector is used which indicates the average arrival direction of muons. Local anisotropy vector \( \vec{A} \) is defined as the sum of unit vectors, each representing the direction of the individual track, normalized to the total number of muons [6]. In addition, the value of the vector of the relative anisotropy of \( \vec{A} \) is considered.

3. Analysis of URAGAN data

Muon hodoscope URAGAN detects cosmic ray muons in a continuous mode since May 2005. Variations of total counting rate of muons measured by means of the URAGAN during 2007 – 2011 are presented in figure 1. Data presented in the figure (about \( 4 \times 10^{11} \) muons) were obtained by summation of counting rates of three SMs of the URAGAN for zenith angle range 25º ≤ \( \theta < 76º \). The frequency spectrum obtained as a result of the Fourier analysis of time dependence of hourly average counting rate is shown in figure 2. This analysis shows the presence of annual, 27-day, diurnal and semi-diurnal variations. More detailed information about long-term variations of the parameters of muon angular distribution is presented in [7].

Figure 1. Time dependences of daily average of muon counting rate (for zenith angle interval 25-76º, normalized to one SV) estimated by URAGAN data.

Figure 2. Fourier power spectra of time sequence of muon counting rate. In the boxes, the values of the periods (in days) are specified for corresponding peaks.

3.1 GLE#70 analysis

GLE#70 of December 13, 2006 was detected by two URAGAN supermodules at six sigma level (for ten-minute bins). Maximum of the enhancement was observed at 03:00 UTC. On the basis of the analysis of 2D-images of muon flux, the proton energy spectrum in the GLE event was estimated. The characteristics of proton spectra were obtained by means of the solution of the inverse task by using coupling functions for the muon hodoscope, which join the differential muon flux at the Earth's surface and the proton flux above the atmosphere [8, 9]. Estimates of solar CR spectrum in the GLE#70 event were obtained in two versions: 1) according to only muon hodoscope data \( J_p(E) = 65 \times E^{5.5\pm2.8} \) [cm\(^{-2}\cdot s^{-1}\cdot sr^{-1}\cdot GeV^{-1})], 2) according to muon hodoscope data and data of Moscow neutron monitor \( J_p(E) = 21 \times E^{5.06\pm0.33} \) [cm\(^{-2}\cdot s^{-1}\cdot sr^{-1}\cdot GeV^{-1})] [10]. Calculations of average and maximum energies of solar protons show that effective energies for the muon hodoscope are about 3 times higher than those for the neutron monitor. However, even for the muon hodoscope estimated maximum energies of solar protons do not exceed 30 GeV.
3.2. Analysis of Forbush decreases

For the analysis of variations of muon flux during Forbush decreases (FD) detected by the URAGAN a technique that allows to investigate their energy, angular, and temporal characteristics has been developed [11, 12]. Variations in the muon flux during FDs were investigated using both the integral counting rate, summed over three SMs (averaged 10-minute data corrected for barometric and temperature effects), and the counting rates for five zenith-angular ranges: 0°–17°, 17°–26°, 26°–34°, 34°–44°, and over 44°, the boundaries of which were chosen to provide nearly equal statistics. Threshold muon energies depend on zenith angle and vary from 300 to 600 MeV. FDs detected in the URAGAN during 2006 – 2011 with amplitude of the decrease in the integral counting rate ≥ 0.5% were selected. In figure 3, results of the study of variations of muons and neutrons (from Moscow neutron monitor) during FD of July 11, 2011 are presented. Solar wind and IMF parameters also are shown.

![Figure 3](image)

Figure 3. Variation of CR muons in FD of July 11, 2011. Left: from top to bottom: solar wind velocity; values of the vector of IMF ($B_t$ and $B_z$); counting rate of the URAGAN; counting rate of the MNM; changes of $r_h$. Right: GSE-images obtained for moments indicated on $r_h$ plot at left panel.

Note the behavior of the parameter of anisotropy $r_h$. Increase of $r_h$ (up to 4σ level) started 2 days before FD beginning. In the right panel of the figure, GSE-images obtained for moments of maximum increasing of $r_h$ during the period July 07 - 14, 2011 are presented. To obtain GSE-image, a "muon snapshot" is projected to magnetopause using asymptotic directions and is transformed into GSE coordinate system. A more detailed analysis of FDs for 2006 - 2011 period is presented in [13].

3.3. Monitoring of atmospheric processes

For the analysis of muon flux variations caused by active phenomena in the atmosphere, 5 minute integrated URAGAN matrices were used. Examples of plots of various parameters which are calculated basing on the matrix data, are presented in figure 4: left – "muon snapshots" obtained for different periods of thunderstorm on June 19, 2011 and combined with map of Moscow region [14]; right – behaviour of atmospheric pressure, relative variation of integral rate, absolute value of the vector of the local anisotropy and its horizontal projection. Development of thunderstorm cells is accompanied by powerful
turbulent and convective processes which cause different wave processes in the upper troposphere. In figure 5, results of wavelet analysis of a sequence of URAGAN counting rate during the thunderstorm of June 19, 2011 evolution are presented. The moment of thunderstorm passing above the observation point is clearly seen. The waves with periods of about 40 and 65 minutes appeared several hours before the event beginning. The distribution of wave periods identified in the URAGAN data in thunderstorm events of 2009 – 2010 before the storm starts was estimated in [14]. The most characteristic periods correspond to 40-70 min. The distribution of periods for the range 1 – 6 h reveals the maximum at 3 – 4 hours.

During 2008 – 2011, 67 thunderstorms were identified around the point of URAGAN location. The analysis of muon hodoscope response has shown that more than 70% events have a clear reaction in the integral counting rate. Moreover, the reaction in different characteristics of muon anisotropy appeared practically in all thunderstorms.

Figure 4. Sequence of “muon snap-shots” (left) and muon flux anisotropy characteristics (right) during the thunderstorm in Moscow, June 19, 2011

Figure 5. Wavelet analysis of the counting rate of URAGAN for the thunderstorm of June 19, 2011.

4. Conclusion
The use of cosmic rays as a penetrating component in the heliosphere and muons – in the atmosphere, and muon hodoscopes as apparatus for formation of “muon images” of the atmosphere and extra-terrestrial space opens new perspectives for remote monitoring of the environment. The analysis of muon flux anisotropy during heliosphere perturbations related with solar activity by means of even a single wide-aperture hodoscope gives possibility to obtain unique information about the structure and dynamics of such events and to compare predictions of various models of heliospheric processes with direct measurements of muon flux variations. Muon diagnostics of active phenomena in the atmosphere may give possibility to forecast of dangerous local atmospheric phenomena.
Acknowledgments
The research was performed in Scientific and Educational Centre NEVOD with the support of the Russian Ministry of Education and Science (contract no. 16.518.11.7053) in frame of the Federal Target Program "Scientific and pedagogical cadres for innovative Russia" and leading scientific school grant NSh-6817.2012.2.

References
[1] Barbashina N S et al 2007 Bull. Rus. Acad. Sci., Phys. 71 1041
[2] Timashkov D A et al 2007 Proc. 30th Int. Cosmic Ray Conf. (Merida) vol 1 p 685
[3] Barbashina N S et al 2008 Instrum. Exp. Tech. 51 180
[4] Chernov D V et al 2005 Proc. 29th Int. Cosmic Ray Conf. (Pune) vol 2 p 457
[5] Dmitrieva A N et al 2011 Astropart. Phys. 34 401
[6] Timashkov D A et al 2008 Proc. 21st European Cosmic Ray Symp. (Koshice) p 338
[7] Shutenko V V et al 2012 Proc. 23rd ECRS (Moscow) Submitted to Jorn. Phys. (Conf. Ser.)
[8] Yakovleva E I et al 2009 Bull. Rus. Acad. Sci: Phys. 73 357
[9] Bogdanov A G et al. 2008 Proc. 21st European Cosmic Ray Symp. (Koshice) p 341
[10] Timashkov D A et al 2008 Astroparticle Physics 30 117
[11] Barbashina N S et al 2011 Bull. Rus. Acad. Sci.: Phys. 75 814
[12] Barbashina N S et al 2011 Proc. 32nd Int. Cosmic Ray Conf. (Beijing) vol 10 p 278
[13] Barbashina N S et al 2012 Proc. 23rd European Cosmic Ray Symp. (Moscow) Submitted to Jorn. Phys. (Conf. Ser.)
[14] Astapov I I et al 2011 Proc. 32nd Int. Cosmic Ray Conf. (Beijing) vol 11 p 444