Characteristics of the Forbush decrease of 22 June 2015 measured by means of the muon hodoscope URAGAN

N S Barbashina, N V Ampilogov, I I Astapov, V V Borog, A N Dmitrieva, A A Petrukhin, O A Sitko, V V Shutenko and E I Yakovleva
National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia
E-mail: NSBarbashina@mephi.ru

Abstract. Results of the studies of cosmic ray muon flux variations during the powerful Forbush effect registered by the muon hodoscope URAGAN on June 22, 2015 are presented. From the muon flux angular distribution, the dependence of the intensity decrease amplitude on the primary particle energy in the region above 10 GeV has been obtained. The changes of this dependence at different phases of the Forbush effect development have been studied. Based on the analysis of spatial and angular variations of the muon flux, the values of the local anisotropy vector parameters, as well as unique muon snapshots (muonographies) have been obtained. The characteristics of the heliospheric and magnetospheric disturbances during the considered event have been analyzed.

1. Introduction
Muon hodoscope URAGAN [1] has been operated as a part of the Unique Scientific Facility "Experimental complex NEVOD" [2] since 2006. One of the tasks being solved using the hodoscope is a muon diagnostics of the near-Earth space. One of the brightest examples of the solar activity influence on the cosmic rays are drastic decreases of the secondary particle flux detected at the Earth's surface by various detectors – the so-called Forbush decreases (FD). To study the FD detected in the hodoscopic mode, a special technique [3, 4] has been developed. This technique provides a wide range of characteristics of the cosmic ray muon flux variations during the FD: integral, energy, spatial-angular and temporal. As a result of the analysis of these characteristics, we obtain the FD amplitudes, the power indices of the energy dependence of the cosmic ray intensity decrease amplitude in the energy range of 10 – 30 GeV, their temporal dependences at different phases of the FD development, the muon snapshots (muonographies), the horizontal projections of the muon flux relative anisotropy vector during the FD, and the correlations between its projections to the North-South and East-West directions. Such studies are carried out for all FD registered by the URAGAN.

In this work, the above-mentioned characteristics of one of the most powerful FD (June 22, 2015) registered by the URAGAN are presented.

2. Information about the event of June 22, 2015
The decrease in the URAGAN counting rate on June 22, 2015 is the second in the FD amplitude registered over the period from 2006 to 2015. Figure 1 shows the cosmic ray flux variations measured by the muon hodoscope URAGAN and Moscow neutron monitor (MOSC) in the period from June 15 to July 1, 2015.
It is clearly seen that the decrease of the counting rate in the muon flux is substantially less than in the neutron component. It is due to the fact that muons are sensitive to higher primary energies than neutrons.

Analysis of the Sun has shown that the flare activity preceding the FD was high. Most likely, the variations in the URAGAN counting rate were caused by the flares of M-class on 21.06.2015 at 01:02 (M2.0) and at 02:06 (M2.6) and by the subsequent CMEs (halo II type) at 02:36 with velocity of up to 1560 km/s and the CME at 02:48 with velocity of up to 1950 km/s [5].

The near-Earth space was also in disturbed conditions during the analyzed period. Figure 2 shows the variations of the interplanetary magnetic field ($B_t$, $B_z$), the solar wind velocity ($V_{SW}$) and the muon counting rate.

According to ACE [6] it can be seen that a strong disturbance of the interplanetary magnetic field begins simultaneously with the increasing of the solar wind velocity at 16.00 on June 22. The IMF parameters $B_t$ and $B_z$ change to 30 and -30 nT, correspondingly. The solar wind velocity changes from 400 to 700 km/s. Geomagnetic disturbances were registered on the Earth: as SSC on June 21, 2015 at 17:00, by $Dst$-index – on June 23 at 05:00, by $Kp$-index – on June 22 at 18:00.

3. Results of the URAGAN data analysis during the FD of June 22, 2015

In the muon flux, as also in the neutron flux according to the MOSC data, the decrease beginning was registered by the muon hodoscope on 22.06.2015 at 19:10. The amplitude of the URAGAN integral counting rate decrease (determined according to the technique described in [3]) amounted to $2.41\% \pm 0.16\%$. The amplitude of the MOSC counting rate decrease was $5.60\% \pm 0.20\%$. The ratio of the URAGAN and MOSC decrease amplitudes $A_{FD}^{URG} \approx 0.43A_{FD}^{MOSC}$. 
Study of the event energy characteristics [4, 7] is based on the analysis of dependences of the FD amplitudes \( (A_{FD}) \) in five zenith-angular intervals \((0^\circ – 17^\circ, 17^\circ – 26^\circ, 26^\circ – 34^\circ, 34^\circ – 44^\circ \) and over 44\(^\circ\)) on the mean logarithmic energy \( (E_{ln}) \) of primary protons which contribute differently to the muon hodoscope counting rate variations (14.7 GeV, 15.5 GeV, 17.5 GeV, 19.7 GeV and 25.3 GeV, correspondingly). Such dependences are approximated by function \( E^\alpha \). Registration of the muon flux in hodoscopic mode enables to estimate the amplitude spectrum index \( \alpha \) with a small time increment at different phases of the event development: decrease, minimum and recovery.

Figure 3a shows the dependence of \( A_{FD} \) on \( E_{ln} \) and the estimated value of \( \alpha \). And figure 3b shows the temporal variations of the amplitude spectrum index.

The earlier analysis of all FDs registered by the URAGAN has shown that, on average, the power index \( (\alpha) \) of the energy dependence is close to \(-1\). As can be seen from the figure 3a, the amplitude spectrum for the FD of June 22, 2015 is ‘harder’ \( (\alpha = -0.76 \pm 0.16) \) and the amplitudes for zenith angles above 44 degrees (for the mean logarithmic energy of primary particles exceeding 25 GeV) are about 2%. Temporal variations of the index \( \alpha \) (figure 3b) for the investigated event show that at the phase of the decrease its average value is \(-0.98 \pm 0.05\), at the minimum \( \alpha = -0.80 \pm 0.09 \) and during the recovery period \( \alpha = -1.20 \pm 0.30 \). From the obtained data it can be seen that at the counting rate minimum the amplitude spectrum is harder than at the phase of the decrease, but during the recovery phase a softer spectrum is observed.

As a result of the analysis of spatial and angular characteristics of the muon flux registered in the hodoscopic mode, the muon snapshots (muonographies) of the FD of June 22 have been obtained. These muonographies illustrate the two-dimensional dynamics of muon flux variations during the analyzed FD. Figure 4 shows such muonographies for the phase of the decrease.

**Figure 3.** FD on June 22, 2015: a) the dependence of \( A_{FD} \) on \( E_{ln} \); b) temporal variations of the amplitude spectrum index.

**Figure 4.** Two-dimensional dynamics of the hourly averaged changes of muon flux during the FD on June 22, 2015 for three periods: 19:00 - 20:00, 21:00 – 22:00 and 23:00 – 00:00 (UT).
For the quantitative description of the muonography shots, correlations between the projections of the muon flux relative anisotropy vector on the North-South and East-West directions have been plotted [8] (figure 5).

Figure 5. Correlations between $r_S$ and $r_E$ for the FD on June 22, 2015 from 19:00 to 23:00 UT at three phases of the event development (typical errors of the $r_S$ and $r_E$ are shown in points 1, 2 and 3).

The circles in the figures 5 correspond to 4σ variations of the $r_S$ and $r_E$ equal to $0.52 \times 10^{-3}$ in a quiet period. An exceedance of the circle limits indicates an appearance of a strong anisotropy. We see that this event had a strong anisotropy at all phases. At the first phase, a large anisotropy is observed from the north-west direction, in the second phase there is a moving from north to south and vice versa, and at the phase of the recovery again in the north-west direction.

4. Conclusion
The FD of 22 June 2015 was investigated by means of the muon hodoscope technique, and the following results were obtained: amplitude of this FD was about 2.4%; dependence of the amplitude on the energy of primary cosmic rays gives a ‘hard’ spectrum ($\alpha = -0.76$), and the FD amplitude for the mean logarithmic energy of primary particles more than 25 GeV is about 2%; this FD had a strong anisotropy at all phases: before FD and at the recovery a large anisotropy was observed from the north-west direction, in the phase of the decrease it was moving from north to south and vice versa.

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