Investigations of Forbush decreases by means of muon hodoscope

N.S. Barbashina, I.I. Astapov, V.V. Borog, A.N. Dmitrieva,
R.P. Kokoulin, K.G. Kompaniets, A.A. Petrukhin, O.A. Sitko,
V.V. Shutenko, E.I. Yakovleva, I.I. Yashin

*National Research Nuclear University MEPhI
(Moscow Engineering Physics Institute), Moscow 115409, Russian Federation
E-mail:* NSBarbashina@mephi.ru

Contents:
- *Muon hodoscope and integral counting rate.*
- *Zenith angular dependence of counting rate.*
- *Muonography ("muon snapshots") of FD.*
- *Azimuth angular anisotropy of muon flux.*

Muon hodoscope URAGAN: the new generation apparatus for studies of solar-terrestrial phenomena

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 variations of the total muon flux.

- **Hodoscopic mode** provides simultaneous measurements of muon flux coming from different directions of the celestial hemisphere.

- **Matrix method for storing information:**
     - zenith-angular dependence ; azimuthal dependence; muon flux anisotropy.

The hodoscope is operated in Moscow Engineering Physics Institute since 2006.

Specific features of the study of Forbush decreases in the muon flux

   The interest in the study of the FD in the cosmic-ray muon flux was significantly increased in recent time, due to the fact that new research approaches and experimental techniques were developed.
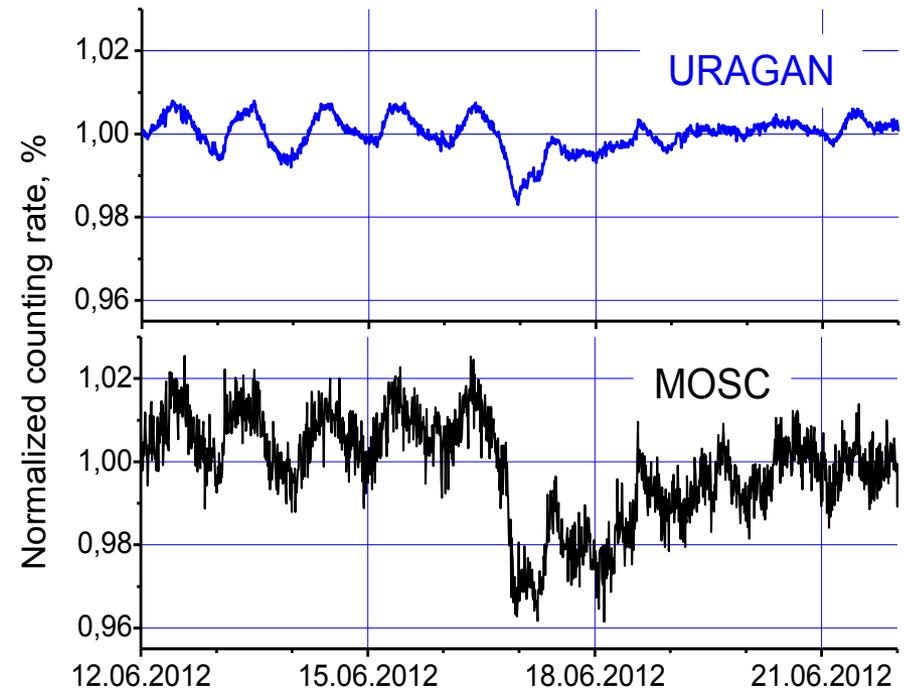
Though the effect in the muon flux is less than in neutrons, there are **some features**:

Firstly, muons are sensitive to higher (than neutrons) energies of primary cosmic rays.

Secondly, and more important, the muons retain the primary particle direction.

Muon hodoscope allows these investigations in a wide range of zenith and azimuth angles by using a single setup.
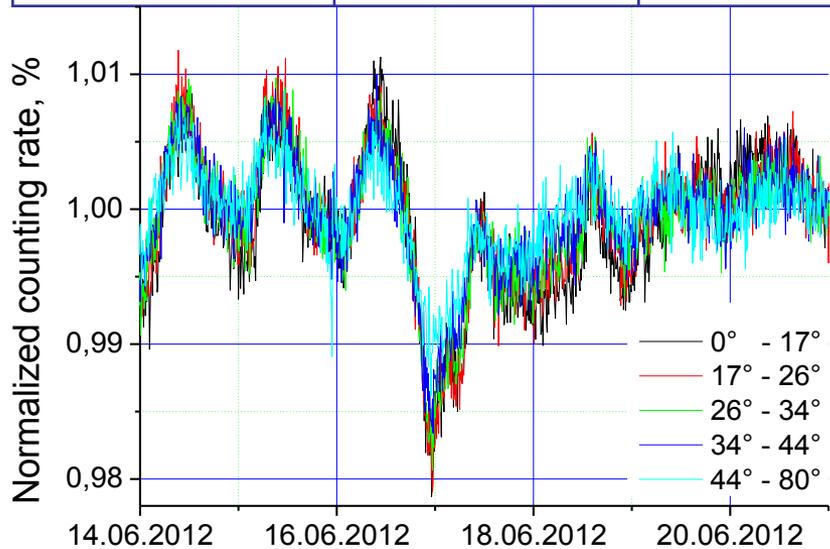
During the period from 2006 to 2013, in total **62 FD** with amplitudes **≥ 0.5%** were selected according to the URAGAN data.

Method of the analysis of the FD energy characteristics

For the analysis of the FD energy characteristics, the entire zenith angle range was divided into **five intervals** with approximately equal statistical reliability.
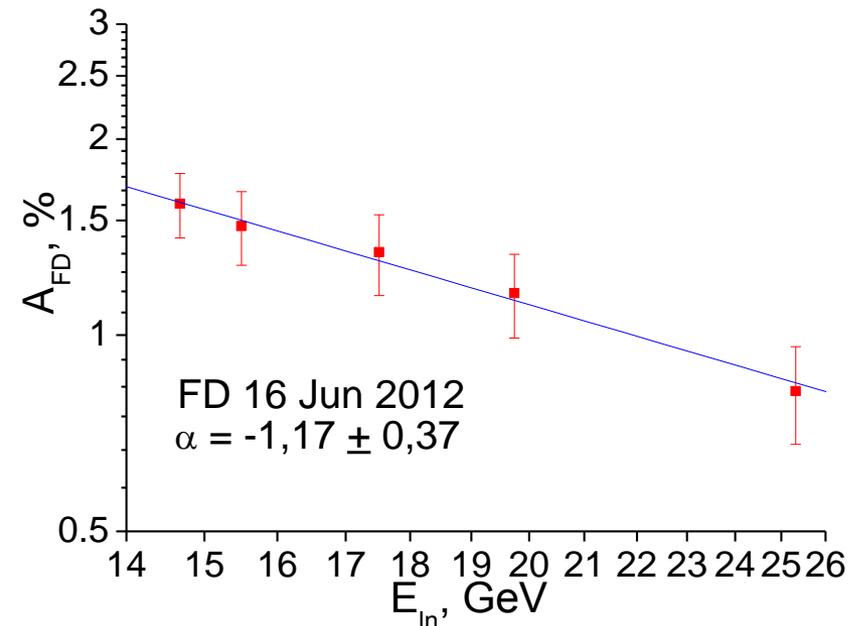
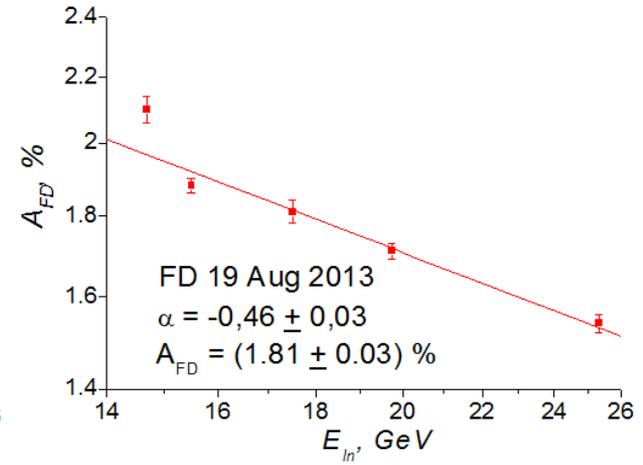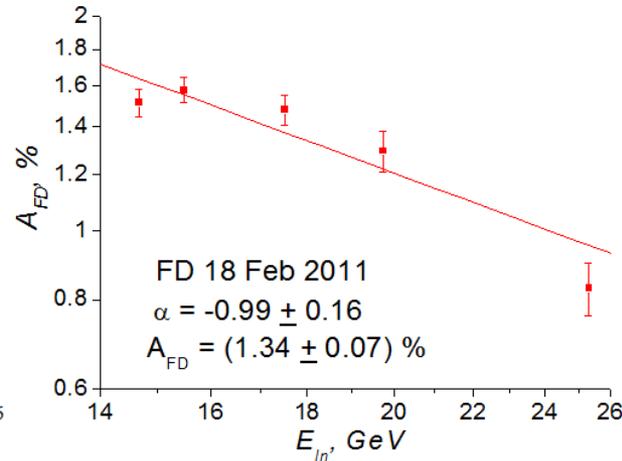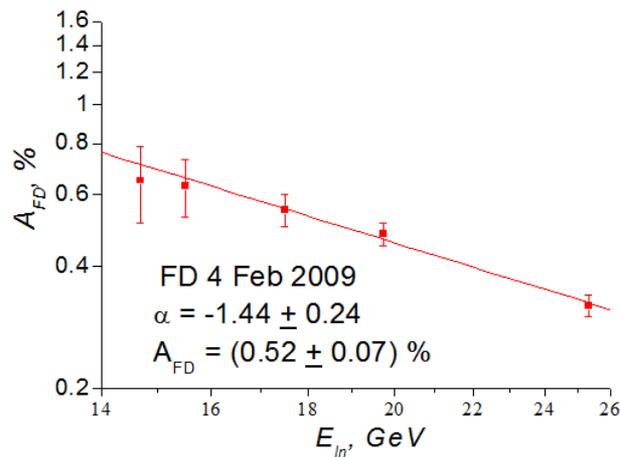| Zenith angles	A_{FD}, %	E_{ln}, GeV
$0 - 17°$	1.59 ± 0.18	14.68
$17 - 26°$	1.47 ± 0.19	15.50
$26 - 34°$	1.34 ± 0.19	17.51
$34 - 44°$	1.16 ± 0.17	19.74
$44 - 80°$	0.82 ± 0.14	25.32

The analysis of the cosmic ray energy spectrum modulations during the FD was conducted on the basis of dependences of A_{FD} on E_{ln}.

These dependences were fitted by a power function E^{α}.

A very good similarity for different angles.

FD 16 Jun 2012
$\alpha = -1,17 \pm 0,37$

Results of the analysis of the FD energy characteristics

Examples of the dependences of the decrease amplitude on the mean logarithmic energy of primary particles for several FDs.
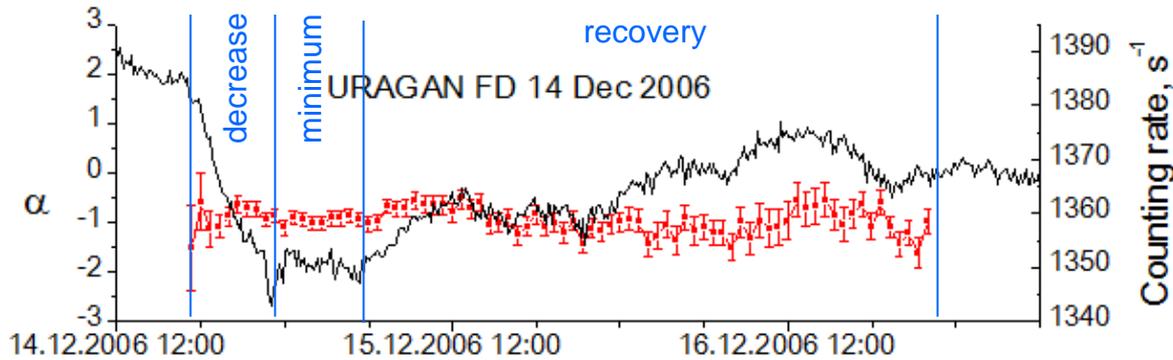

FD 4 Feb 2009
$\alpha = -1.44 \pm 0.24$
$A_{FD} = (0.52 \pm 0.07)$ %

FD 18 Feb 2011
$\alpha = -0.99 \pm 0.16$
$A_{FD} = (1.34 \pm 0.07)$ %

FD 19 Aug 2013
$\alpha = -0,46 \pm 0,03$
$A_{FD} = (1.81 \pm 0.03)$ %

Distribution of the amplitude spectrum indices for 62 FD.

As seen from the plots, the index α takes different values for FD with various amplitudes. Mainly, α is about -1, but it can be "softer" (with the value of α about -1.5) or "harder" (with the value ~ -0.5).
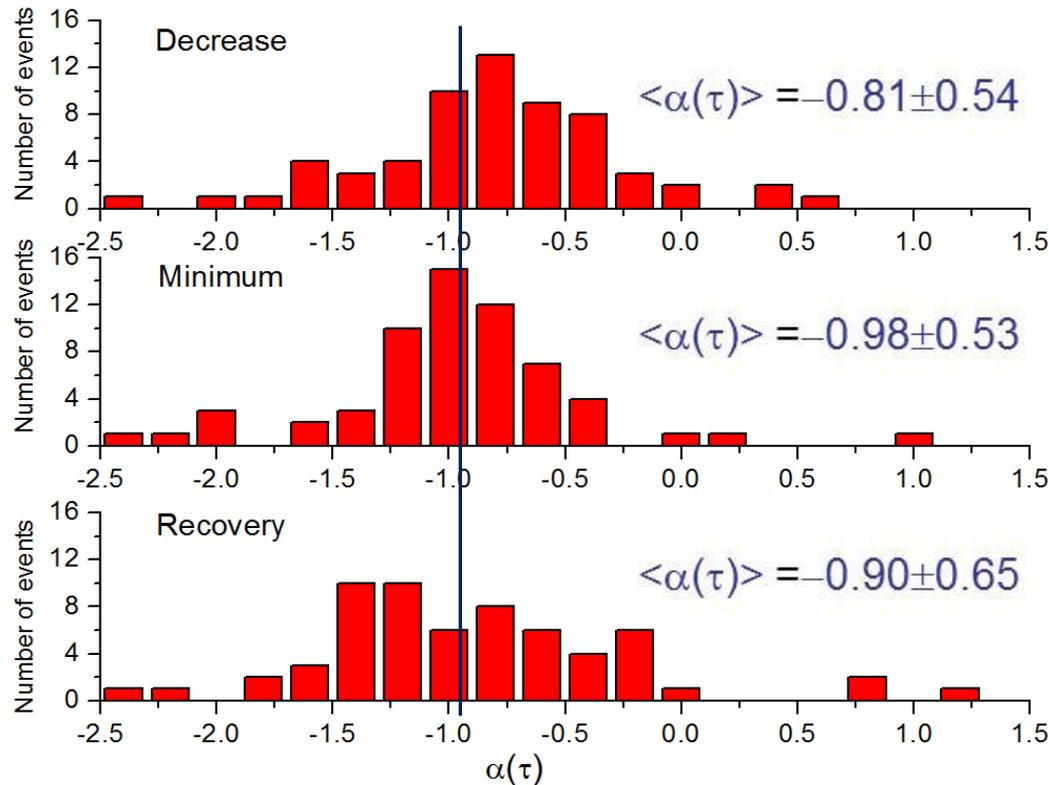
This distribution is characterized by the average α of about -1.00 with the rms-spread of ± 0.48.

The study of the amplitude spectrum index $\alpha(\tau)$ dynamics

This study of α was done for each point of the FD, and then summed for different phases of the FD development: the decrease, the minimum and the recovery.

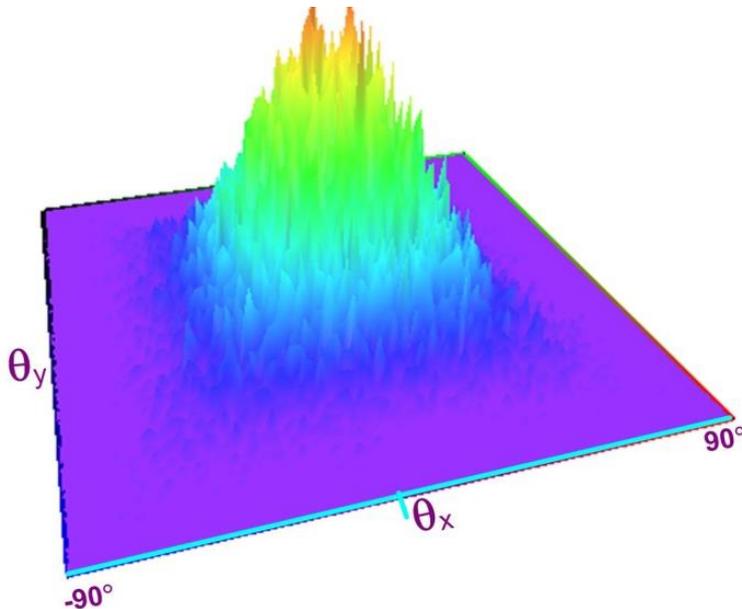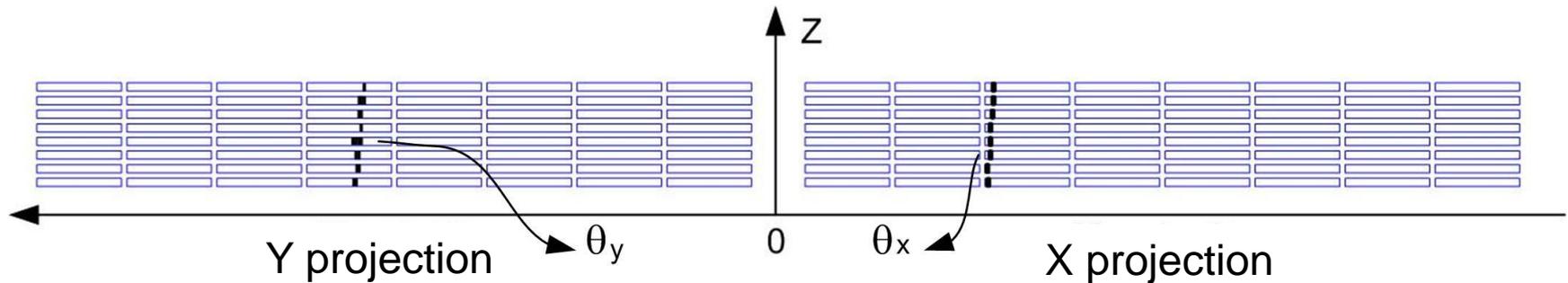Distribution of the weighted average values of $\alpha(\tau)$ for 62 FD at different phases.

From these distributions it can be concluded that, in general, no significant changes of $\alpha(\tau)$ at different phases are observed.

However, qualitatively one can see that at the phase of the decrease the spectrum of FD amplitudes is harder, at the minimum phase $\alpha \approx -1$, and in the recovery phase the distribution is quite wide, although the average value is of about -1.

Matrix method of registration

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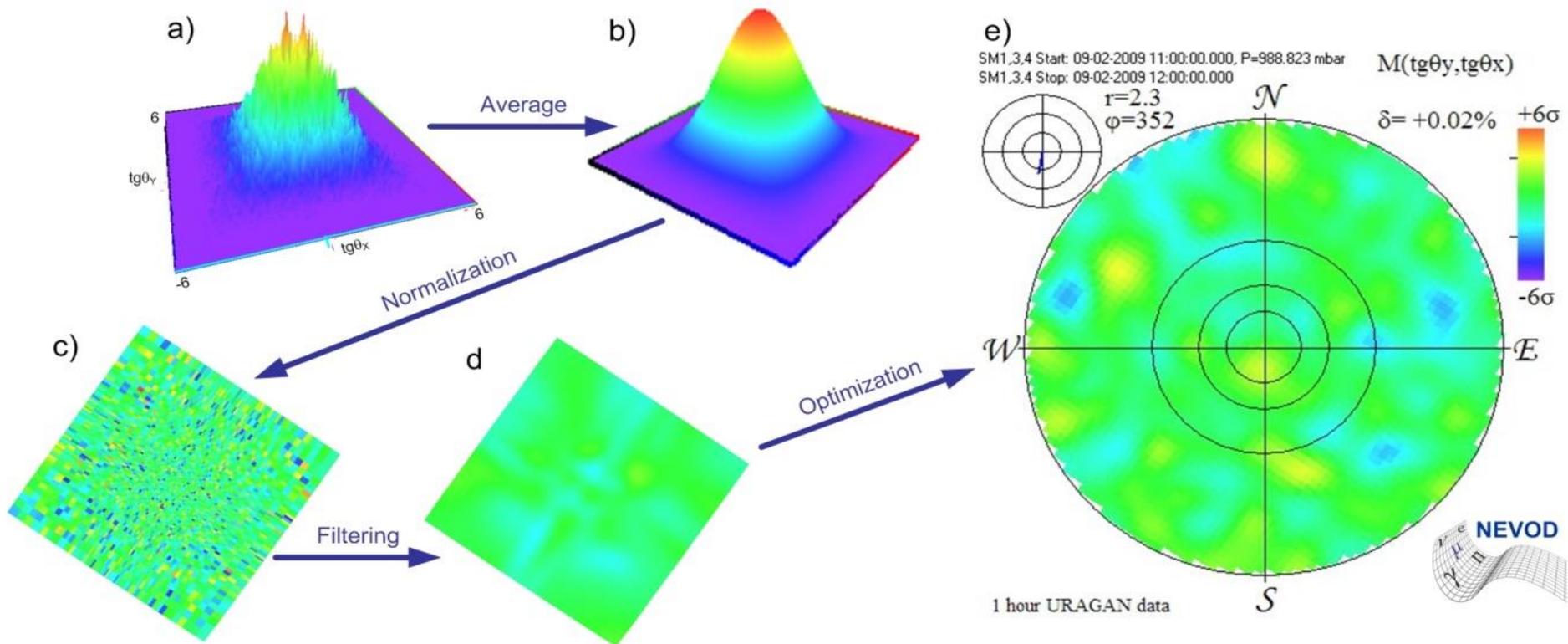
The arrival direction of each muon is determined in real-time. Each event is added in the appropriate cell of the two-dimensional matrix of projection angles having the size of 2 by 2 degrees.

Y projection θ_y 0 θ_x X projection

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).

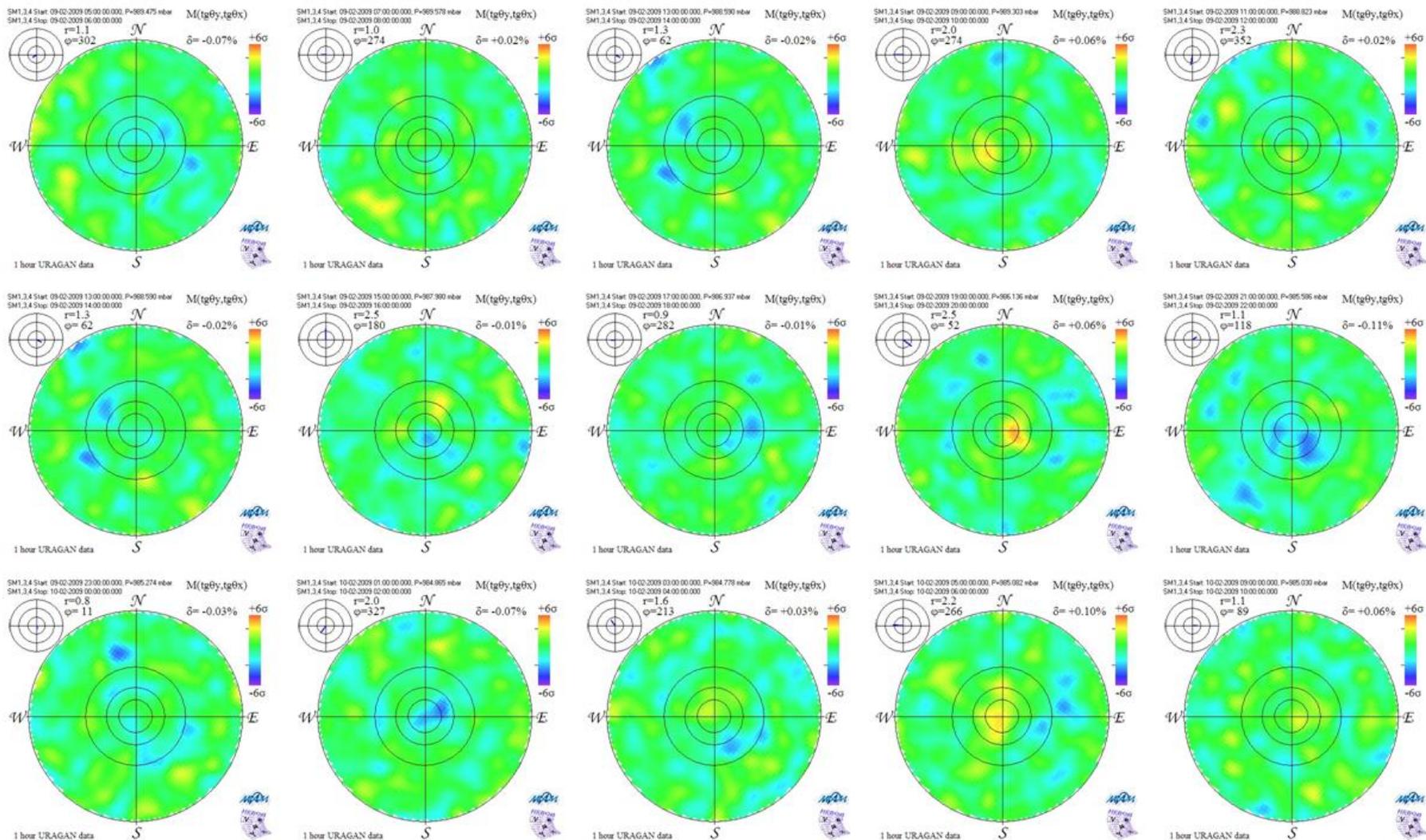# Methods and results of the analysis of FD according to the spatial angular characteristics of the muon flux

To visualize the spatial-angular variations of the muon flux intensity in time, the muonography technique is used. Muonographies allow to study the dynamics of two-dimensional muon flux variations.

Such a matrix is a muonography of the upper hemisphere bounded by the aperture of the detector.

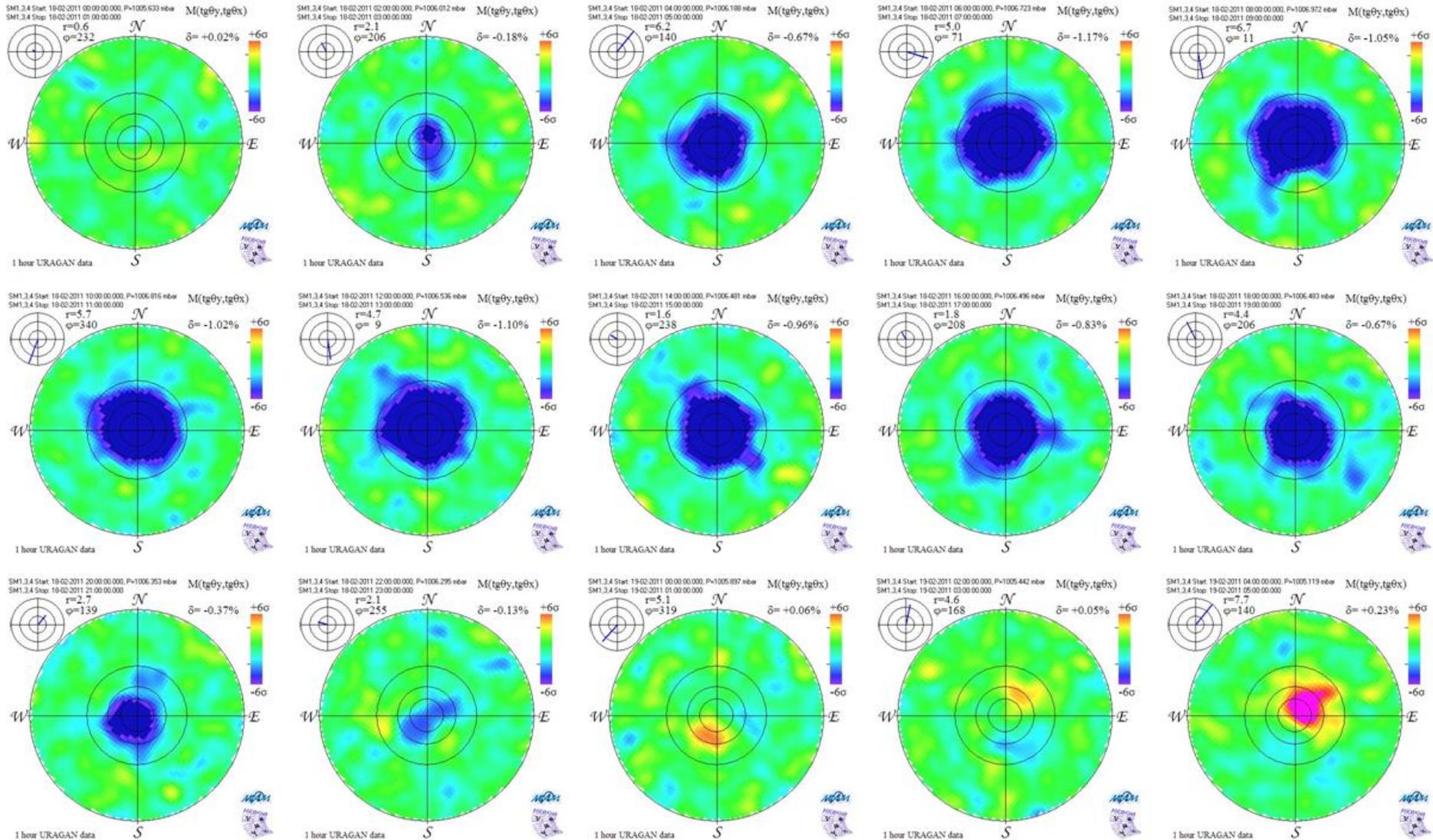# Two-dimensional dynamics of the muon flux in a quiet period

$<V_{SW}> \sim 325$ km/s; $<B_{max}> = 4.5$ nT; $<Dst>=2,5$ nT

Time variations in the muon flux intensity measured with MH URAGAN between 09.02.2009 05:00 and 10.02.2009 10:00 with a 60 minute interval.

Two-dimensional dynamics of the muon flux during FD 18.02.2011
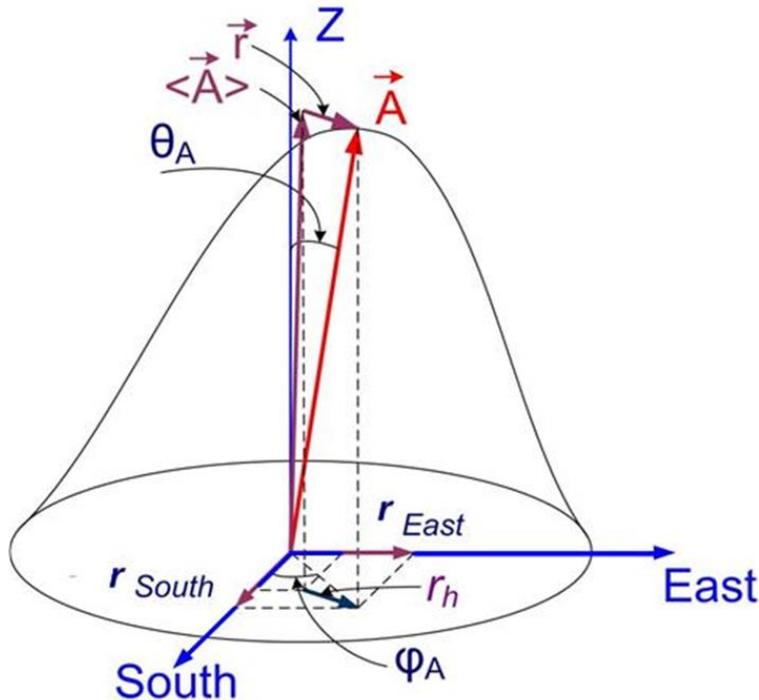
$A_{FD} = 1.36\ \%$, $V \sim 700$ km/s

The rows correspond to three phases of FD with 60 minute increments.
These muonographies give qualitative information about the dynamics of changes in the intensity of the muon flux.

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.

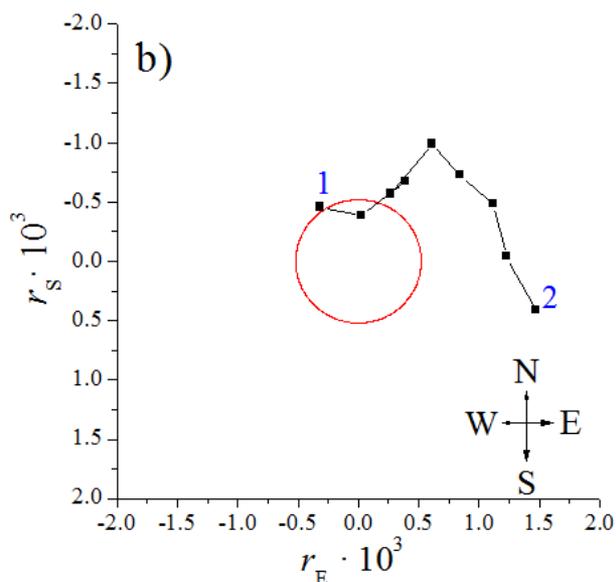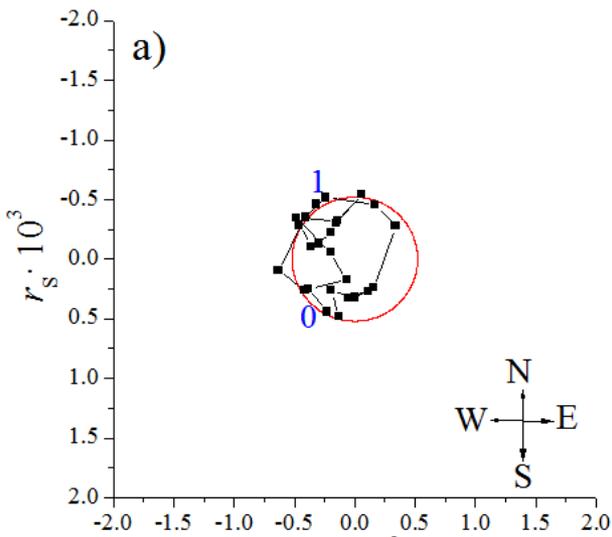$$\vec{r} = \vec{A} - \left\langle \vec{A} \right\rangle$$

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

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

Correlations between projections of the relative anisotropy vector r_E and r_S

FD of June 23, 2013 at four phases of the event development.
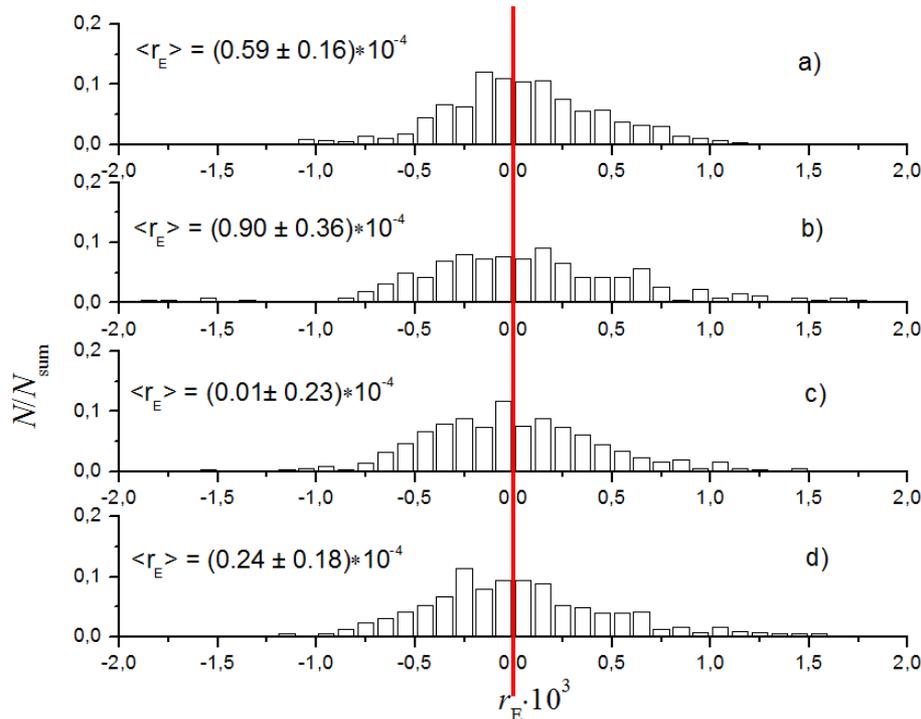Time moments: a) before the beginning of FD; b) decrease; c) minimum; d) recovery.

The circles in the figures correspond to 4σ variation of the r_S and r_E equal to $0.52*10^{-3}$ in a quiet period. An exceedance of the circle limits indicates an appearance of a strong anisotropy.

For this event, the maximum anisotropy was observed in the phase of the decrease, it moves in the direction from West to East, and at the phase of the minimum - vice versa.
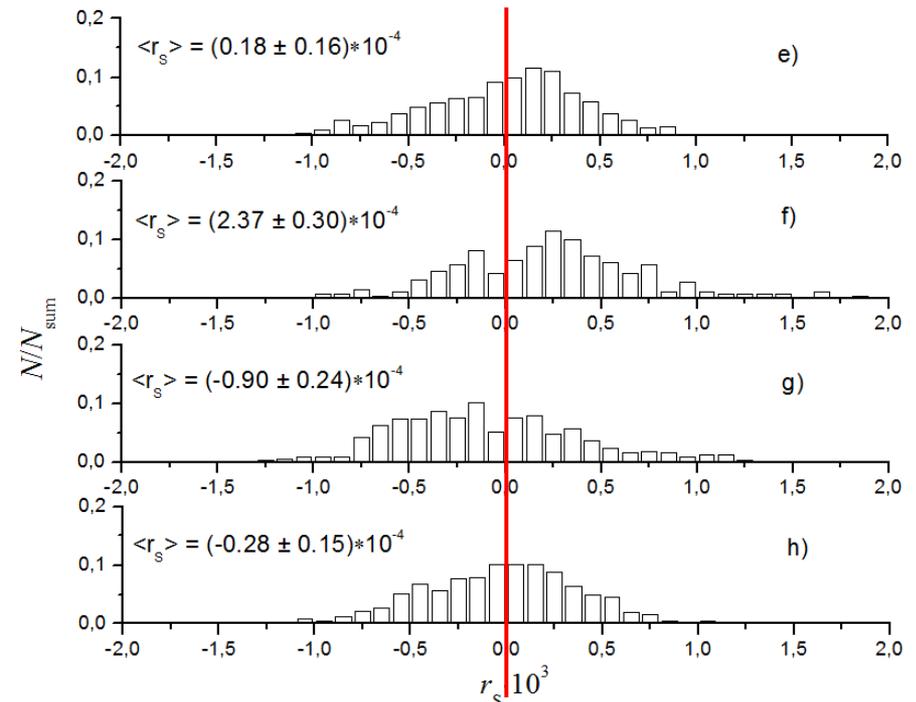
Results of the analysis of projections of the relative anisotropy vector r_E and r_S

Such analysis was conducted for 57 FD (2007 – 2013) and showed that the relative anisotropies exceeding 4σ were observed at all phases of 12 FD, at three phases of 13 FD, at two phases of 12 FD, at one phase of 7 FD, and were absent at all phases of 13 FD.
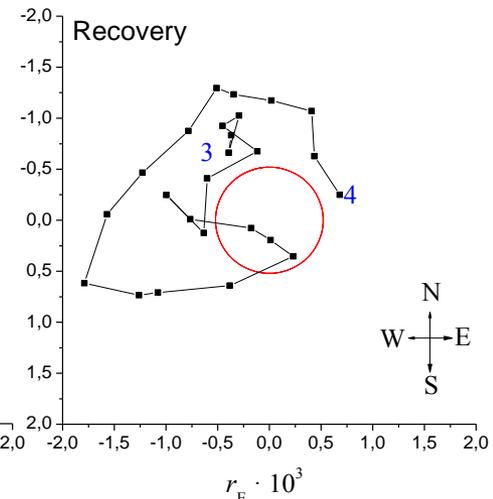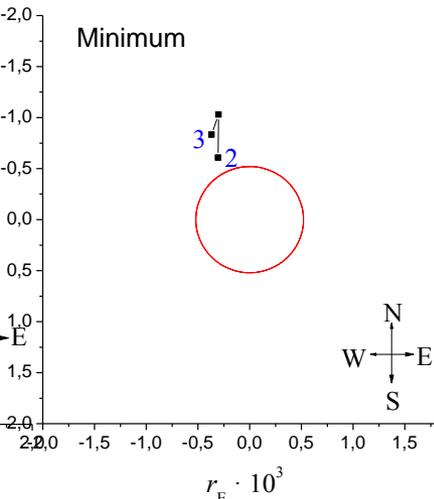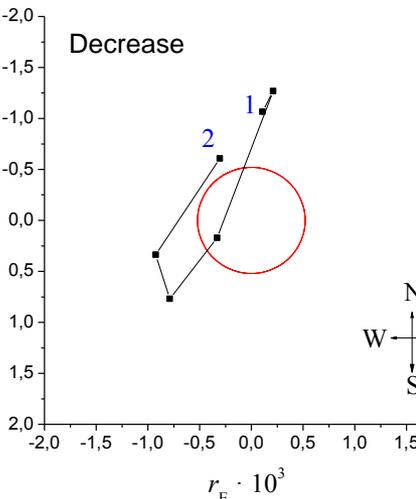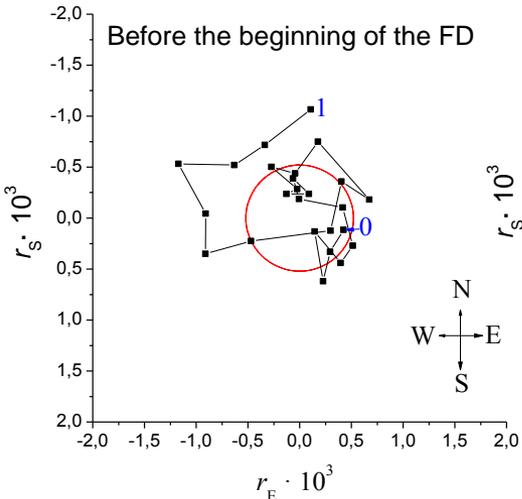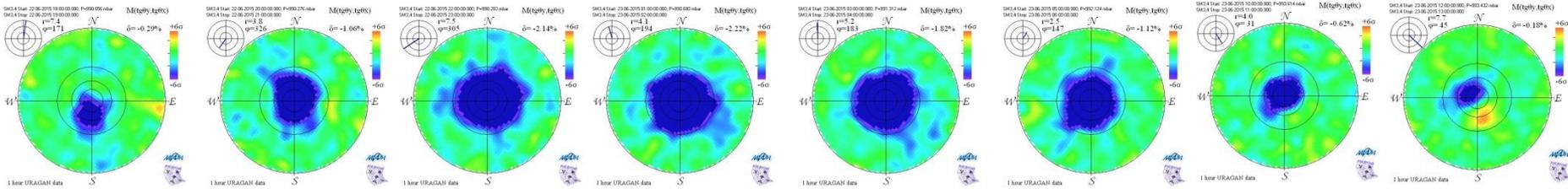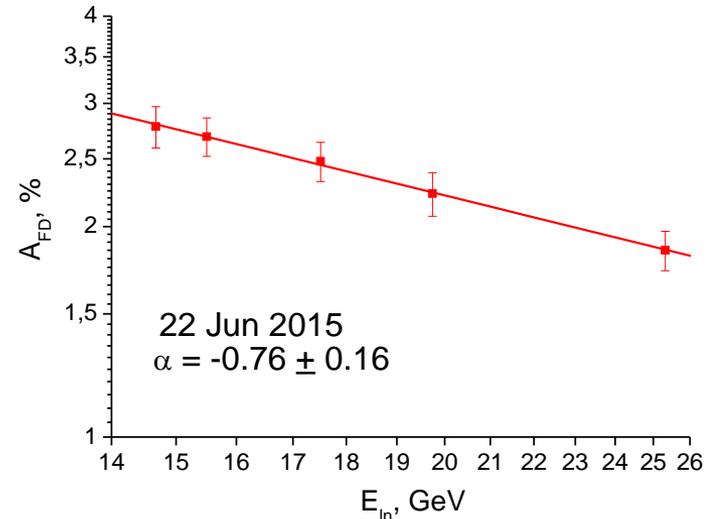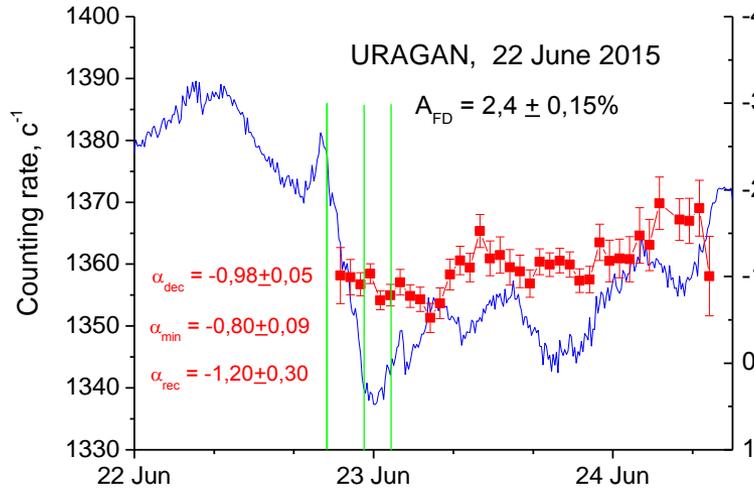

The distributions of the projection r_E are practically symmetrical. The distributions of the projection r_S are clearly shifted at the phase of the decrease to the South and at the phase of the minimum - vice versa. At the other FD phases, the distributions of r_S remain practically symmetrical.

Forbush decrease of 22 June, 2015

Conclusion

1. Muon hodoscope technique and method of muonography allowed to realize a new approach to investigations of Forbush decreases in cosmic rays.

2. The main results obtained by means of the MH URAGAN:

    *   The energy spectrum of muon flux variations during FD is measured by means of the single detector.

    *   This spectrum has a power law character with average index $\alpha = -1.00 \pm 0.48$ in the energy range 10 – 30 GeV.

    *   Correlations between the local relative anisotropy vector projections r_E and r_S for different phases of the FD development were obtained. It was found that there is a shift of the projection r_S to the South during the decrease phase and to the North during the phase of the minimum.

Thank you very much!

http://ununevod.mephi.ru/en/

http://nevod.mephi.ru/English/sample3.php