Studies of magnetosphere perturbations by means of wavelet analysis of atmospheric muon data

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Results of investigations of perturbations in the Earth's magnetosphere with three independent wide aperture muon detectors: DECOR, TEMP and URAGAN situated in the experimental complex NEVOD (MEPhI, Moscow) are presented. Experimental data obtained during 2004-2005 have been analyzed by means of the method of wavelet transformation adapted for processing of very long-term data sequences. Developed technique for calculation of wavelet coefficients and power spectra has allowed to obtain continuous picture of muon variations during a whole considered period in a broad range of frequencies. Analysis of obtained data reveals both stationary cycles concerned with permanent processes like Earth's rotation and localized in time variations caused by effects like Forbush decreases, determining not only their periods but also the moments of their appearance. Preliminary data from the new unique muon detector URAGAN indicate the motion of muon flux asymmetry direction over the sky during the Forbush decrease.

1. Introduction

Magnetic field of the Earth influences many geophysical processes, and studies of the magnetosphere are very important. For this purpose, different methods and apparatus are used. One of the consequences of magnetosphere distortions is the decrease of cosmic ray flux at the surface. At present, such effects are registered by the neutron monitor net. In this work, the perturbations in the magnetosphere are studied on the basis of observation of time and spatial variations of atmospheric muon intensity. Analysis of such data is of great interest for exploration of both atmospheric and extra-atmospheric phenomena. Traditional way of studying of variations is the use of Fourier transform that gives only frequency information. But for the analysis of non-stationary signals, a two-dimensional time-frequency picture is necessary. New method of signal analysis, named wavelet, gives such a possibility. In this work, the method of wavelet transformation is applied for the analysis of experimental data obtained with DECOR, TEMP and URAGAN setups.

2. Apparatus and experimental data

At present, in the experimental complex NEVOD [1] a unique system of muon coordinate detectors that allow to measure cosmic ray muons in a wide range of zenith angles is being operated. The muon hodoscope TEMP [2] has two pairs of coordinate planes (X, Y) with sensitive area of 9 m^2. Separate planes are assembled of narrow scintillator counters-strips (2.5 cm × 1 cm × 300 cm). The total number of counters is 512. The angular resolution is $1 - 2°$. The data are continuously registered as intensity arrays with dimension 255×255 cells.

Coordinate detector DECOR [3] is arranged around the Cherenkov calorimeter NEVOD. The side part of DECOR includes eight 8-layer supermodules (SM) with vertical planes of streamer tube chambers, deployed in a gallery around the water tank. Four supermodules of DECOR are situated on the cover of calorimeter water pool and are assembled of eight horizontal layers, each of 20 streamer tube chambers, interlaid with 10 cm foam plastic. Each chamber contains 16 tubes with 9×9 mm^2 inner cross section and 3.5 m length integrated in PVC box. Total area of each SM of the top part of DECOR is about 11 m^2. Every layer of streamer tube chambers is equipped with two-coordinate external strip readout system (320X+ 288Y

channels with 1.0 and 1.2 cm pitch respectively). The angular resolution is about 0.7°. Triggering system of DECOR has two levels and is intended for effective registration of single muons and muon groups. For the present analysis, the coincidences between signals from any side DECOR supermodule and any top DECOR SM (trigger #9) are used. Such condition provides registration of muons with $E > 1$ GeV. Total rate of trigger #9 is about 90 s^{-1}. To reduce the volume of registered data, only one of every 64 events is recorded.

In 2005, on the basis of top DECOR supermodules a new multipurpose muon detector URAGAN [4] has been constructed. Setup provides particles detection in a wide range of zenith angles (from 0 to 80 degrees) with spatial and angular accuracy about 1 cm and 1 degree, correspondingly. For continuous monitoring of the atmosphere, new electronics with possibility of every muon detection was developed and manufactured. Such system allows to register total muon rate and to reconstruct muon track characteristics in the on-line mode. Every SM of URAGAN is equipped with a computer for data acquisition and data processing.

The system of three independent detectors operating in one experimental complex gives a possibility to analyze variations of muon flux with different threshold energies and to compare them with each other. For the analysis, data collected during 2004 and 2005 experimental runs are used. In 2004, two coordinate detectors (DECOR and TEMP) were operated. Experimental data sequences of 10-minute counting rates of both setups during January 2004 are presented in Fig. 1. Correction for the barometric effect was evaluated and introduced. This period of observations is especially interesting since strong perturbations of the Earth's magnetic field occurred, like Forbush decreases on January 7 and 22. For comparison, data of Moscow neutron monitor station (IZMIRAN, Troitsk) [5] are presented. From the figure, one can conclude that our muon detectors are sensitive to muon intensity variations caused by Forbush effects, though the relative decrease is less than that for neutron rate (approximately two times).
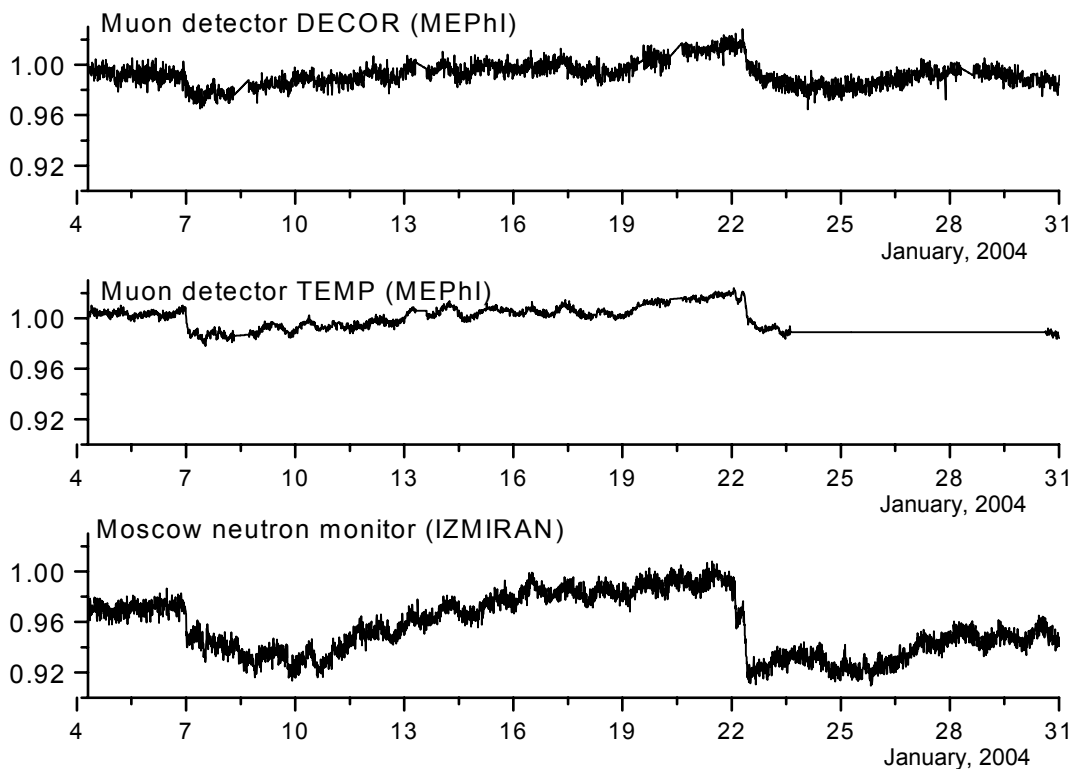

Figure 1. Variations in the counting rate of muon detectors DECOR and TEMP (MEPhI, Moscow) and Moscow neutron monitor station (IZMIRAN, Troitsk) over January 2004.

3. Data analysis

For the analysis of experimental data, wavelet transformation technique is used. Wavelet transformation is constructed on the basis of functions $\psi_{a,b}(t)$ given by continuous scale transforms and shifts of wavelet prototype function, or "mother wavelet" $\psi(t)$, with arbitrary values of basis parameters (scale coefficient a and shift parameter b). Any function can be presented as a superposition of wavelets, and coefficients of wavelet transform can be written in the following form:

$$C(a,b) = \int_{-\infty}^{\infty} f(t) \cdot \psi_{(a,b)}(t) \, dt, \quad \psi_{a,b}(t) = 1/\sqrt{a} \cdot \psi\left(\frac{t-b}{a}\right), \tag{1}$$

where $f(t)$ is the analysed signal. In our analysis, the modified Morlet wavelet is used as a mother wavelet:

$$\psi_{modMorlet} = \frac{1}{\sqrt{\pi^{1/2}\sigma}} \cos(\omega_0 t) e^{-\frac{t^2}{2\sigma^2}}, \quad \sigma = N\frac{2\pi}{\omega_0}, \tag{2}$$

based on widely-used Morlet ansatz [6]. Such modification allows to change wavelet own frequency in a broad range. In this work the value $\omega_0 = 8$ Hz is used. The parameter N defining the number of oscillations under the Gaussian function was chosen equal to 5. For unification of contributions of various periods with equal amplitudes, the wavelet coefficients were divided by the factor $\sqrt{2\pi a / \omega_0}$.

The investigated data were separated in two types of signals: long-periodical (larger than 6 hours) obtained by a smoothing procedure with 6-hour sliding window, and short-periodical ones which are the difference between the original signal and a smoothed sample. In Fig.2a, data from DECOR during first half of 2005 (black line) and their smoothed dependence (grey line) as well as wavelet coefficients for periods 6–36 hours are shown. Below, a short-periodical constituent during May 2005 and its wavelet image are presented.
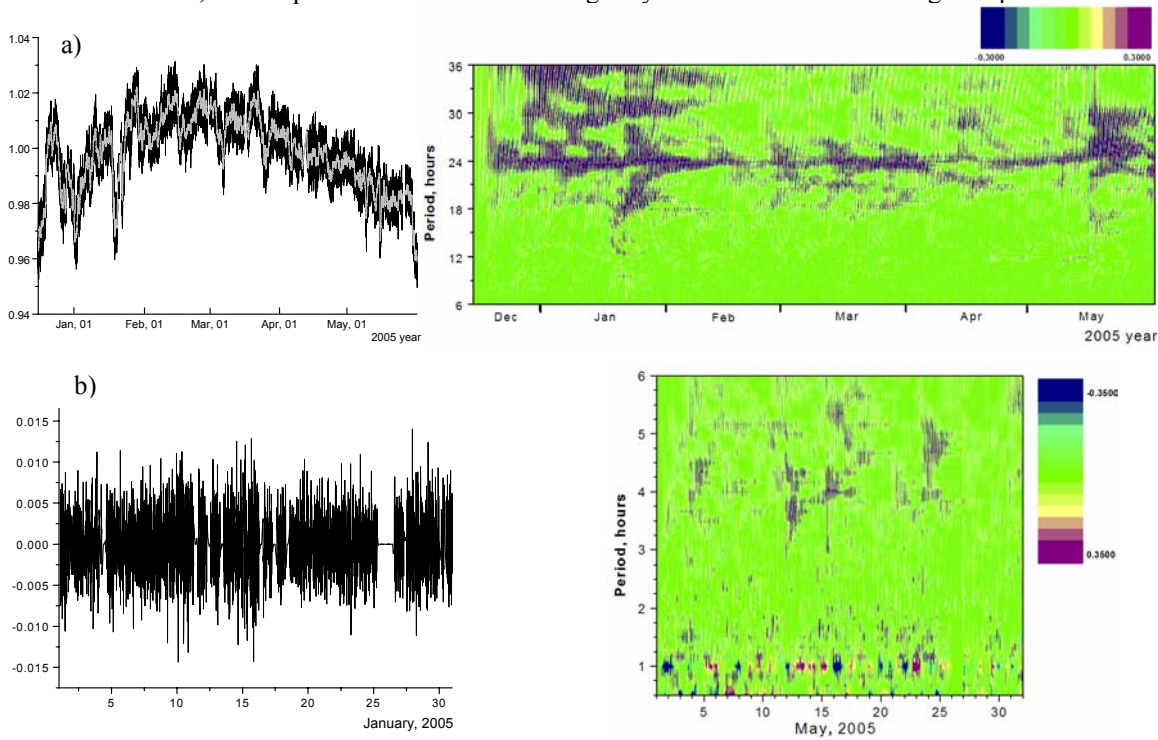

Figure 2. a) The counting rate of DECOR with a smoothed line (grey) and its wavelet image during the first half of 2005, b) short-periodical constituent and its wavelet image during May 2005.

4. Discussion

In Figure 2a, a 24-hour cycle related with the Earth's rotation is clearly observed. Apparently, the strong Forbush decreases on January 17–19 and May 15 are visible. From the picture of wavelet coefficients of short-periodical data during May 2005, a fine structure of muon flux variations during the Earth's magnetic field perturbations (May 8, 15 and 29) is revealed. But such results demand a further analysis as new Forbush decreases happen and the statistical material becomes more rich.

The new muon detector URAGAN launched in March 2005 allows to investigate a spatial-angular structure of muon flux. In Fig.3, the preliminary URAGAN data on anisotropy of muon flux during the Forbush decrease of May 15 are shown. The results have been obtained by summation of muon numbers from 25° to 65° zenith angles for separate azimuth angle φ bins. Coordinate system is attached to the NEVOD calorimeter with X-axis directed to south-west. From the figure, the change of muon flux asymmetry direction approximately by 60 degrees (from 180° to 120°) is seen. Such variations can be explained by the Earth rotation (during four hours) relatively to solar plasma cloud coming to the Earth.
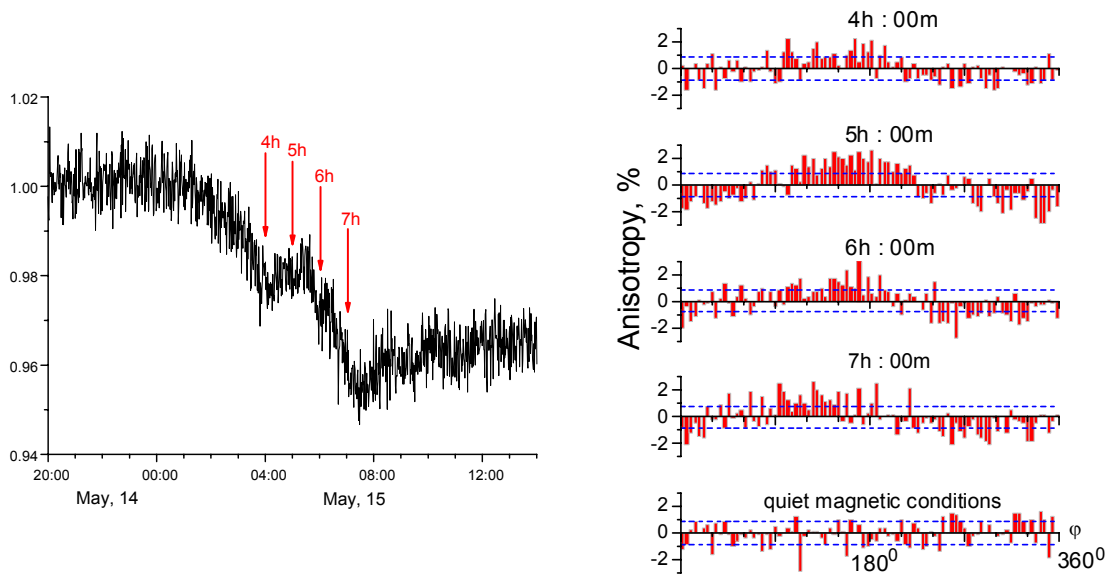

Figure 3. Preliminary URAGAN data on anisotropy of muon intensity during Forbush decrease of May 15, 2005.

4. Acknowledgements

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