Variations in the intensity of muon bundles detected at the ground level

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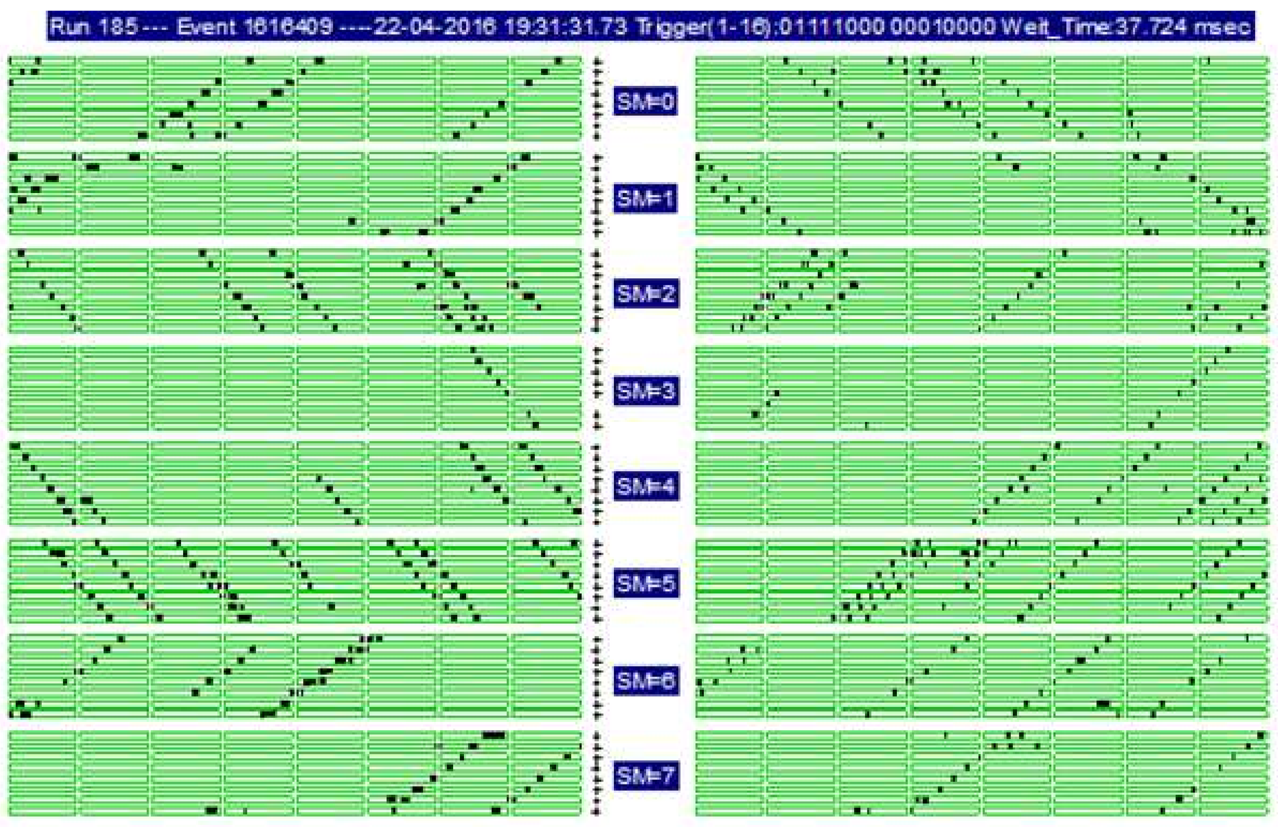
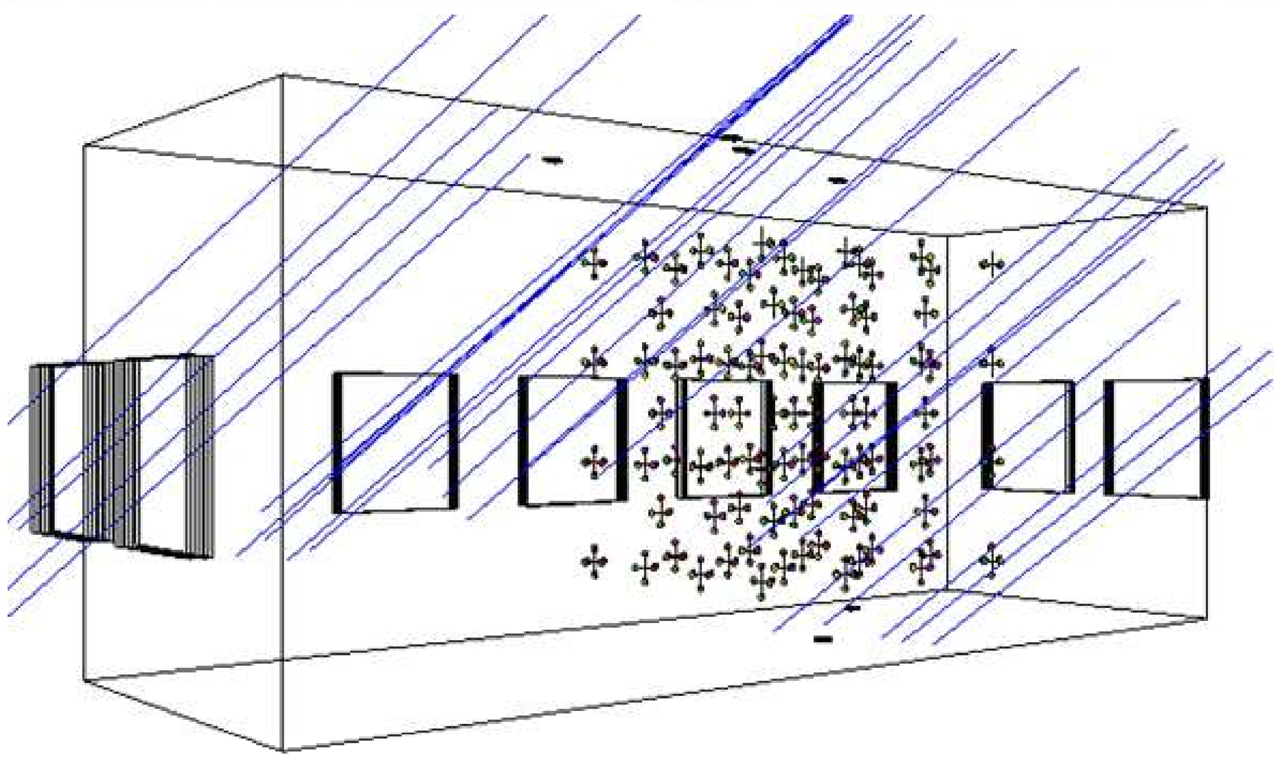
Poster 36

Abstract. Experimental data on muon bundles collected with the coordinate-tracking detector DECOR for the period from May 2012 till February 2017 are analyzed. Events containing at least three muons were selected. Such events are formed as a result of interactions of primary cosmic ray particles with energies more than about 1 PeV. The counting rate of the bundles exhibits significant variations related with atmospheric conditions. Seasonal changes of muon bundle intensity, barometric and temperature effects, and correlations with altitudes of various levels of the residual atmospheric pressure are considered.

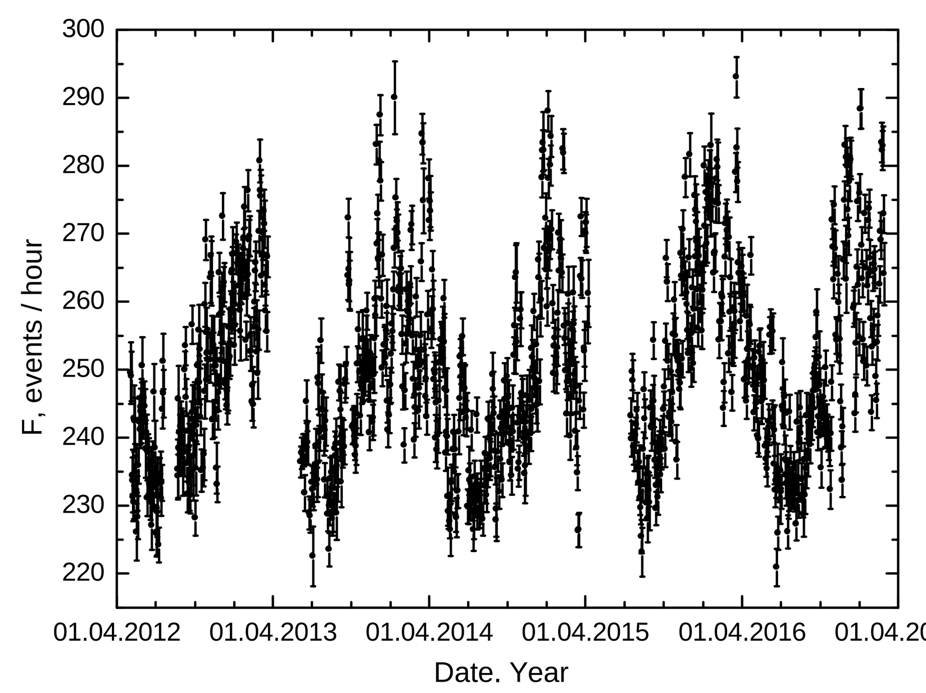
Experimental setup and data

DECOR consists of eight supermodules (SMs) deployed around the Cherenkov water detector NEVOD (MEPhI). Each supermodule includes eight vertical planes of streamer tube chambers. Total area of DECOR is about 70 sq. m. Angular accuracy of muon track reconstruction in the SM is better than 1 degree. An example of muon bundle event detected in DECOR and its geometry reconstruction are shown in the figures.



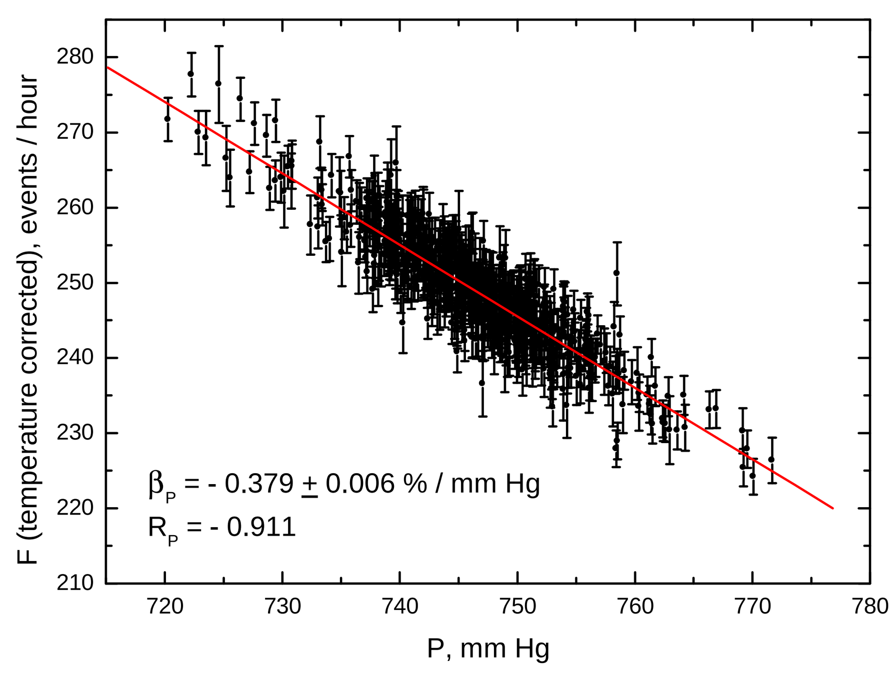


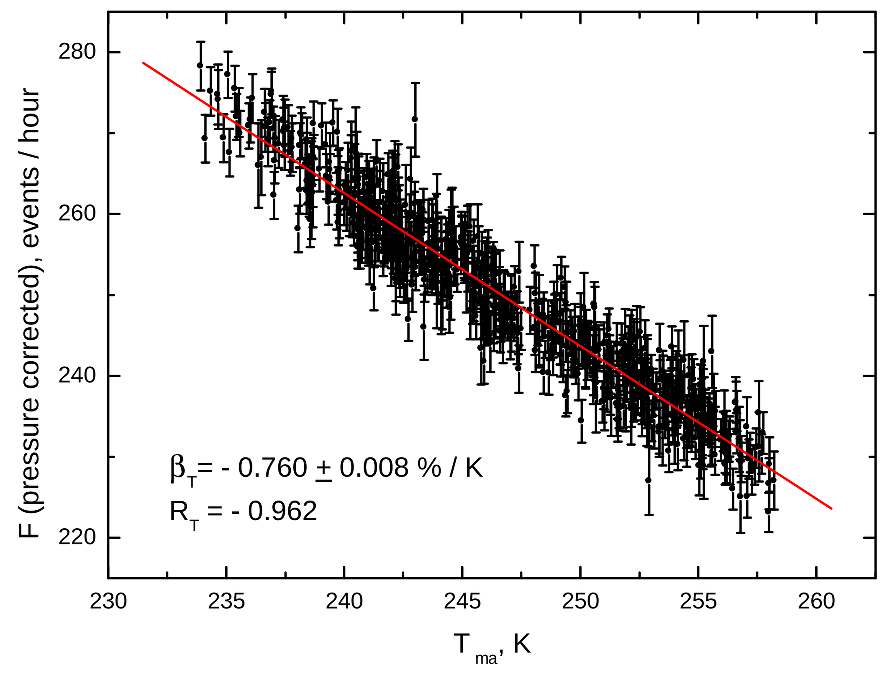
Muon bundles containing at least 3 quasiparallel particles detected in 3 different DECOR SMs have been analyzed. A typical counting rate for such events is about 250 per hour. The interval of zenith angles from 21 to 65 degrees contains about 90 % of the bundles; the median zenith angle is close to 42 degrees. Data from three long-term measurement series conducted in the period from May 2012 to February 2017 have been used. In all, they include 939 data sets (runs) with duration from 10 to 40 hours, 7.3 million events, 29.2 thousand hours live observation time. Variations of the measured counting rate of muon bundles during the five-year period are shown in the figure. Every point represents a separate data set (with statistical errors).



Barometric and temperature effects

The measured event rate exhibits clear seasonal variations. On the average, the intensity of muon bundles detected in summer and in winter differs by more than 10 %; maximal intensity is usually observed in January, and the minimal one in July. On the background of the seasonal changes, short-term variations with duration of few days are seen. The spread between minimal and maximal event rates reaches 25 - 30 %. It is naturally to assume that these changes are related to atmosphere conditions. The next figures represent correlations of the event rate with barometric pressure and mass-average temperature of atmospheric air.





The absolute values of barometric and temperature coefficients appeared unexpectedly high (2 - 3 times higher than corresponding coefficients for single muons). Taking into account that the average energies of muons comprising the bundles at the ground level are of the order of tens GeV, it is impossible to explain observed effects in frame of usual mechanisms related with absorption and decay of low energy particles in the atmosphere.

Geometrical mechanism of bundle intensity variations

Alternative explanation of variations in the muon bundle intensity was suggested in our papers earlier (N.V. Tolkacheva et al. Bull. RAS: Physics. 2011. V. 75. No. 3). Detection of the bundles with a setup small compared to EAS dimensions corresponds to selection of events according to the local muon density. With some simplifying aproximations, the integral local muon density spectrum can be evaluated as:

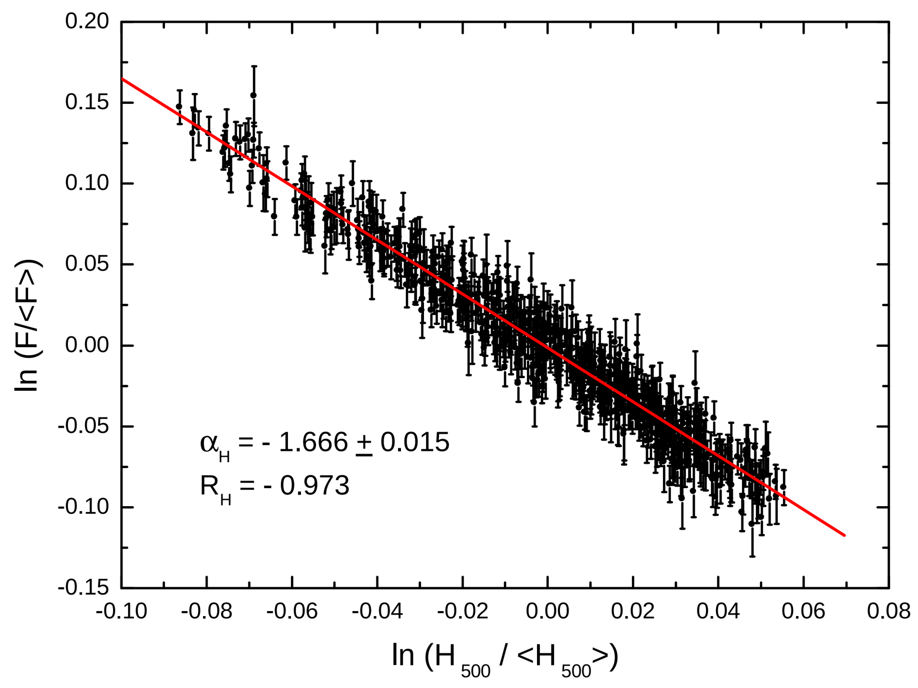
$$F(\ge D) = N_0 D^{-\beta} \int [\rho(E_0, \mathbf{r})]^{\beta} dS \ ,$$

where $\rho(E_0, \mathbf{r})$ is the lateral distribution function (LDF) of EAS muons, E_0 is some effective primary energy, $\mathbf{r}$ is the point in the shower cross section, and β is the slope of the local muon density spectrum.

Muons are created near the EAS core, and their spread at the ground level is determined mainly by transverse momenta at production and decay of parent mesons, and is also proportional to the generation altitude. Changes in the state of the atmosphere (ground level pressure, air temperature profile, etc.) lead to variations of the geometrical altitude of muon bundle formation, and hence to scaling variations of muon LDF at the observation level. In these circumstances, the event intensity should follow a power law

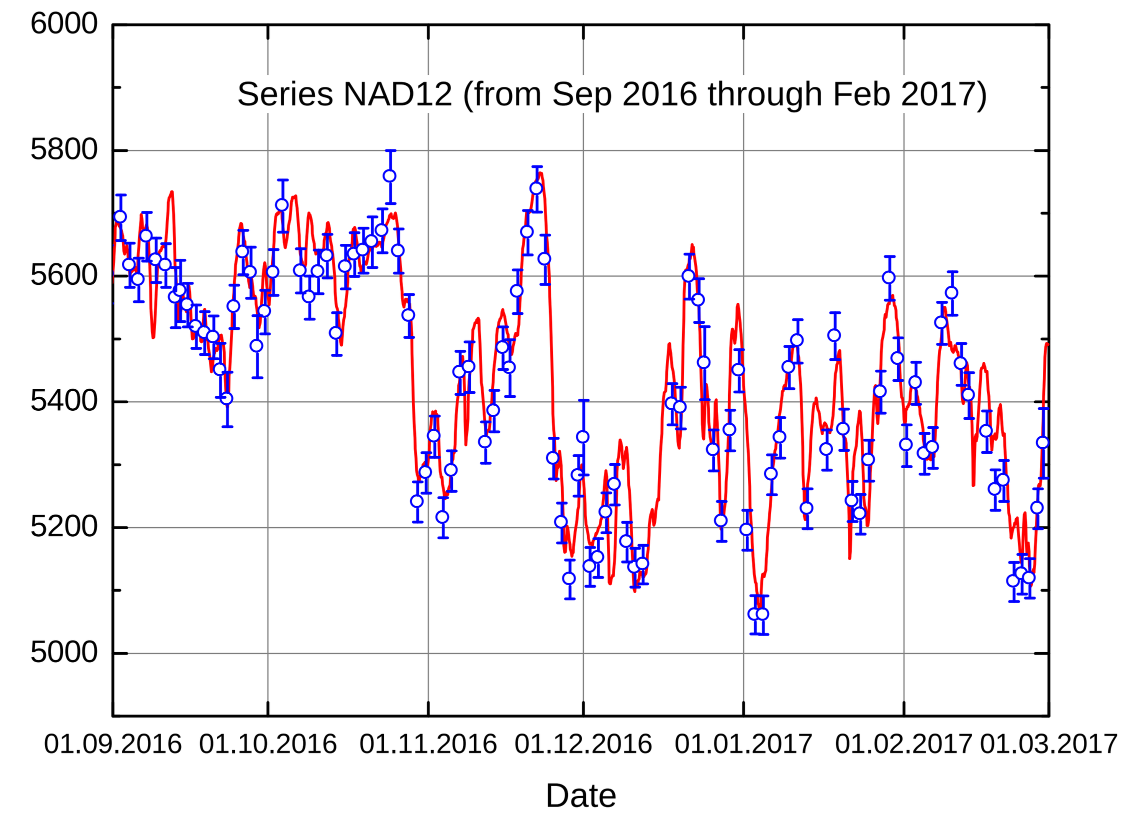
$$F(\ge D) \sim (H / \langle H \rangle)^{\alpha}, \ \alpha = -2\,(\beta - 1) \ ,$$

where H is the effective altitude of generation of the bundle muons. In the next picture, correlations of the muon bundle counting rate with the altitude of a level corresponding to 500 mb residual pressure (500 mb isobar surface) are presented in a double-log scale. The line in the figure corresponds to a power law fit of the event rate. The value of the correlation coefficient (R_H = - 0.973) evidences for almost functional relation between muon bundle intensity and 500 mb isobar surface altitude. All measured points, including extremely low and extremely high ones, lie close to the power law approximation. The power law index α = - 1.67 is in a good agreement with the expected one if we take into account the independently estimated local muon density spectrum slope ($\beta \approx$ 1.9, or $\alpha \approx$ - 1.8). Thus, the considered mechanism of muon bundle intensity variations is in a good qualitative and quantitative agreement with measurement results.



An "inverse" task

Close correlations between muon bundle frequency and some of the atmospheric parameters allow us to consider an inverse task, for example, estimation of isobar surface altitude from the measured event rate. The points in the next figure represent the altitudes of 500 mb residual pressure level reconstructed from DECOR muon bundle data for the period Autumn 2016 - Winter 2017. The curve in the figure corresponds to the data of independent meteorological observations (taken from retrospective GDAS database). The agreement is impressive!



Conclusion

A simple geometrical model of variation mechanism, based on a concept of a scaling transformation of the lateral distribution function of EAS muons in a varying atmosphere, explains well the observed changes in the intensity of muon bundles at the ground level.

The work has been performed at the Unique scientific facility Experimental complex NEVOD with a state support from the RF Ministry of Education and Sciense (contract RFMEFI59114X0002, MEPhI Academic Excellence Project, and government task).