NEVOD-DECOR experiment: results and future

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Abstract. Russian-Italian NEVOD-DECOR experiment on the measurements of the local muon density spectra (LMDS) at various zenith angles gave possibility to obtain information on primary cosmic ray flux and interaction characteristics in a record wide energy range from $10^{15}$ to more than $10^{18}$ eV. Comparison of the measurement results with CORSIKA-based simulations showed the increase of LMDS slope at PeV energies of primaries (corresponding to the first knee); a trend to a heavier primary mass composition above the knee; indication for a second knee (a further increase of the spectrum slope near $10^{17}$ eV). At large zenith angles and high muon densities (corresponding to primary energies around $10^{18}$ eV) a considerable excess of muon bundle events in comparison with the expectation based on independent estimates of the primary spectrum and widely used hadron interaction models has been found. In 2011, a new phase of measurements of the energy spectrum of cascade showers initiated by high-energy muons in water and of the energy deposit of muon bundles at various zenith angles and muon multiplicities started. Further plans include the deployment of a traditional EAS array around the NEVOD-DECOR complex.

1. Introduction

The first cooperation agreement between MEPhI and Italian scientific institutions (Institute of Cosmogeophysics, Torino, and Torino University) was signed 20 years ago, in 1992. The main objective of this cooperation was the construction of the large area coordinate-tracking detector DECOR around the Cherenkov water calorimeter NEVOD [1] (MEPhI) for investigations of multi-particle cosmic ray events at large zenith angles. For this purpose, streamer tube chambers, front-end electronics and other equipment used earlier in the NUSEX experiment [2] were delivered in Moscow. After development of the mechanical construction of the detector and elaboration of new triggering and data acquisition systems, the first experimental assembly (supermodule) consisting of eight vertically suspended planes of streamer tube chambers was deployed in the gallery of the NEVOD building [3]. The first experiments with this supermodule confirmed a good reliability of detection and separation of inclined muon bundles originated in the atmosphere by high-energy cosmic rays [4]. Construction of the side part of DECOR (eight supermodules) was completed in 2001 [5]. During 2002-2007, long-term series of measurements on registration of cosmic ray muon component (about
20,000 hours net operation time) with NEVOD-DECOR experimental complex were conducted, and unique experimental data on zenith angular dependence of muon bundle intensity with particle multiplicities from 3 to about 100 were obtained. Application of a novel approach to the analysis of experimental data on muon bundles based on the phenomenology of local muon density spectra (LMDS) [6, 7] allowed obtaining information about primary cosmic ray flux and interaction characteristics in a record wide energy range from $10^{15}$ to more than $10^{18}$ eV. In this paper, the description of basic results of multi-muon event analysis is presented, and also the current status and nearest perspectives of experimental investigations with the NEVOD-DECOR complex are outlined.

2. Experimental data
A general layout of the NEVOD-DECOR experimental complex is shown in figure 1. The detecting system of Cherenkov water detector NEVOD with a volume 2000 m$^3$ is formed by a spatial lattice of quasi-spherical optical modules (QSMs), each of them consisting of six photomultipliers with flat 15 cm diameter photocathodes directed along rectangular coordinate axes. Such construction provides nearly isotropic sensitivity to Cherenkov light; at the same time, amplitude responses of the PMTs allow determining the light arrival direction. Modules are hanged on the vertical strings (3 or 4 QSM in each). The distance between the modules in the string is 2 m; the string planes (consisting of 9 or 16 QSM respectively) are located with spacing 1.25 m along the water tank and 1 m across it. Thus, the detecting lattice has a nearly cubic shape; in total, it includes 91 QSM. NEVOD is equipped with a calibration telescope system (CTS); 40 scintillation counters with dimensions 20×40 cm$^2$ are placed on the roof of the water tank, and 40 ones on the bottom. CTS provides the possibility of QSM response calibration for 1600 different trajectories of muons crossing the water volume.

Figure 1. General layout of the NEVOD-DECOR experimental complex.

The side part of the coordinate-tracking detector DECOR is deployed in the galleries of the NEVOD building, from three sides of the water tank. Two pairs of supermodules (SM) are located in the opposite short galleries, and four supermodules in the long gallery. Each SM has an effective area 8.4 m$^2$ and consists of eight planes of streamer tube chambers with resistive cathode coating hanged vertically with 6 cm spacing. The chambers are operated in a limited streamer mode with a continuous gas flow of (Ar + CO$_2$ + n-pentane) mixture. The length of the chambers is 3.5 m, inner tube cross section is 9×9 mm$^2$. The planes of the chambers are equipped with a two-dimensional system of external readout strips (256 X- and 256 Y-channels in each plane with 1.0 and 1.2 cm pitch respectively). As a first-level trigger condition of the SM, a 4-fold coincidence of signals from at least 2 odd and 2 even planes is used. The accuracy of the reconstruction of the tracks crossing the SM is about 1 cm in space and better than 0.7º and 0.8º for projected zenith and azimuth angles, correspondingly.
The upper part of DECOR consists of four eight-layer SMs, each with area 11.5 m$^2$, deployed horizontally on the movable platforms on the roof of the NEVOD water tank. In 2005, on the basis of the upper DECOR supermodules a wide-aperture precise muon hodoscope URAGAN [8] was created, which is now being used for the development of the technique of the muon diagnostics of the heliosphere, the Earth’s atmosphere and near-terrestrial space [9] and solution of various tasks related with cosmic ray flux variations [10, 11, 12].

In 2002 – 2007, long series of measurements with NEVOD-DECOR complex were conducted. Net operation time for good quality data with the full configuration of the side DECOR (eight supermodules) amounted to 19,922 h. The basic set of event selection conditions, based on the coincidences of the signals between different parts of the coordinate detector, NEVOD QSM lattice and CTS signals, was kept unchanged during the measurements. Selection of inclined muon bundles from DECOR data is based on the fact that tracks of muons originated in the atmosphere (far from the detector) are nearly parallel. The muon bundle selection procedure included several stages: hardware trigger condition of the coincidence of signals from at least 3 supermodules of the side part of DECOR; program reconstruction of tracks in the SM and soft program selection of muon bundle candidates, containing a certain minimal number of quasi-parallel tracks; final event classification and muon track counting by the operators. The latter procedure is rather laborious; therefore the data were analyzed part by part, for certain ranges of multiplicity and zenith angle. A more detailed description of the experimental data treatment is given in [13]. In all, about 40 thousand events in different ranges of muon multiplicities (from 3 to about 100) and zenith angles (from 30º to almost a horizon) have been analyzed. Phenomenological distributions of muon bundles in particle multiplicity for several zenith angle intervals and in zenith angle for 3 values of the minimal number of muons are presented in figure 2. As it is seen from the figures, the obtained data on muon bundles cover about 6 orders of magnitude in the event intensity.

![Figure 2](image)

**Figure 2.** Integral distributions of muon bundles in particle multiplicity for several ranges of zenith angle (left) and zenith angle distributions of the bundles with different minimal number of muons (right).

### 3. Local muon density spectra: results and discussion

At large zenith angles (more than 50 - 70º, depending on primary particle energy) EAS are detected on the ground level as practically pure muon component. Due to a large distance from the shower generation point to observation level, transverse dimensions of EAS in muons rapidly increase with zenith angle, the effect being additionally enhanced by the particle deflection in the geomagnetic field. Therefore, a muon detector with sizes of the order of tens meters may be considered as a point-like probe. In an individual event, the local density of EAS muons (at the observation point) may be estimated as the ratio of muon bundle multiplicity $m$ to detector area for a given direction: $D \sim \frac{m}{S_{\text{det}}}.$
Contribution to events with a certain muon density give showers with different primary energies, detected at different (random) distances from the axis. However, due to a fast decrease of primary cosmic ray (PCR) intensity with the increase of energy, the effective primary energy band appears relatively narrow (see figure 3). It is important to mark that at different zenith angles the events with a fixed muon density are formed by primary particles with substantially different energies. At that, the event collection area is determined not by the detector size, but by the dimensions of EAS in muon component which near the horizon reach several kilometers. Two last circumstances allow one to explore a very wide range of PCR energies by means of LMDS method in a single experiment with a relatively small detector. The dependence of the effective EAS collection area on zenith angle is presented in figure 4. Noteworthy, the estimates of $S_{\text{eff}}$ only slightly depend on assumptions about primary composition, hadron interaction model and the range of primary energies. On the other hand, at large zenith angles an important role plays the Earth magnetic field (EMF) and $S_{\text{eff}}$ is sensitive to the field strength and direction. For zenith angles more than 80°, $S_{\text{eff}}$ exceeds 1 km$^2$ which is sufficient to collect acceptable event statistics at energies near $10^{18}$ eV.

![Figure 3.](image-url) Distribution of primary cosmic ray particle energies contributing to events with a fixed muon density ($D = 0.2$ muons/m$^2$) at different zenith angles. Solid curves correspond to calculations for primary protons, a dashed curve for iron nuclei.

![Figure 4.](image-url) Dependence of the effective EAS collection area in the LMDS technique on zenith angle [14].
Distributions of the events in muon density – local muon density spectra – are sensitive to the shape of the spectrum of primary cosmic rays. Similarly to the spectrum of EAS in the number of muons, LMDS vary (mainly in absolute intensity) with the primary mass composition. Finally, local muon density spectra are formed mainly by the central part of the EAS and are determined by the most energetic muons (and the most energetic parent hadrons) propagating near the shower axis; hence, they carry additional information about the forward kinematical region of hadron interactions. A comprehensive description of the phenomenology of the LMDS technique and features of its application to the analysis of DECOR data on muon bundles was recently published in [13].

A general approach to the analysis of muon bundle data includes the following steps: reconstruction of local muon density spectra in a detector-independent form from the measured distributions of muon bundle characteristics, taking into account Poisson fluctuations of the number of muons that hit the setup, triggering and selection conditions, detector efficiencies, etc.; calculation of the expected LMDS for various assumptions about the primary spectrum, mass composition and hadron interaction models on the basis of 2-dimensional muon lateral distribution functions (LDF) simulated by means of the CORSIKA code [15] taking into account geomagnetic field effects; comparison of data with calculation results.

In figure 5, experimental LMDS reconstructed from DECOR data on muon bundles are compared with CORSIKA-based calculations for 4 different zenith angles (35°, 50°, 65°, and 78°). As a model of the primary flux for the comparison, a power type energy spectrum with differential slope 2.7 below the knee energy (4 PeV) steepening to (γ+1) = 3.1 above the knee was assumed; absolute normalization was chosen according to the bulk of experimental data around the knee presented in the

![Figure 5](image_url)

*Figure 5*. Measured (points) and calculated differential local muon density spectra for 4 zenith angles (labels in the frames). Thin lines represent partial power fits of the data between $10^{16}$ and $10^{17}$ eV (integral spectrum slope $\beta_1$), and above $10^{17}$ primary energy ($\beta_2$).
As it is seen from the results for the moderate zenith angles (θ = 35°, upper left frame), at energies around the knee the experimental LMDS is in a reasonable agreement with calculations, including the absolute normalization. The increase of the LMDS slope related with the knee in the primary spectrum is clearly seen. This result may be considered as an indirect check of the energy scale calibration.

At effective primary energies $E_0 > 10^{16}$ eV (zenith angles 50° and 65°), a progressive increase of LMDS in comparison with calculations is observed, which can be interpreted as a trend to a heavier mass composition, though an alternative interpretation related with increasing deficit of muons in simulated EAS is also possible. Near $10^{17}$ eV, a hint for a second (possibly, “iron”) knee was found [17]: partial fits of the data obtained at zenith angle 65° below and above this energy indicate the increase of the integral LMDS slope β by 0.20 ± 0.09. This result is also in quantitative agreement with slope estimates derived from the data at other zenith angles (thin lines in the figures, the intervals of $E_0 = 10^{16} - 10^{17}$ eV for 50° and $E_0 > 10^{17}$ eV for 78°). Combining statistically independent data for different angles, we obtain $\Delta \beta = 0.15 ± 0.04$. Taking into account the relation between the LMDS slope β and the integral primary energy spectrum index γ (β ~ γ/0.9) [13], it corresponds to the increase of the primary spectrum slope by $\Delta \gamma = 0.13 ± 0.04$. Later, conclusion about the steepening of the all-particle cosmic ray spectrum near $10^{17}$ eV was confirmed by the KASCADE-Grande experiment: the increase of (γ + 1) from 3.02 to 3.24 ± 0.08, or $\Delta \gamma = 0.22 ± 0.08$, was revealed [18].

Finally, data points at high muon densities and the largest zenith angle (78°), which correspond to primary energies around $10^{18}$ eV, lie near the upper edge of the calculation uncertainty band, and even somewhat exceed the expectation for pure iron flux.

The relation between the local muon density spectrum and the primary cosmic ray flux is determined by the muon LDF, which in its turn depends on the hadron interaction model and primary particle type. Therefore, under certain assumptions about primary mass composition and hadron interaction model, LMDS may be converted into the estimates of the primary cosmic ray spectrum [19]. Such procedure was applied to data samples with high muon multiplicities ($m \geq 10$) and two zenith angle intervals: θ ≥ 75° and θ ≥ 80° (395 and 49 events respectively). These data correspond to mean logarithmic primary energies around $10^{18}$ eV and higher. The conversion was performed with two limiting assumptions on primary composition (pure protons and pure iron nuclei), using five different hadron interaction models available in recent CORSIKA versions: SIBYLL2.1, QGSJET01, QGSJET-II, EPOS1.61 and EPOS1.99. Thus, for every data sample, 10 estimates of the differential primary energy spectrum have been obtained.

In figure 6, primary intensity estimates derived from DECOR data are compared with results of recent measurements of PCR energy spectrum in the EeV energy range. Though a reasonable agreement in absolute normalization with AGASA data [20] is observed, it is seen from the figure that none of the examined interaction models allows us to match the data on muon bundles at large zenith angles with PCR spectrum measurements performed by means of the fluorescence method in HiRes [21], Auger [22] and Telescope Array [23] experiments, even for a heavy (iron nuclei) mass composition. This contradiction becomes even more significant, if one takes into account that both HiRes and Auger data on $X_{\text{max}}$ distribution favor a light (predominantly proton) primary composition near 1 EeV [24, 25]. If one assumes the proton primaries, the observed intensity of muon bundles will be about 2-3 times higher than the expectation. Recently, basing on the analysis of the surface detector (SD) data on the muon content in inclined EAS simultaneously registered by means of the fluorescence detector (FD), the Auger collaboration came to the same conclusion that ‘none of the current shower models, neither for proton or iron primaries, are able to predict as many muons as are observed’ [26].
4. Other results

A rich experimental material accumulated during long-term experimental series with NEVOD-DECOR complex was also used for solution of various other problems related with investigations of single muons and muon bundles in inclined EAS. Thus, high-statistics measurements of absolute muon intensity in a wide range of zenith angles with threshold muon energies in the interval from 1.2 to 7 GeV were performed [27]. The first estimates of the flux of albedo muons (cosmic ray muons of atmospheric origin scattered in the surrounding ground and detected in the setup with arrival zenith angles in the range from 90º to 95º) were obtained [28].

Influence of the Earth magnetic field on EAS muon component was studied [29]. A serious non-uniformity of the azimuth dependence of muon bundle intensity was revealed; this non-uniformity being enhanced with the increase of zenith angle. This phenomenon is quantitatively explained by the distortion of the lateral distribution function of EAS muons by the geomagnetic field. A new effect – the presence of a coplanar component in the directions of muon tracks within a bundle in a plane determined by EAS direction and Lorentz force vector – was found.

For the first time, experimental estimates of meteorological effects in the intensity of muon bundles detected at the ground surface were obtained [30]. It was found that the frequency of registration of muon bundles was appreciably different during a year; in winter, the intensity was 10-15% higher than in summer. As a result of a more detailed study, the temperature and barometric coefficients for muon bundle intensity were estimated. It was shown that, similar to geomagnetic field effects, variations of the intensity of the bundles are caused by changes of muon LDF in the extensive air showers developing in a changeable atmosphere.

5. Present status of the experiment and future plans

In 2008 – 2010, a deep modernization of the NEVOD electronic systems was performed [31]. The photomultipliers in the QSM were replaced with a new low-noise FEU-200 type (Russia) which allowed refuse of the formerly used requirement of double PMT signal coincidences within the QSM, and thus substantially increased the detection efficiency of faint Cherenkov light flashes. System of signal digitization and data acquisition was completely changed. New system has the cluster architecture: each string of the QSM is served by an outer block of electronics. In order to provide a
wide dynamic range of spectrometric measurements (from 1 to $\sim 10^5$ photoelectrons), the output signals from 9th and 12th dynodes of the PMT are used. Also the new measuring electronics of the calibration telescope system was developed which provides now the measurements of response amplitudes of CTS scintillation counters. This modernization significantly extended possibilities of the NEVOD-DECOR complex and allowed beginning a new phase of experiments related, first of all, with investigations of energy characteristics of muon component. New long-term series of measurements with NEVOD-DECOR complex started in 2011.

In figure 7, first preliminary results of measurements of the energy spectrum of cascade showers produced by nearly horizontal muons in water are presented [32]. The analysis is based on about 4100 h registration live time. The events with unambiguously reconstructed muon tracks crossing two DECOR supermodules located in the opposite short galleries of the building (see figure 1) have been used. Such condition corresponds to selection of muons with zenith angles more than 85º and threshold muon energy 7 GeV. Moreover, estimates show that about 30% of these muons have energies greater than 100 GeV. Individual cascade curves (number of relativistic light-emitting particles vs depth) are reconstructed on the basis of NEVOD PMT responses, and then cascade energies are estimated by means of the fit of the longitudinal profiles of the cascades (figure 7, left). In the explored energy range from 10 GeV to few hundred GeV, experimental data are in a good agreement with expectation based on usual processes of muon production in pion and kaon decays with parent meson generation spectrum slope 2.7 (the curve in figure 7, right). At a next step, selection of cascades with zenith angles more than 60º in a whole azimuth range with reconstruction of their energy and geometry characteristics on the basis of QSM responses is planned; in the latter case, statistically significant data on muon energy spectrum up to about 10 TeV can be obtained.

![Figure 7. An example of the reconstruction of the individual cascade curve in the Cherenkov water detector (left) and the measured energy spectrum of cascade showers generated by muons in water (right).](image)

Another high priority experimental task is investigation of the energy deposit of muon bundles in the water tank. Measurements will be performed in a wide range of muon multiplicities and zenith angles, and hence in a wide range of primary particle energies. Comparison of the measured dependence of the energy deposit on muon density and zenith angle with expectation will provide additional information on primary spectrum and composition and will also allow searching for possible deviations from usual EAS development models. Accumulation of experimental data and selection of muon bundle events have been started. An example of a bundle registered in NEVOD-DECOR complex is shown in figure 8.
Further plans include the deployment of a traditional type EAS array around the NEVOD-DECOR experimental complex [33]. As of preliminary, the array for the detection of electron component in the primary energy range $10^{15} - 10^{17}$ eV will consist of about 40 clusters of scintillation counters located on the roofs of the surrounding laboratory buildings. The use of the counters operating now in the KASCADE-Grande experiment is considered as a possible option. The scintillation array will allow determine the shower size, location of its axis and to perform the cross-calibration of the traditional EAS detection method and LMDS technique. Other investigations related with studies of EAS muon and hadron components near the knee energy region may be also conducted.

6. Conclusions
During long-term measurements conducted with the NEVOD-DECOR experimental complex in 2002-2007, unique data on muon bundles of various multiplicities detected at the ground level in a wide range of zenith angles have been accumulated. Application of a novel approach to EAS studies based on the phenomenology of local muon density spectra at various zenith angles gave possibility to obtain information on primary cosmic ray flux and interaction characteristics in the energy range from $10^{15}$ to $10^{18}$ eV in frame of a single experiment with a relatively small setup. Comparison of the measurement results with CORSIKA-based simulations showed the increase of LMDS slope at PeV energies of primaries (corresponding to the first knee), a trend to a heavier primary mass composition at energies above the knee, indication for a second knee (the further increase of the LMDS slope near $10^{17}$ eV). At large zenith angles and high muon densities (corresponding to primary energies around $10^{18}$ eV) a considerable excess of muon bundle events in comparison with the expectation based on independent estimates of the primary spectrum and widely used hadron interaction models has been found, even under assumption of a heavy (pure iron nuclei) mass composition.

In 2011, a new phase of the NEVOD-DECOR experiment started. A new measuring system of the Cherenkov calorimeter with the extended dynamic range provides possibility to perform measurements of the energy spectrum of cascade showers initiated by high-energy muons in water as well as to obtain distributions of the energy deposit of muon bundles at various zenith angles and muon multiplicities. The further plans include the deployment of a traditional EAS array around the NEVOD-DECOR complex for determination of the shower size, axis location and cross-calibration of different techniques of EAS detection in the energy interval $10^{15} - 10^{17}$ eV.
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