Measuring module of the Cherenkov water detector NEVOD

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Abstract. Quasispherical Module (QSM) of Cherenkov water detector NEVOD represents six low-noise FEU-200 photomultipliers with flat photocathodes (15 cm in diameter), oriented along the axes of orthogonal coordinate system. Such configuration allows to register Cherenkov radiation arriving from any direction with almost equal efficiency. The results of measurements of QSM characteristics in the sensitive volume of the NEVOD detector during the registration of Cherenkov radiation of single muons at different distances and angles are discussed.

Introduction
Cherenkov water detectors (CWD) are one of the most perspective instruments for ultrahigh energy cosmic rays study. For their creation, water reservoirs of natural or artificial origin are used. Inside the water reservoir the spatial lattice of optical modules (OM) is located. In optical modules for the detection of Cherenkov radiation, the photomultipliers with large area photocathode are used. Usually OM consists of a glass sphere, one photomultiplier tube with hemispherical photocathode and internal electronics. The spatial lattice is formed of vertical strings in which OMs are located at distances of several tens of meters and have a preferred direction: upwards and downwards as in the NTC200+ [1] setup or just downwards as in ANTARES [2] and IceCube [3]. Sometimes OMs are combined in clusters of two or three. Disadvantage of such optical modules is that they have a dead zone from which the Cherenkov radiation is not recorded. The solution to this problem could be the creation of a spherical photocathode photomultiplier which response is independent on the angle of incidence of Cherenkov radiation. But creation of such PMT is related with solution of serious technical problems. Therefore, PMTs with hemispherical photocathode are widely used. Particle direction in such detectors is determined by the Cherenkov radiation arrival time. Amplitude of the OM response signals is used only as additional information. The presence of selectivity in choosing the OM registration direction does not allow to create 4\(\pi\)-detectors that register Cherenkov radiation from any direction with the same efficiency.

Another approach to construction of OM for 4\(\pi\)-detectors which is based on the usage of flat photocathode photomultipliers arranged symmetrically was proposed for the first time on the 16th ICRC in 1979 [4]. The amplitude response of such PMT for relativistic charged particle depends on the angle of incidence of the Cherenkov light to the photocathode and can be calculated using the following formula:
where $S_{\text{PMT}}$ and $r_{\text{PMT}}$ are photocathode area and radius respectively; $\cos \alpha$ is the cosine of the angle of incidence of the Cherenkov light on the photocathode; $R$ is a distance from the PMT photocathode center to the particle track; $dN/d\lambda$ is distribution of Cherenkov photons in wavelengths; $\theta_C$ - Cherenkov radiation angle; $\eta(\lambda)$ is PMT quantum efficiency; $L(\lambda)$ is absorption length of light in water, $\lambda_{\text{min}}$ and $\lambda_{\text{max}}$ are boundaries of the PMT sensitivity range.

Simple OM, which has a response of a spherical PMT can be made of six photomultipliers arranged symmetrically along the axes of orthogonal coordinate system (in the cube faces). According to the formula (1), the response of such OM is determined by the approximate expression:

$$A_i(R, \alpha) = \frac{S_{\text{PMT}} \cdot \cos \alpha}{2\pi(R + r_{\text{PMT}}) \cdot \sin \theta_C} \cdot \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \frac{dN}{d\lambda} \cdot \eta(\lambda) \cdot \exp\left(-\frac{R}{L(\lambda) \cdot \sin \theta_C}\right) d\lambda,$$

where $S_{\text{PMT}}$ and $r_{\text{PMT}}$ are photocathode area and radius respectively; $\cos \alpha$ is the cosine of the angle of incidence of the Cherenkov light on the photocathode; $R$ is a distance from the PMT photocathode center to the particle track; $dN/d\lambda$ is distribution of Cherenkov photons in wavelengths; $\theta_C$ - Cherenkov radiation angle; $\eta(\lambda)$ is PMT quantum efficiency; $L(\lambda)$ is absorption length of light in water, $\lambda_{\text{min}}$ and $\lambda_{\text{max}}$ are boundaries of the PMT sensitivity range.

Simple OM, which has a response of a spherical PMT can be made of six photomultipliers arranged symmetrically along the axes of orthogonal coordinate system (in the cube faces). According to the formula (1), the response of such OM is determined by the approximate expression:

$$A_i = \frac{C}{R \cdot \sin \theta_C} \cdot \exp\left(-\frac{R}{I \cdot \sin \theta_C}\right) \cdot \sqrt{\sum_{i=1}^{1} \cos^2 \alpha_i},$$

where $C$ is a constant; $I$ is some effective absorption length; $\cos \alpha$ is the cosine of the angle between the normal to the plane of the photocathode and the arrival direction of the Cherenkov radiation; $R$ is a distance from the center of the module to the particle track. Since for the cube $\sum_{i=1}^{1} \cos^2 \alpha_i = 1$, the OM response will not depend on direction of Cherenkov light for distances more than about two sizes of the module. Therefore, these OM are called quasispherical (QSM).

An important advantage of quasispherical modules in comparison with spherical PMTs is that this module allows to determine the arrival direction of Cherenkov radiation using the ratio of the amplitudes of triggered photomultipliers. This principle of registration was implemented into quasispherical module (QSM) of the NEVOD detector.

1. Quasispherical module of the CWD NEVOD

For the registration of main components of cosmic rays on the Earth's surface, including neutrinos from the lower hemisphere, a multi-purpose Cherenkov water detector NEVOD [5] with a volume of 2000 m$^3$ was created in MEPhI. Inside the detector, the spatial lattice of quasispherical measuring modules is located. QSM consists of a waterproof metal housing, internal electronics and six FEU-200 photomultipliers with flat photocathodes (15 cm in diameter) with plastic protective illuminators. Six photomultipliers are oriented along the axes of orthogonal coordinate system (figure 1).

![Figure 1. Quasispherical module.](image-url)
spectral characteristics in the range of 410-430 nm, electrostatic electron focusing system and 12-dynode louver type multiplier system. To obtain a large dynamic range of the recorded signals from 1 to $10^5$ photoelectrons, the readout of signals from the 12th and 9th dynodes is used. In this case spectrometric channel of the 12th dynode allows to measure signals in the range of $1 - 1000$ ph.e. and the channel of the 9th dynode in the range of $10^2-10^3$ ph.e. Internal electronics of the module provides detection of Cherenkov radiation by the photomultipliers in the regular measurement mode and the procedure of operation monitoring. Quasispherical modules are combined into strings (clusters) of 3-4 in each. Three strings of 3 QSMs or 4 strings of 4 QSMs form the plane. The current configuration of CWD NEVOD includes 4 planes of 16 QSMs and 3 planes of 9 QSMs (91 QSM in total). For the calibration of CWD spectrometric channels during long experimental series, the System of Calibration Telescopes (SCT) and the coordinate detector DECOR [6] are used. SCT consists of 80 scintillation detectors (figure 2). Forty detectors are located on the top and forty on bottom of the pool (upper and lower planes). Any pair of detectors (one detector from the upper and one from the lower planes) forms a muon telescope. Telescopes allocate single muons in the range of zenith angles from 0° to 45° with an accuracy of ~ 2°.

DECOR (figure 2) is the world's first large-scale coordinate detector specially designed for the study of cosmic radiation on the Earth's surface at large zenith angles up to the horizon. Detector consists of eight vertically arranged supermodules with total area of ~ 70 m², which ensure spatial and angular accuracy of the muon track reconstruction better than 1 cm and about 0.7°, respectively.

![Figure 2. The layout of SCT system and DECOR detector around the CWD NEVOD.](image)

2. **Response of the QSM to the single muons**

The first characteristic of the QSM is the PMT amplitude response at single-particle events in the sensitive volume of the detector. The selection of events for the PMT calibration is performed by SCT telescopes. High positioning accuracy of the allocated events allows to obtain the dependence of the PMT amplitude response on the distance to the particle tracks. An example of the event is shown in figure 3.
Figure 3. An example of CWD response to a vertical muon. 59 triggered QSMs, total amplitude ~ 355 ph.e., the number of upward oriented PMTs is 45, the number of downward oriented PMTs is 5, PMT registration threshold is 0.25 ph.e.

The responses of two PMTs (amplitude spectra) to the vertical muons selected by the SCT at a fixed distances $R = 0.72$ m and 1.0 m, and angles of incidence of the Cherenkov light $48.8^\circ$ and $41.2^\circ$ from the side PMT photocathode and the top PMT photocathode are shown in figures 4 and 5.

Figure 4. Amplitude responses of the side PMT of the central QSM to single muons selected by the SCT telescope.  
Figure 5. Amplitude responses of the top PMT of the central QSM to single muons selected by the SCT telescope.

The second characteristics of the QSM is the total QSM responses as a function of on the distance to the particle track. To obtain the dependence of the QSM response on the distance, the events with single near-horizontal tracks allocated by the DECOR supermodules were selected. An example of the event with the near-horizontal muon allocated by the DECOR supermodules is shown in figure 6.
Figure 6. An example of the response of the detecting QSM lattice for the near-horizontal muon. 91 triggered QSM, total amplitude ~ 1260 ph.e.

Figure 7 shows the dependence of the average response $B = \sqrt{\sum_{i=1}^{3} A_i^2}$ of three PMTs (photomultipliers that register direct Cherenkov light) on the distance from the center of QSM to the particle track.

![Graph showing the dependence of the average amplitude response $B$ on the distance from the QSM center to the particle track, registration threshold 0.25 ph.e.](image)

Figure 7. The dependence of the average amplitude response $B$ on the distance from the QSM center to the particle track, registration threshold 0.25 ph.e.

For evaluation of accuracy of muon track reconstruction particles of near horizontal flux were used. The developed technique of such reconstruction is described in paper [7]. The average accuracy is better than 6.5°. Obtained results of PMTs and QSMs calibrations can be used at reconstruction of real events detected by NEVOD-DECOR complex. For evaluation of accuracy of cascade shower reconstruction the events generated by near-horizontal muons were used, too. Method of reconstruction of the cascade curves [8] in the CWD is based on the recalculation of the response of each PMT, which “sees” the track, into the number of emitting relativistic particles on the track. Estimates of the direction and geometrical position of the cascade axis based on the analysis response amplitudes of the CWD PMTs give the following results: better than 16° for the direction and about 30 cm for the axis position.
Conclusion
The main advantage of quasispherical modules compared to hemispherical PMTs is a possibility to measure Cherenkov light direction by the amplitude analysis only. This opens a way to the use in Cherenkov water detectors of PMTs with flat photocathodes, inexpensive compared to hemispherical ones.

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