The engineering prototype of the wide-field Cherenkov telescope for the Yakutsk array

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Abstract. The Yakutsk array group is developing the wide FOV Cherenkov telescopes to be operated in coincidence with the surface detectors of the array under modernization. Currently the engineering prototype of the reflecting telescope with front-end electronics is designed and assembled to prove the feasibility of the concept. In this report the status and parameters of the engineering prototype are presented.

1. Introduction
The aim of the modernization program of the Yakutsk array is to construct a precise instrument capable of measuring the highest-energy galactic cosmic rays (CRs) – their sources, energy spectrum, and mass composition. Another aim is to study a transition region between galactic and extragalactic components of CRs where some irregularities in spectrum and composition may be revealed [1].

A crucial role in this program should play a subset of wide field of view (FOV) telescopes -

![Figure 1. Modeling rays (yellow points) from a distant point source in the telescope. Blue curves illustrate the mirror and photocathode surface. Black rectangle imitates shadowing by the PMT case.](image-url)
differential detectors of Cherenkov light emitted by extensive air showers (EASs), intended to measure the angular and temporal structure of the signal connected to EAS longitudinal profile above $E = 10^{15}$ eV [2].

2. Astrophysical expectations for the Cherenkov telescopes working in coincidence with the Yakutsk array detectors

Our interest in Cherenkov light differential detectors of EAS is caused by the possibility to measure the depth of cascade maximum, $x_{\text{max}}$, and/or the shower age via angular and temporal distributions of the Cherenkov signal. In particular, it was shown using EAS model simulations that the pulse width measured at the periphery of the shower, $r > 300$ m, at sea level is pronouncedly connected with $x_{\text{max}}$ [3].

Combining $x_{\text{max}}$ and the shower age with other EAS characteristics measured with surface detectors of the array, e.g. the energy and muon content, one is able to estimate the average mass composition of CRs. Experimental arguments in elucidating the origin of the knee and ankle in CR spectrum will significantly strengthen due to the measurements of the angular and temporal distributions of the Cherenkov signal in the energy range above $10^{15}$ eV. Existing scenarios of CR acceleration in the sources are different in composition expected around the knee and in the transition region between galactic and extragalactic components, so the accurate estimation of the average mass of the particles/nuclei in addition to the improved measurement of the sharpness of the knee and ankle should allow us to discriminate some scenarios [2].

3. Ray tracing in the telescope

The engineering prototype of the wide FOV Cherenkov telescope consists of the spherical mirror and multi-anode PMT as an imaging camera in the focus. Data acquisition system (DAQ) includes 32 operational amplifiers and amplitude-to-digital converters (ADCs) connected to the industrial PC.

To model the focusing of the aluminized spherical mirror in the wavelength interval (300,600) nm we have used a point source of light placed at infinity, with angle $\alpha$ between the line to source and optical axis of the mirror. The image of the point source is calculated on the target plane near the focus of the mirror. The mirror size, $D_{\text{mirror}}$, radius of curvature, $R_{\text{mirror}}$, and target position, $F$, are optimized in order to get as wide a FOV as possible where the size of blurred image is comparable to the pixel size of the position-sensitive PMT.

We have chosen Hamamatsu R2486 series PMT with $16 \times 16$ crossed wire anode as an imaging
camera of the telescope. With $D_{\text{PMT}} = 50$ mm effective area and $d = 3.75$ mm distance between wires it provides approximately $d \times d$ pixel size. In this way, we have found the optimal parameters of the telescope to be: $D_{\text{mirror}} = 260$ mm; $R_{\text{mirror}} = 225$ mm; $F = 110$ mm; FOV=28°.

The scheme of ray tracing is illustrated in Fig. 1, where the spherical aberration of the point source image is seen on the PMT photocathode surface. 3D image of intensity distribution of light in the target plane is given in Fig. 2 for three typical incident angles. Here we didn’t apply the background signal reduction to the PMT output.

4. Engineering prototype of the wide FOV Cherenkov telescope

is shown in Fig. 3. The spherical mirror is mounted at the bottom of the telescope housing with vertical adjusting bolts beneath. Support staffs of the PMT are used additionally to fit it exactly in the focal plane. Coordinate sensitivity of the PMT\(^1\) to the light source of 1 mm diameter (optical fiber illuminated by W-lamp) is illustrated in Fig. 4.

Voltage-divider circuit and 32 signal cables are attached to the bearing plate. 16 two-channel operational amplifiers are mounted on the telescope housing. Block diagram of the DAQ system

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**Figure 3.** The prototype of the wide FOV Cherenkov telescope.

**Figure 4.** Coordinate sensitivity of the PMT to the standard light source.

**Figure 5.** Schematic overview of the telescope DAQ system.
is shown in Fig. 5.

In this design telescope provides the effective aperture $D_{\text{eff}}(0^\circ) = 10.9$ cm due to shadowing of the mirror by the PMT and support. Angular dependence of the telescope aperture is given in Fig. 6. We calculated it through a ratio of the light intensity on the photocathode surface to the initial intensity falling into actual aperture of the telescope, taking into account the reflectance of aluminium, 92.4%, in the PMT sensitivity interval $\lambda \in (300; 600)$ nm.

The quality of the optical system is characterized by the “spot” size, where the spot is an image of the point source at infinity, on the focal plane. We have measured the spot size of the image on the photocathode formed by the laser pointer at 3 m from the telescope. Angular dependence of the spot size is shown in Fig. 7. It’s approximately consistent with results of our modeling. Corresponding angular resolution of the telescope is $\sim 1.4^\circ$ within FOV.

5. Conclusions
We have designed and assembled the engineering prototype of the wide FOV Cherenkov telescope to work in cooperation with surface detectors of the Yakutsk array. Our next task is field testing of the telescope and DAQ system during the next winter.

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