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LED based calibration systems of the Baikal-GVD neutrino telescope

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Abstract. Baikal-GVD is a cubic-kilometer scale neutrino telescope, which is currently under construction in Lake Baikal. GVD will consist of an array of optical modules arranged in clusters of strings. The first GVD-cluster has been deployed and put in operation in April 2015. We describe equipment and methods for the calibration of the first GVD-cluster and discuss the accuracy of the calibration procedures.

1. Introduction

Baikal-GVD will be a kilometer-scale high-energy neutrino observatory, which is currently under construction in the southern basin of Lake Baikal [1–5]. The main scientific goal of GVD is to map the high-energy neutrino sky in the Southern Hemisphere including the region of the Galactic center. The Baikal-GVD will have a modular structure: it will consist of functionally independent setups – clusters of vertical strings of optical modules (OM). Each optical module comprises a light sensor (PMT R7081-100), which detects Cherenkov radiation produced by the relativistic charged particle moving through water. The first GVD-cluster has been deployed and commissioned in April 2015. It comprises 192 OMs arranged along 8 strings. Each string includes a chain of 24 OMs spaced uniformly at depths 900–1250 m. Event reconstruction with the GVD-cluster is based on the measurements of time and charge of the pulses detected with the OMs. Except the light sensors located in the OM, measuring channels include 200 MHz ADCs that provide measurements of the pulse parameters: time and charge. The measuring channels have slightly different time and amplitude characteristics: time offsets and sensitivity. The precise measuring of these characteristics (channel time and charge calibration) is the necessary condition of reliable event reconstruction. In this article we describe equipment and methods for the calibration of the first GVD-cluster and discuss the precision of calibration procedures.

2. LED based calibration system

Methods of the GVD-cluster calibration are determined by the design of the data acquisition system (DAQ) of the installation [6–9]. The DAQ of the GVD-cluster is constructed from three basic building blocks: optical modules (OMs), sections of OMs (main detection units), and strings. OMs contain light sensors and pulse amplifiers. The section includes 12 OMs connected to the central 12-channel 200 MHz ADC unit by 90 meter coaxial cables. Each string consists of two sections of OMs. The section electronics produces the section trigger request that is transferred to the cluster DAQ centre. The electronics of the DAQ centre generates a global trigger for all sections of the GVD-cluster. The global trigger produces a stop signal simultaneously for all ADC channels and initiates the "section event". Each section event contains waveform data for 12 ADC channels, global trigger number and local time. The trigger number and local time of the section provide the possibility to combine all section events into a unified cluster event.

There are three basic calibration parameters for such a DAQ organisation: relative time offset of the channels, relative time offset of the sections and channel sensitivity. Correspondingly, the calibration of the array recording system consists of the following procedures: charge and time calibrations of the measuring channels, time calibration of the sections, and channel charge calibration. Channel calibration procedures are based on the usage of OM's internal calibration LEDs L-7113 (two LEDs inside each OM). The LED beacons are used for the time calibration of the sections. The dominant wavelength of LEDs is 470 nm, the LED pulses have a width of $\sim$5 ns (FWHM). LED light intensity can be regulated in the range from $\sim$1 up to about 10^8 photons. The cross talk between LED channels is less than $<1\%$.

2.1 Time calibration of the channels

During the time calibration of the channels the relative time offsets of signals recorded by the OMs are derived. The signal delay of a channel is formed by the internal PMT delay and the delay caused by signal passing through an about 90 m long cable connecting OM and ADC unit. Cable delays are measured once in the laboratory. They are the same during array operation. The PMT delay depends on the power voltage and thus it requires regular calibration during array operation. There is a specialized test pulse which is generated by the OM controller and is delivered to the point of signal creation in the PMT preamplifier. The test pulse initiation is synchronized with the start time of the LED. From the measured difference between arrival times of LED signal and test pulse the PMT delay is obtained (see Fig. 1).

The measured PMT delays for the GVD-strings #4 and #5 as a function of PMT power voltages and the distribution of the OM cable delays (RMS = 0.6 ns) are shown in Fig. 1. The sum of the PMT and cable delays forms the channel time offset: T_{TST}. A straightforward test of the obtained channel time offsets is to pulse the internal LED in an OM and measure the arrival time of photons at this OM and the OMs above. The distances between adjacent OMs are known with good accuracy, and the differences between expected and measured arrival times give the relative time offsets of two channels: dT_{LED}. A similar parameter dT_{TST} can be obtained using results of the measuring of the PMT and cable delays. The distribution of the channels with respect to the differences between dT_{LED} and dT_{TST} is shown in Fig. 2 for the GVD-strings #4 and #5 (mean = 0.6 ns, RMS = 1.8 ns). The relative time offsets measured with

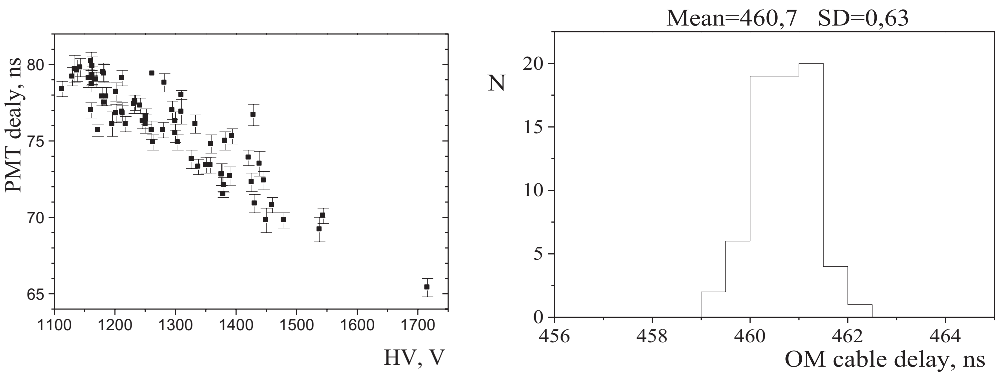

Figure 1. The PMT delays in dependence of the PMT voltages (left) and distribution of the OM cables on the delay (right).

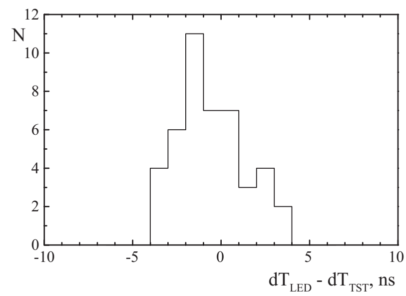

Figure 2. Distribution of channels with respect to the parameter $dT_{LED} - dT_{TST}$.

LEDs are consistent with the results of the channel time calibration. The uncertainties of the calibration coefficients are less than 2 ns.

2.2 Time calibration of the sections

OM LEDs are faced vertically and, therefore, cannot be used for the time calibration of sections located on different strings. For this purpose LED beacons were installed. A LED beacon contains 12 LEDs. Six of them point upward and six horizontally. The LED flashes can be detected simultaneously by OMs of different sections. The GVD acoustic positioning system provides information about the OM positions. The relative time offset of the sections is calculated as the time difference between expected time delay between OM signals dT_{EXP}, and the measured one, dT. An example of time calibration of the sections located on string #2 and string #8 is presented in Fig. 3. The calibration data contain information obtained with 9 pairs of OMs: the mean relative time offset is 142 ns, the RMS is 1.7 ns. The section calibration accuracy is about 2 ns including channel calibration uncertainties.

2.3 Charge calibration

We apply a standard procedure for the charge calibration of PMTs, based on an analysis of the single photoelectron spectrum (s.p.e.). In this calibration mode the pulses of two LEDs of an OM are used. The intensity of the first LED is fitted to provide a detection of s.p.e. signals with a detection probability of about 10%. These pulses are used to measure the s.p.e. distribution of channel signals. Pulses of the

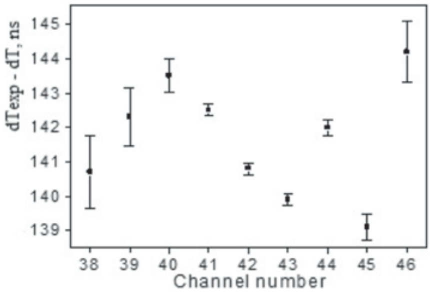

Figure 3. Results of time offset measurement for string #2 vs string #8.

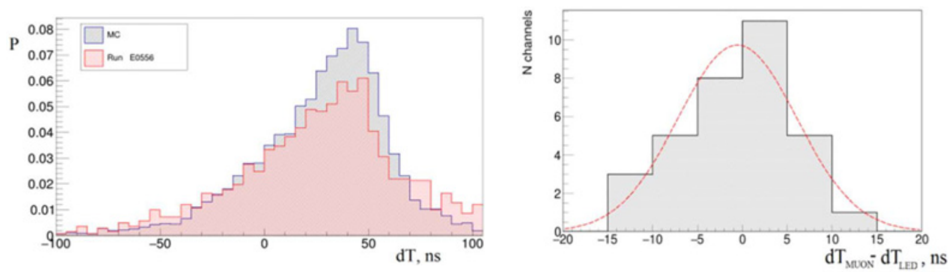

Figure 4. Experimental and modeled time difference distributions for adjacent channels obtained with muons (left), and distribution of the measuring channels (string #4 and #5) on differences of pairwise time offsets dT obtained with muons and LEDs (right).

second LED with intensities corresponding to about 50 p.e. PMT's signal are delayed by 500 ns and are used as a trigger to suppress background signals with small amplitudes initiated by PMT dark current, as well as light background of the lake's deep water.

3. Time calibration crosscheck with atmospheric muons

Atmospheric muons can be utilized to verify the data acquired via the LED calibration system. The relative time offset between two measuring channels can be obtained via the time difference of signals from down-going muons on neighboring OMs. In this case, pairwise channel delays are equal to the time shift between the experimental and modeled muon time difference distribution. An example of experimental and modeled time difference distributions after time shift optimization is presented in Fig. 4. Comparing pairwise channel delay differences acquired by LED flashers and by muons yields a near-normal distribution with an average value of 0.4 ± 1ns (see Fig. 4), that gives an estimation of the systematic uncertainties of the calibration procedure.

4. Conclusion

The Baikal-GVD calibration system comprises LED flashers installed in each optical module as well as LED beacons. The OM LED flashers provide time and amplitude calibration of the measuring channels, the LED beacons are used for time calibration of the GVD-sections. Comparison of two independent calibration methods gives a calibration accuracy of about 2 ns. A time calibration crosscheck with atmospheric muons does not show any systematic biases.

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