Time calibration of the neutrino telescope Baikal-GVD

A.D. Avrorin[1], *A.V.* Avrorin[1], *V.M.* Aynutdinov[1], *R.* Bannash[7], *I.A.* Belolaptikov[2], *V.B.* Brudanin[2], *N.M.* Budnev[3], *A.A.* Doroshenko[1], *G.V.* Domogatsky[1], *R.* Dvornický[2,8], *A.N.* Dyachok[3], *Zh.-A.M.* Dzhilkibaev[1] , *L.* Fajt[2,8,9,**], *S.V.* Fialkovsky[5], *A.R.* Gafarov[3], *K.V.* Golubkov[1], *N.S.* Gorshkov[2], *T.I.* Gres[3], *K.G.* Kebkal[7], *O.G.* Kebkal[7], *E.V.* Khramov[2], *M.M.* Kolbin[2], *K.V.* Konischev[2], *A.P.* Korobchenko[2], *A.P.* Koshechkin[1], *V.A.* Kozhin[4], *M.V.* Kruglov[2], *M.K.* Kryukov[1], *V.F.* Kulepov[5], *D.A.* Kuleshov[1], *M.B.* Milenin[5], *R.A.* Mirgazov[3], *V.* Nazari[2], *A.I.* Panfilov[1], *D.P.* Petukhov[1], *E.N.*Pliskovsky[2], *M.I.* Rozanov[6], *E.V.* Rjabov[3], *V. D.* Rushay[2], *G.B.* Safronov[2], *B.A.* Shaibonov[2], *F.* Šimkovic[2,8], *M.D.* Shelepov[1,*], , *I.* Shtekl[9], *A.G.* Solovjev[2], *M.N.* Sorokovikov[2], *O.V.* Suvorova[1], *V.A.* Tabolenko[3], *B.A.* Tarashansky[3], *S.A.* Yakovlev[7], and *A.V.* Zagorodnikov[3]

[1]Institute for Nuclear Research, Moscow, 117312 Russia
[2]Joint Institute for Nuclear Research, Dubna, 141980 Russia
[3]Irkutsk State University, Irkutsk, 664003 Russia
[4]Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia
[5]Nizhni Novgorod State Technical University, Nizhni Novgorod, 603950 Russia
[6]St. Petersburg State Marine Technical University, St. Petersburg, 190008 Russia
[7]EvoLogics, Berlin, Germany
[8]Comenius University, Bratislava, Slovakia
[9]Czech Technical University in Prague, Prague, Czech Republic

Abstract. Baikal-GVD is a cubic-kilometer scale neutrino telescope, which is currently under construction in Lake Baikal. Baikal-GVD is an array of optical modules arranged in clusters. The first cluster of the array has been deployed and commissioned in April 2015. To date, Baikal-GVD consists of 3 clusters with 864 optical modules. One of the vital conditions for optimal energy, position and direction reconstruction of the detected particles is the time calibration of the detector. In this article, we describe calibration equipment and methods used in Baikal-GVD and demonstrate the accuracy of the calibration procedures.

1 Introduction

The Baikal Gigaton Volume Detector (Baikal-GVD) is a cubic-kilometer scale neutrino telescope installed in Lake Baikal at 1366 m depth and 3.6 km from shore [1,2]. It consists

* Corresponding author: shelepov-1992@mail.ru
** Corresponding author: fajtak.l@gmail.com

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of a three-dimensional array of Optical Modules (OMs) arranged in clusters, each comprising 288 OMs. At present, Baikal-GVD consists of 3 clusters with 864 OMs in total. Every cluster comprises 8 strings of 525 m length, separated horizontally by 60 m. A string carries 36 OMs with 15 m spacing divided into 3 sections (a section consists of 12 OMs). Every section has a Central Module (CM) with a 12-bit FADC responsible for digitization and processing of the pulses [3]. The OM is the basic detection unit which contains a 10" PMT R7081-100, a controller, calibration LEDs, amplifiers and a high voltage (HV) converter, all enclosed in a 17" pressure-resistant glass sphere. The important requirement for high angular resolution of the reconstructed tracks is a precise timing of individual OMs which can be achieved with specialized time calibration systems. In this article, the different light sources as well as the procedures used for time calibration of Baikal-GVD are described, and the results of the 2017 time calibration of the two clusters are presented.

2 Time Calibration

Every channel, represented by individual OMs, has a slightly different time shift with respect to its neighboring OMs. Shifts are caused by: different PMT transit times, channel cable delays (between OM and CM) and section cable delays (between CM and cluster center). The PMT transit times are measured in specialized calibration runs during which artificial test pulses are produced. The test pulse is a special pulse created by the OM's controller, which gives it a very easily recognizable signature among all other real PMT pulses. The time of the test pulse production can be adjusted with respect to the LED light production thus allowing for using test pulses as a reference time. In addition, the test pulse is sent directly to the amplifiers while the real pulse has to propagate through the PMT's dynode chain. Comparing the time of detection of the test pulse and the real pulse, one can calculate the transit time of the given PMT. The delays of the channel cables connecting the OMs with their CM are measured in the laboratory (transition time of a pulse). Moreover, a combination of the PMT delay and the channel cable delay are also measured by calibration runs with PMT built-in calibration LEDs, which provides a cross check of the obtained calibration parameters. The time delays of the section cables connecting CMs and Cluster Center (CC) are measured with LED matrix runs (inter-section calibration).

2.1 Intra-section calibration

In the intra-section calibrations, the relative time delays between neighboring OMs in the same sections, processed by the same CM, are determined. In this case, the typical time delays are up to tens of nanoseconds. As mentioned in the previous paragraph, two different methods for the intra-section calibrations are used: the dT_{TST} method and the dT_{LED} method. The intra-section calibration can be obtained from both methods, providing a simple technique to compare results of time calibration and evaluate its precision.

In the first method, the time delay T^{i}_{TST} of the i^{th} channel is calculated as the sum of PMT delay and cable delay of the i^{th} channel. The cable delays are measured on-shore and PMT delays are measured as the time difference between test pulse detection and LED light detection with both pulses produced in the OM controller at the same time. The relative time delay between two neighboring channels can then be calculated as

$$dT_{TST} = T^{i}_{TST} - T^{i-1}_{TST} \, . \quad (1)$$

In the second method, we study events when the light from an OM’s built-in LED illuminates a set of upper OMs collectively (up to 10 OMs). The relative time delay between two neighboring OMs is calculated as the difference between the time of the LED light detection at the i^{th} OM and $(i-1)^{th}$ OM corrected for the expected time of light propagation between these two OMs. An additional requirement in this method is that the amplitude of both signals has to be small enough (Q < 50 p.e.) so the influence of the Time Walk Effect is almost negligible. The relative time delay is thus measured as:

$$dT_{LED} = T^i - T^{i-1} - T_{th} \, , \tag{2}$$

where T^i, T^{i-1} are the times of the light detection on the i^{th}, $(i-1)^{th}$ OM, respectively and T_{th} is the theoretical time of light propagation between the OMs. The distance between two OMs is known with a high level of precision thanks to the acoustic positioning system, which means that T_{th} can be calculated with sufficient precision.

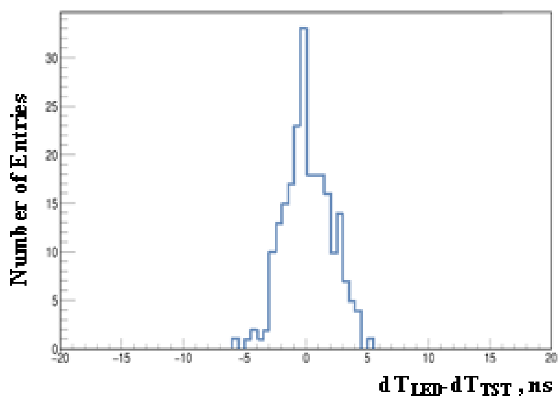

Figure 1. Distribution ΔT for all OMs, demonstrating the precision of our intra-section calibration.

Both methods were used to obtain the calibration parameters for all OMs. The time shifts of channels in each section were calculated relative to a reference channel of the section. To evaluate the accuracy of the obtained calibration parameters we obtain the time residuals

$$\Delta T^i = dT^i_{LED} - dT^i_{TST} \, , \tag{3}$$

which represent the time variance between the two calibration methods. The distribution of ΔT^i is shown in Fig. 1. The mean of the distribution is 0.1 ns and the RMS, representing the uncertainty of our intra-section calibration, is 1.9 ns. This value can be further improved after taking into account the proper Time Walk Correction function discussed in section 4.

2.2 Inter-section calibration

Every cluster contains 5 LED matrices which are powerful enough to illuminate simultaneously OMs from different sections and thus can be used to obtain the relative time offsets between different sections (inter-section calibration). Moreover, the LED matrix runs can also be used as another completely independent cross check of the intra-section calibration. A LED matrix comprises 12 LEDs divided into two groups controlled separately. One group of LEDs is oriented vertically and the second one horizontally. The LEDs pulse width is ~6 ns, the wavelength λ = 470 nm. The LEDs intensity can be adjusted up to ~10^8 photons. Thanks to the clear Baikal water, the LED matrix illuminates OMs more than 100 m away. In the inter-section calibrations, the expected and measured times of the LED matrix light detection are compared for all OMs and the remaining residuals are interpreted as a time calibration parameters. To be able to calculate the expected times of detections, the actual distances between LED matrix and all OMs have to be measured. The GVD's acoustic positioning system provides information about positions of all OMs and LED matrices with approximately 10 cm precision every 40 second. We use expected and measured time differences between two OMs on different sections. Expected and measured time differences between different pairs of channels of two strings are shown in Fig. 2.

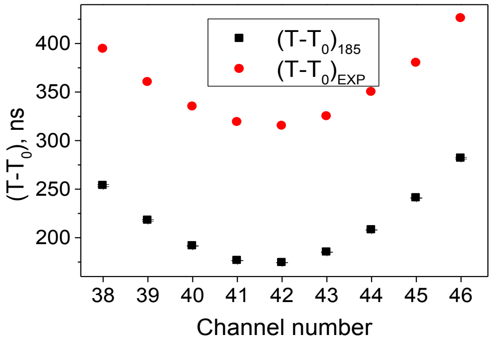

Figure 2. Expected (red dots) and measured time differences between different pairs of channels of two strings.

3 External calibration units

In 2017 two external calibration sources were put into operation: the Precision Optical Calibration Module (POCAM) [5] and the laser calibration source.

POCAM is a pulsed, highly isotropic light source with 475 nm wavelength developed by the IceCube collaboration for IceCube-Gen2. It was located on the top section of the 5th string of the first GVD cluster and has been operated during 2017. From the measurements with POCAM, it was found that POCAM is functioning according to the expectations. It can illuminate OMs on the four closest strings (up to 100 meters away) which means that it could be used as an analogue of the LED matrix for inter-section time calibration.

The external laser source was located between the first and second cluster at the level of the bottom sections of the clusters. The specifications of the laser source are the following: wavelength λ=532 nm, pulse energy 0.37 mJ (~10^{15} photons), flash duration ~1 ns. For the highest laser intensity, almost the entire detector in the 2017 configuration (2 clusters) – with exception of the most upper OMs on every string – was illuminated, as demonstrated in Fig. 3 and 4 for the first and second cluster, respectively. In the figures, the time of the pulse detection on the individual channels of these two clusters is shown, with exception of some channels, which have been excluded from the configuration. In both figures, one can see parabolically ordered times of detections on the individual strings, which are caused by the increasing distance of the OMs from the laser.

It can be seen, that the laser illuminates almost the entire detector in the 2017 configuration (again with the exception of several upper channels). Thanks to the high power of the laser, we can use it to check the time calibration obtained with the LED matrices. To do that we compare the relative time delays between neighboring channels obtained by using the laser source and LED matrices:

$$\Delta T^{ij} = dT^{ij}_{\mathrm{LED}} - dT^{ij}_{\mathrm{laser}} . \quad (4)$$

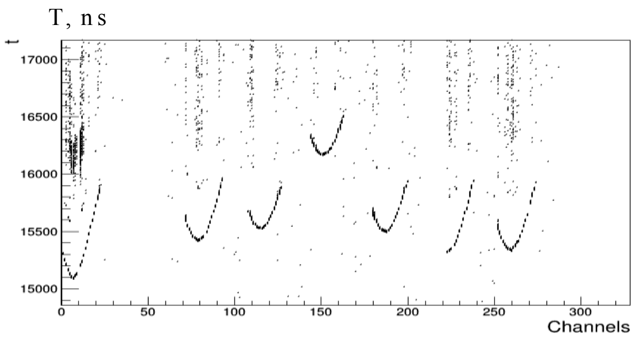

Figure 3. Measured arrival time distribution of the laser signals at the channels of the first cluster.

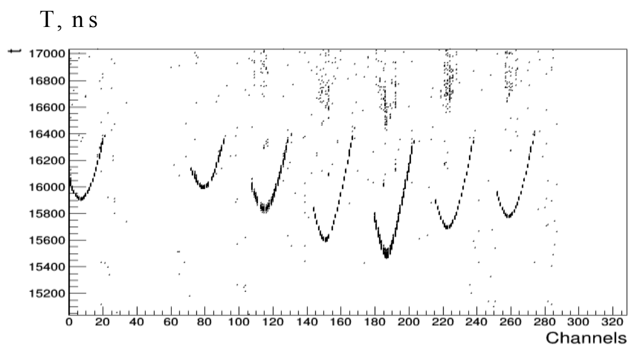

Figure 4. Measured arrival time distribution of the laser signals at the channels of the second cluster.

The comparison between the results obtained with the LED matrices and the laser is illustrated in Fig. 5. The results obtained by two completely different calibration sources agree within ~2 ns. The approximate laser illumination range is about 300 m, which means that such a light source will be able to illuminate even three GVD clusters.

4 Time walk effect

The Time Walk Effect (TWE) is an effect influencing the precise time of the pulse depending on its charge. The strength of the TWE is dependent firstly on the shape of the pulses and secondly on the method of time extraction (in Baikal-GVD, the time at 50% of the pulse front is used). This effect can be compensated if the time walk correction (TWC) function is known. Special calibration runs with 18 different LED intensities (thus different deposited charge) were performed to study the behaviour of the TWC function. The PMT transit time of individual PMTs was extracted according to the previous sections for every LED intensity individually which gives us 18 different values of the transit time for every functioning OM with respect to the average charge detected with given intensity. These values show the TWE and thus enables the determination of the TWC function. The measured TWC functions for 275 OMs are shown in Fig. 6. The average difference between maximum and minimum time shifts is about 4 ns which means that for events with a substantial difference in the measured charges on the individual OMs (cascade like events) the TWE has to be taken into account since its effect can reach twice the inaccuracy of the time calibration.

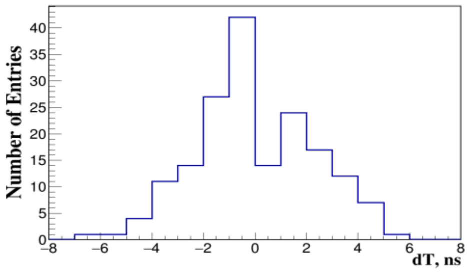

Figure 5. Time residuals between LED matrix and laser calibration.

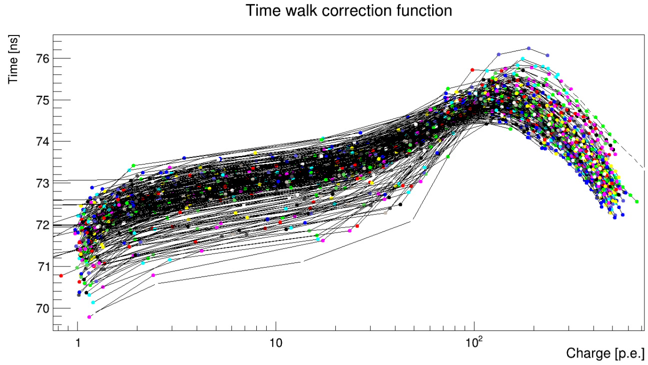

Figure 6. TWC functions for 275 OMs.

5 Conclusion

In this article, the methods and systems used to perform the time calibration for the Baikal-GVD neutrino detector have been reviewed. The accuracy of the obtained calibration parameters was checked by comparing results of independent time calibration methods. The overall precision of the recently implemented time calibration systems and procedures reaches 2 ns. Moreover, the study of the Time Walk Effect in situ was performed and the individual Time Walk Correction functions were obtained. In the worst case, the Time Walk Effect can affect the measured time by 4 ns which means that this effect should be undoubtedly taken into account.

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