The prototyping/early construction phase of the BAIKAL-GVD project

A.D. Avrorin, A.V. Avrorin, V.M. Aynutdinov, R. Bannach, I.A. Belolaptikov, D.Yu. Bogorodsky, V.B. Brudanin, N.M. Budnev, I.A. Danilchenko, G.V. Domogatsky, A.A. Doroshenko, A.N. Dyachok, Zh.-A.M. Dzhilikibaev, S.V. Fialkovsky, A.R. Gafarov, O.N. Gaponenko, K.V. Golubkov, T.I. Gress, Z. Honz, K.G. Kebkal, O.G. Kebkal, K.V. Konishchev, E.N. Konstantinov, A.V. Korobchenko, A.P. Koshechkin, F.K. Koshelev, V.A. Kozhin, V.F. Kulepov, D.A. Kuleshov, V.I. Ljashuk, A.I. Lolenko, M.B. Milenin, R.A. Mirkazov, E.A. Osipova, A.I. Panfilov, L.V. Pan’kov, A.A. Perevalov, E.N. Pliskovsky, V.A. Poleshuk, M.I. Rozanov, V.F. Rubtsov, E.V. Rjabov, B.A. Shaybonov, A.A. Sheifler, A.V. Skurikhin, A.A. Smagina, O.V. Suvorova, B.A. Tarashchansky, S.A. Yakovlev, A.V. Zagorodnikov, V.A. Zhukov, V.L. Zurbanov

Abstract

The Prototyping phase of the BAIKAL-GVD project has been started in April 2011 with the deployment of a three string engineering array which comprises all basic elements and systems of the Gigaton Volume Detector (GVD) in Lake Baikal. In April 2012 the version of engineering array which comprises the first full-scale string of the GVD demonstration cluster has been deployed and operated during 2012. The first stage of the GVD demonstration cluster which consists of three strings is deployed in April 2013. We review the Prototyping phase of the BAIKAL-GVD project and describe the configuration and design of the 2013 engineering array.

Keywords: neutrino, neutrino telescope, Baikal

1. Introduction

The BAIKAL-GVD Project is a logical extension of the research and development work performed over the last several years by the BAIKAL Collaboration. The optical properties of the lake deep water have been established [1], and the detection of high-energy neutrinos has been demonstrated with the existing detector NT200 [2][3]. This achievement represents a proof of concept for commissioning new instrument, Gigaton Volume Detector (BAIKAL-GVD), with superior detector performance and an effective telescope size at or above the kilometer-scale. The next generation neutrino telescope BAIKAL-GVD in Lake Baikal will be research infrastructure aimed primarily at studying astrophysical neutrino fluxes and particularly, mapping the high-energy neutrino sky in the Southern Hemisphere including the region of the galactic center. Other topics include indirect search for dark matter by detecting neutrinos produced in WIMPs annihilation in the Sun or in the center of the Earth. GVD will also search for exotic particles like magnetic monopoles, super-symmetric Q-balls or nuclearites. The detector will utilize Lake Baikal water instrumented at depth with light sensors that detect the Cherenkov radiation from secondary particles produced in interactions of high-energy neutrinos inside or near the instrumented water volume. Signal events consist of up-going muons produced in neutrino interactions in the bedrock or the water, as well as of electromagnetic and hadronic showers (cascades) from CC-interactions of $\nu_e$ and $\nu_\mu$ or NC-interactions of all flavors inside the array detection volume. Background events are mainly downward-going muons from cosmic ray interactions in the atmosphere above the detector. The site chosen for the experiment is in the southern basin of Lake Baikal, near the outfall of a small river, named Ivanovka, and about 40 km west of the place, where the Angara river leaves the lake. Here combination of hydrological, hydrophysical, and landscape factors is optimal for deployment and operation of the neutrino telescope. The geographical coordinates of the detector site are $51^\circ50^\prime\mathrm{N}$ and $104^\circ20^\prime\mathrm{E}$. Lake depth is about 1360 m here at distances beginning from about of three kilometers from the shore. A flat the lake bed through-out several tens of kilometers from the shore allows practically unlimited instrumented water volume for deep underwater Cherenkov detector. A strong up to 1 m thick ice cover from February to the middle of April allows telescope deployment, as well as maintenance and research works directly from the ice surface, using it like a solid and fixed assembling platform. The quality of the ice cover, the absence of stable hummocking fields and backbone slits determining conditions from the viewpoint of safety equipment assembling and underwater cable lines deployment. The period of safety works is usually longer than 8 weeks. Vanishingly small values of under-ice water currents allow the required precision of the assembling.
works. The light propagation in the Baikal water characterized by an absorption length of about 20–25 m and a scattering length of 30–50 m. The water luminescence is moderate at the detector site. The rate of light pulses from $^{40}$K-decays is negligible. The first generation Baikal Neutrino Telescope NT200 is operating in Lake Baikal since April 1998 [4, 5, 6]. The upgraded Baikal telescope NT200+ was commissioned in April, 2005, and consists of central part (the former, densely instrumented NT200 telescope) and three additional external strings. The deployment of the NT200+ was a first step towards a $k m^3$-scale neutrino telescope in Lake Baikal. The first prototype of the GVD electronics was installed in Lake Baikal in April 2008 [7]. It was reduced-size section with 6 optical modules (OMs). This detection unit provided the possibility to study basic elements of the future detector: new optical modules and FADC based measuring system. During the next two years different versions of prototype string were tested in Lake Baikal as a part of the NT200+ detector. The 2009 prototype string consists of 12 optical modules with six photomultiplier tubes (PMTs) R8055 and six XP1807 [8, 9]. In April 2010, the string with 8 PMTs R7081HQE and 4 PMTs R8055 was deployed in Lake Baikal. The operation of these prototype strings in 2009 and 2010 allows first assessment of the DAQ performance [10, 11, 12].

2. GVD design

The concept of BAIKAL-GVD is based on a number of evident requirements to the design and architecture of the recording system of the new array: the utmost use of the advantages of array deployment from the ice cover of Lake Baikal, the extendability of the facility and provision of effective operation even in the first stage of deployment, and the possibility implementing different versions of arrangement and spatial distribution of light sensors within the same measuring system.

The design for the BAIKAL-GVD neutrino telescope is an array of 10386 photomultiplier tubes each enclosed in a transparent pressure sphere to comprise an optical module. The OMs are arranged on vertical load-carrying cables to form strings. The basic configuration of telescope consists of 27 clusters of strings - functionally independent subarrays, which are connected to shore by individual electro-optical cables (see figure 1, 2). Each cluster comprises eight 705 m long strings of optical modules – seven peripheral strings are uniformly arranged at a 60 m distance around a central one. Each string comprises 48 OMs spaced by 15 m at depths of 600 m to 1300 m below the surface. All OMs are faced downward. OMs on each string are combined in four sections – detection units of telescope. The distances between the central strings of neighboring clusters are $H = 300$ m. The clusters are spaced over an area of approximately $2 km^2$. The water volume instrumented by OMs is about of $1.4 km^3$.

The objective of the optimization of the GVD design was to provide a large cascade detection volume with the condition of also effective recording high energy muons. Muon effective areas for two optimized GVD configurations are shown in figure 3. The curves labeled by GVD*4 and GVD relate to configurations with 10368 OMs and 2304 OMs, respectively. Muon effective area (6/3 event selection requirement - at least 6 hit channels on at least 3 strings) rises from 0.3 $km^2$ at 1 TeV to about of 1.8 $km^2$ asymptotically. The fraction of events induced by muons ($E_{\mu} > 1$ TeV) with mismatch angles between

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1 Design of array with 2034 OMs was discussed earlier elsewhere [9, 10, 11].
generated and reconstructed muon directions less than a given value $\psi$ is shown in figure 4. Muon arrival direction resolution (median mismatch angle) is about 0.25 degree.

Shower effective volumes for two GVD configurations are shown in figure 5. Shower effective volumes (11/3 condition - at least 11 hit channels on at least 3 strings) for basic configuration are about of 0.4–2.4 km$^3$ above 10 TeV. The accuracy of shower energy reconstruction is about of 20–35% depending on shower energy. The accuracy of a shower direction reconstruction is about of 3.5–6.5 degrees (median value). Distribution of the mismatch angle between generated and reconstructed directions of 1 PeV showers is shown in figure 6.

3. Prototype arrays

The prototyping phase of the BAIKAL-GVD project aims at in situ comprehensive tests of all elements and systems of the future telescope as the parts of engineering arrays operating in Lake Baikal. Prototyping phase will be concluded with deployment in 2015 of the first demonstration cluster of the GVD in Lake Baikal. Demonstration cluster will comprise total of 192 optical modules arranged on eight 345 m long strings (7 side strings located at 60 m distances from a central one). Each string comprises 24 OMs spaced by 15 m at depths of 950 m to 1300 m below the surface. OMs on each string are combined in two sections. Also the demonstration cluster will comprise an acoustic positioning system and instrumentation string with equipment for array calibration and monitoring of environment parameters.

In April 2011 the first autonomous engineering array which includes preproduction modules of all elements, measuring and communication systems, as well as prototype of acoustic positioning system of GVD-cluster has been installed and commissioned in Lake Baikal [12]. Array comprises total of 24 optical modules with the different types of PMTs (16 PMTs R7081HQE, 3 PMTs XP1807 and 5 PMTs R8055) which are arranged on three 70 m long vertical strings. Distances between strings are about of 40 m. Eight OMs on each string are spaced by 10 m and form one section.

In April 2012 the next version of engineering array which comprises 36 OMs has been deployed in Lake Baikal. This array consists of two short and one long string. Each of short strings consists of six OMs which are combined in one section. The long string comprises 24 OMs with R7081HQE PMTs combined in two sections. Vertical spacing of OMs is 15 m. This string is the first full-scale string of the GVD demonstration
The next important step on realization of the GVD project was made in 2013 by deployment of enlarged engineering array which comprises 72 OMs arranged on three 345 m long full-scale strings of the GVD demonstration cluster, as well as instrumentation string with an array calibration and environment monitoring equipment. The artistic view of this engineering array is shown in figure 7. The vertical spacing of OMs is 15 m and the horizontal distance between strings is about of 40 m. In addition to OMs each string comprises the communication module (CoM), and two central modules of the sections (CeM), as well as one transmitter and 3 receivers of acoustic positioning system (AM) [13]. The modified cluster DAQ-center is located at separate cable station and is connected to shore by electro-optical cable.

4. Data acquisition

The Data Acquisition System of the engineering array is formed from three basic units: optical modules, sections of OMs, and cluster of the sections.

Each OM (figure 8) contains a photomultiplier tube Hamamatsu R7081HQE, which detects the Cherenkov light produced by relativistic charged particles passing through the water. Electronics of optical module is discussed in details elsewhere [7, 8, 9, 10]. Latest version of OM design differs from previous ones by a power supply scheme and a type of used deep underwater connectors. The coaxial single-contact connectors which were used earlier were replaced by SubConn five-contact connectors. These modernizations allow an improvement of reliability of the underwater recording system and employment of different lines of OM cable for PMT signal transmission and OM power supply. Moreover it allows replacement of a low noisy OM power sources with relatively low efficiency (60%) by a switching power supply with efficiency about of 90%. The performed modifications of OMs have decreased a power consumption of array on more than 20%.

The optical modules are grouped into sections, the detection units of array [7, 8, 9, 10, 11]. Each section includes 12 OMs and the central module. PMTs signals from all OMs are transmitted through 90 m long coaxial cables to the central module of the section, where they are digitized by custom-made ADC boards with 200 MHz sampling rate. The waveform information from all measuring channels of the section is transferred to the Master board located in the CeM. The Master board provides data readout from ADC, connection via local Ethernet to the cluster DAQ-center, control of the section operation and the section trigger logic [7, 8, 9, 10, 11]. Request of the section trigger is transferred from the Master board to the cluster DAQ-center, where a global trigger for all sections is formed. The global trigger initiates data transmission from all sections to shore.

Data collected in section central models are transmitted to shore through three different segments of underwater communication network based on Ethernet. The section communication channels connect each CeM with the corresponding CoM. Given the lengths of these communication channels more than 100 m, the shDSL modems are used as the Ethernet extensions for data transmission from CeM to CoM. In CoM the section communication channels are joined into a single one, which connects each section with the cluster DAQ-center. Data transmission between each CoM and the cluster DAQ-center are also based on shDSL technology.

The data transmission between the cluster DAQ-center and shore station is provided through optical fibre lines extended at about of 6 km. Maximal speed of data transmission to shore is limited by bandwidth of a connection channel between a string CoM and the cluster DAQ-center and is about of 8 Mbit/s. To provide the required data rate (not less than 100 Hz), online data processing in each section is performed. As a result a raw data sample is reduced more than 50 times, since the data are refined
by the Master electronic cards located in CeMs. To provide required speed of data processing the ADC and Master cards were upgraded in 2013 with replacement of the FPGA Spartan 3 by the Spartan 6 microcircuits.

5. Slow control

Basic functions of control and monitoring of array recording system are realized by OMs controllers and ADC and Master boards. It means a setup of array operation mode, setting the thresholds and the data accumulating time ranges of measuring channels, PMT’s gains, control and monitoring of equipment parameters and background conditions during array operation. As an example, in figure 9 are shown results of long-term measurements of the channels counting rates of third section of the 2013 array. The main contribution to recorded counting rates is caused by a chemiluminescence of the deep water. During April–June 2013 there were not observed bright bursts provided by water luminosity.

In 2013 electrical power system of engineering array was upgraded substantially. Instead of scheme with disconnecting switches of 300 VDC power lines which were installed in underwater modules and were managed through power supply lines, 12-channel 300 VDC commutators controlled via Ethernet are used now. They were developed and successfully tested in 2012. This modification remarkably simplifies a power control and improves the array reliability in whole. Schematic view of 300 VDC commutation is shown in figure 10. The independent switching of the commutator channels is controlled by COM- server and 16-channel digital output module ICP DAS I-7045. Monitoring of output voltage is processed by 20-channel analog input module ICP DAS I-7017Z.

Cluster power supply system is divided in two levels (see figure 11). First level includes the 12-channel commutator which is used for string power supply and is placed in the cluster DAQ-center. Second level is formed by the commutators of strings which are located inside the string communication modules (CoM). They provide independent switch on/off of power supply of the string sections. This scheme of power supply provides a confident operation of the array in whole even if some elements of recording system like section or string would be broken.

6. Calibration

Calibration of the array recording system consists of the following procedures: amplitude and temporal calibrations of the measuring channels and time calibration of the sections. All these calibration procedures are based on usage of OM’s internal calibration LEDs (two LEDs inside each OM). The LEDs intensities as well as time delays between their light pulses are selected depending on the used calibration mode.

We apply a standard procedure of the amplitude calibration of PMTs based on an analysis of a single photoelectron spectrum (s.p.e.). In this calibration mode the pulses of two LEDs of OM are used. Intensity of the first LED is fitted to provide a detection of s.p.e. signals with detection probability about of 10%. These pulses are used to measure s.p.e. distribution of channel signals. Pulses of the second LED with intensities corresponding to about of 50 p.e. PMT’s signal are delayed on 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 deep water.

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

Intensities of LEDs light bursts are high enough to be detected by PMTs of neighboring sections and strings. It allows synchronization between OM of different sections and different strings, as well as to check out a precision of found delays between channels inside one section. The calibration coefficients are defined on a base of known positions of strings and OMs obtained from analysis of data accumulated by acoustic positioning system. In this calibration mode pairs of light pulses delayed by 500 ns are used. This provides a reliable way to select the calibration signals from PMT’s background.

7. Instrumentation string

The sketch of the instrumentation string is shown in figure 7. Instrumentation string is located at about of 100 m apart from the measuring strings with OMs. It comprises the calibration laser source, eight optical modules, as well as 10 acoustic sensors of positioning system.

The calibration laser source \[13, 14\] is located at 1215 m depth and is used for time synchronization between OM on different strings. High intensity of laser source (up to \(6 \times 10^{13}\) photons/pulse) allows illumination of OMs at distances more than 200 m from the source.

Acoustic sensors are arranged along the instrumentation string starting from the 50 m depth to the bottom of string and perform monitoring of a string displacements at different depths caused by deep or/and surface water currents.

As it was discussed earlier the optical modules of GVD design with 10386 OMs will be located at depths of 600 m to 1300 m below the surface, while OMs of the demonstration cluster are located at depths of 950 m to 1300 m. Eight optical modules housing R8055 or XP1807 PMTs are arranged at the depths from 600 m to 900 m on instrumentation string and aim at monitoring of a light background at these depths.

Earlier these OMs were operated as the parts of engineering arrays during 2011-2012. In figure 12 the normalized counting rates of OMs arranged on the instrumentation string are shown. The rates are normalized on averaged counting rates recorded by same OMs during 2012 at the depths below 1200 m, where background slightly depends on the depth. As one can see from figure 12 characteristic temporal behavior of background does not changed with depth, while intensity of light background increases with depth decreasing and becomes at 600 m depth twice larger comparing to intensity below 900 m. Preliminary results obtained in April–June 2013 indicate an opportunity to exploit the water volume below 600 m depth as instrumented volume of a neutrino telescope. However, the long-term monitoring is required to study a light background behavior during annual exposition of array at interested depths.

8. Conclusion

The construction of a km\(^3\)-scale neutrino telescope – the Gigaton Volume Detector in Lake Baikal – is the central goal of the Baikal collaboration. During the R&D phase of the GVD project in 2008-2010 years the basic elements of GVD – new optical modules, FADC readout units, underwater communications and trigger systems – have been developed, produced and tested in situ by long-term operating prototype strings in Lake Baikal. The Prototyping phase of the GVD project has been started in April 2011 with the deployment of a three string engineering array which comprised all basic elements and systems of the GVD-telescope in Lake Baikal and was connected to shore by electro-optical cable. In April 2012 the first GVD-string with 24 OMs combined in two sections has been deployed as a part of three string engineering array. The first stage of GVD-cluster which comprises three strings has been deployed in 2013. Deployment of the first demonstration GVD-cluster consisting of 8 strings is expected in 2015.

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