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DATA ACQUISITION SYSTEM FOR THE BAIKAL-GVD NEUTRINO TELESCOPE

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The objective of the Baikal-GVD project is the construction of a km^3-scale neutrino telescope in Lake Baikal. The Gigaton Volume Detector consists of a large three-dimensional array of photomultiplier tubes. The first GVD-cluster has been deployed and commissioned in April 2015. The data acquisition system (DAQ) of the detector takes care of the digitization of the photomultiplier tube signals, data transmission, filtering, and storage. The design and implementation of the data acquisition system are described.

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INTRODUCTION

Baikal-GVD is a neutrino telescope of a new generation with an effective volume of ~ 1 km^3. It is currently under construction at Lake Baikal and is based on many years of experience from operating the NT200 detector [1]. Neutrinos are detected using Cherenkov light produced by muons and charged particle cascades that emerge from a neutrino interaction within or in the vicinity of the detector. Neutrino telescopes provide a mean for discovering and studying sites of acceleration of high-energy particles in the Universe, studying the diffuse neutrino flux, searching for Dark Matter particles, investigating the neutrino properties with the help of atmospheric neutrinos, and monitoring environmental parameters.

Baikal-GVD will have a modular structure: it will consist of functionally independent setups — clusters of vertical strings of optical modules. The modular structure of the telescope will offer the chance to acquire experimental data as early as at the initial stage of setup deployment, a practically unlimited increase of its volume, and, if scientific priorities change, adapting its configuration to new requirements. The basic elements of the GVD telescope are 10$''$ Hamamatsu R7081-100 photomultiplier tubes (PMTs). The PMTs with the control electronics are enclosed in deepwater glass spheres, thus forming optical modules (OMs).

The optical modules on a string will be grouped into string sections — the lowest-level DAQ units of the detector serving 12 optical modules. A string section is a complete detection unit that forms a section trigger and provides data transmission from the OMs to the cluster DAQ center. The technical design of the

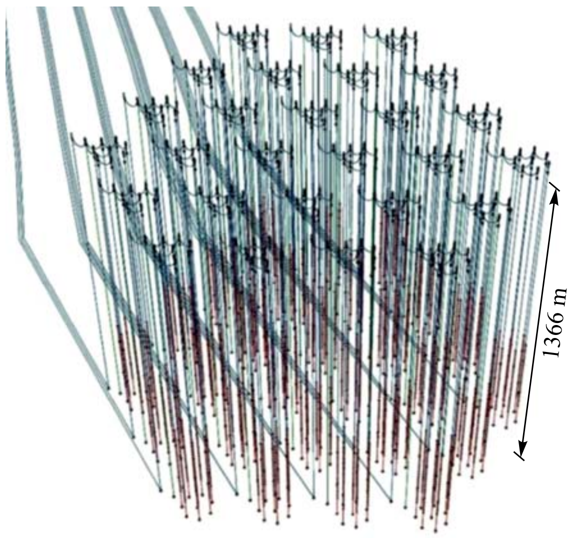

Fig. 1. 3D conceptual model of the GVD telescope (27 clusters)

section electronics provides the possibility to serve up to 12 optical modules. Each string may include several sections. The optimum number and configuration of the sections depend on the distance between optical modules and the instrumented lengths of the strings. This approach to the GVD design provides a relatively flexible structure, which allows for a rearrangement of the main building blocks (clusters and sections) in order to adapt to the requirements of new scientific goals, if necessary. The numbers of strings in the GVD cluster, sections on the strings, and OMs in the section are subject to optimization. Calculations show that a neutrino telescope with an effective volume of about 1.5 km^3 may be formed by 27 clusters (Fig. 1). The cluster includes eight strings, with 24 optical modules, located at a distance of 60 m from each other [2, 3].

1. DETECTION SYSTEM AND DIGITIZING

The optical modules house R7081-100 PMTs with 250-mm diameter hemispherical SBA photocathodes having a quantum efficiency of about 35%. The OMs form the basis for the detection system of the Baikal-GVD (Fig. 2). The electronics of the OM is directly mounted on the PMT base. It consists of high-voltage power supply (SHV 12-2.0 K 1000 P, produced by TRACO Electronic AG), an OM controller (on the basis of a C8051F121 SiLabs micro-controller, designed and manufactured by SNIIP-AUNIS Ltd.), a passive PMT divider (18 MΩ), a fast two-channel preamplifier, and two calibration LEDs (about 470 nm wavelength).

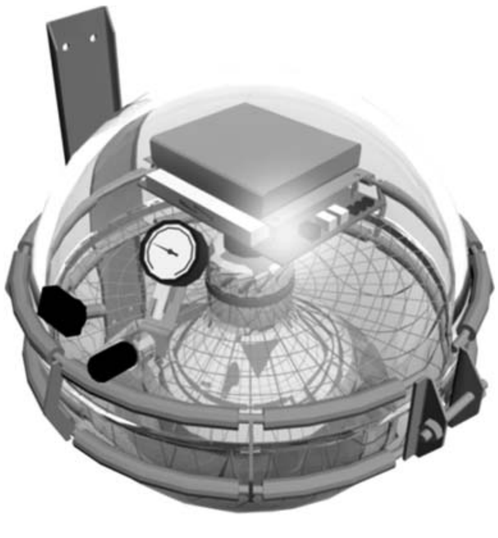

Fig. 2. Optical module

The PMTs detect Cherenkov radiation generated in water by relativistic charged particles — muons or electromagnetic/hadronic showers. The analog signals induced by Cherenkov radiation in the PMTs pass through a two-channel amplifier and a dedicated deep-water 90-m-long cable and then arrive at the center of the section, at the analog-to-digital converter (ADC) board for digitization and processing [4, 5].

The signals arriving from the optical modules are digitized in 12-channel ADC boards located at the center of the section with its 12 optical modules. The functional diagram of one measuring channel of the ADC board is shown in Fig. 3. Each spectrometric channel is based on the AD9430 ADC with a resolution of 12 bit and a sampling frequency of 200 MHz. When digitized, the signal from the ADC is translated into the Xilinx Spartan 6 field programmable gate array (FPGA). The FPGA software loaded over the data transmission channel ensures control and front-end processing of data arriving from the ADC. The 12 Kbyte FPGA memory buffer allows acquisition of data on the input signal waveform over a time interval as long as 5 μs.

A peak detector and a multichannel analyzer are connected to the measuring channel. They accumulate monitoring data (amplitude histograms) allowing control of the measuring channel performance. The trigger is based on the information formed in the channels of requests of ADC board. Each channel of requests includes a signal smoothing device (smoothing level, 1–8) and a two-level digital comparator with adjustable thresholds (low threshold L and high threshold H). Depending on the stated physical task, the values of the comparator thresholds may vary for different channels and, in normal operating mode of the detector, are 0.3 and 3.0 p.e. for L and H, respectively. The expected counting rate of an 8-string cluster at these thresholds is ~ 100 Hz.

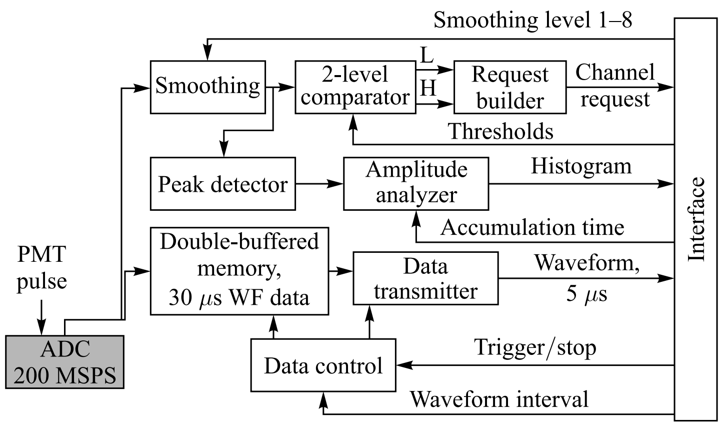

Fig. 3. Functional diagram of one measuring channel of the ADC board

2. TRIGGERING AND DATA TRANSMISSION

An effective suppression of noise events is achieved by using flexible and tunable trigger conditions in the request analyzer. A Spartan 6 FPGA logic has been configured for generating a trigger, reading data from the ADC channels, and transmitting them over the Ethernet channel (the integrated network 100Base-TX interface) into the data acquisition center.

As a result of processing of L and H channel requests from all ADC channels of the section, the request analyzer forms a request of the section. The embedded hardware–software Coincidence Matrix module ($12H \times 12L$) is used to process requests of the channels. This module provides the simplest and fastest method for generating the section request. The trigger system is operative in two modes: majority coincidences of the L request signals in the selected time interval ("L trigger") and coincidences of the L and H requests in any neighboring optical modules ("L&H trigger").

The request signals of all sections are sent to the cluster center, where the acknowledgement signal being a common trigger for all strings is generated. The trigger signal initiates the generation of a common signal "Stop" for all measuring channels, read-out of the ADC data buffer, formation of the output buffer (the time frame) and its transmission to the data acquisition center. The delay time of the common trigger is ~ 15 μs (the delay of the signal passage through 1.2-km line from the central module to the cluster center and backward, as well as the delay in the electronic units). For each channel, the beginning of the time frame may vary within a range of 0–30 μs relative to the moment of trigger arrival. In this case, the frame duration is limited to a maximum value of 5 μs. The Spartan 6 FPGA logic also provides a real time data processing. As a result of this processing, only those parts of the time frame are transmitted to the data acquisition center where an excess over the threshold is observed (i.e., this is a filtering mode). In this case, the data compression ratio is as large as 10^2.

The underwater local-area network (LAN) of the Baikal-GVD is a branched structure of star topology, consisting of a group of communication channels for data exchange between different detector units. Each ADC board with a Spartan 6 FPGA chip at the section center has its own IP address in the cluster LAN, which allows access to it and data read-out from the registers according to the TCP/IP protocol. The cluster LAN is divided into three levels. The first level covers the distance of ~ 6 km from the on-shore data processing center to the cluster center. The second level has a length of ~ 1 km and services data transmission between the cluster center and communication modules of the strings. The third communication level is maintained between sections of optical modules inside one string — in this case, the distances are several hundreds of meters. The functional diagram of the Baikal-GVD cluster triggering and data transmission system is shown in Fig. 4.

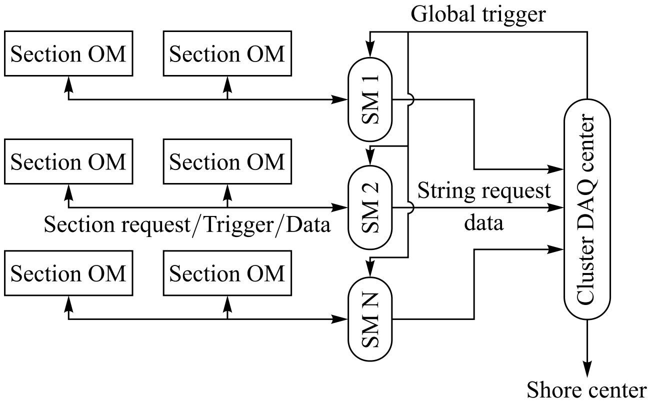

Fig. 4. Diagram of the GVD cluster triggering and data transmission

The calculated total data flow from the cluster has to be about 100 Mbit/s, which is by an order of magnitude lower than the allowed throughput of the fiber line. If necessary, the data transmission along the optical fiber line between cluster center and shore center may be increased by using all modules of the electro-optical cable or by changing over to the Ethernet 10G technology, with a throughput of up to 10 Gbit/s. The second and third levels of the underwater LAN have a length of 100–1000 m and contain numerous distributed data channels (communication from each string to the cluster center); therefore, the use of optical deep-water lines is technologically inexpedient. The alternative for the optical fiber Ethernet technology at distances from 100 m to a few kilometers is the family of DSL technologies. The highest rate of data transfer over the electrical deep-water cables of the Baikal-GVD (a twisted pair with a cross section of 0.5 mm^2) has been obtained with SHDSL modems — up to 10 Mbit/s. For the required event registration rate of detector (100 Hz or higher) to be attained, the data arriving from the sections can be processed in real time mode.

3. THE FIRST BAIKAL-GVD CLUSTER

In April 2015, the first cluster of Baikal-GVD was deployed in Lake Baikal and commissioned. It encloses several Megatons of the clear waters of Lake Baikal. The first cluster of Baikal-GVD comprises a total of 192 optical modules arranged at eight 345-m-long strings, as well as an acoustic positioning system and an instrumentation string with equipment for array calibration and monitoring of environmental parameters. An artistic view of the cluster is shown in Fig. 5. Seven side strings are located at 40-m distance from the central one (still shorter than the baseline distance of 60 m to allow for easier tests). Each string comprises 24 OMs spaced by 15 m at depth of 900–1250 m below the surface.

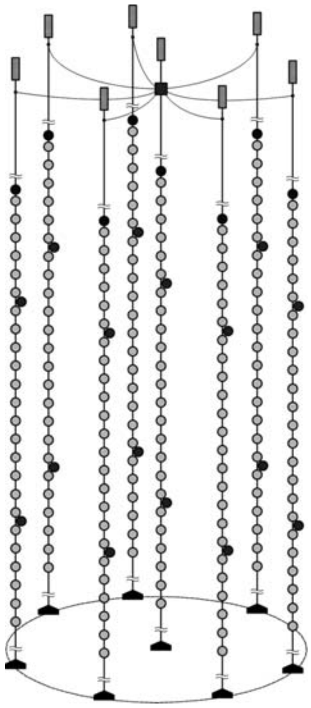

Fig. 5. Configuration of the first GVD cluster

The data acquisition system of the first full-scale cluster is identical to the data acquisition system of the Gigaton Volume Detector and comprises all assemblies of the future detector. Based on the long-term field tests of the produced system, which started in 2013, a decision was made about the possibility of replicating the equipment in the scales of full detector with 27 clusters.

CONCLUSIONS

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 the basic elements — new optical modules, ADC readout units, underwater communications and trigger systems — have been developed, produced, and tested. The first Baikal-GVD cluster consisting of 8 strings has been successfully deployed in 2015.

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