

Acoustic Search for High Energy Neutrinos in Lake Baikal: Status and Perspectives

N.M. Budnev^{3,*}, A.D. Avrorin¹, A.V. Avrorin¹, V.M. Aynutdinov¹, R. Bannasch⁷, I.A. Belolaptikov², D.Yu. Bogorodsky³, V.B. Brudanin², I.A. Danilchenko¹, G.V. Domogatsky¹, A.A. Doroshenko¹, A.N. Dyachok³, Zh.-A.M. Dzhlkibaev¹, S.V. Fialkovsky⁵, A.R. Gafarov³, O.N. Gaponenko¹, K.V. Golubkov¹, T.I. Gress³, Z. Honz², K.G. Kebkal⁷, O.G. Kebkal⁷, K.V. Konischev², A.V. Korobchenko^{2,3}, A.P. Koshechkin¹, F.K. Koshel¹, A.V. Kozhin⁴, V.F. Kulepov⁵, D.A. Kuleshov¹, V.I. Ljashuk¹, M.B. Milenin⁵, R.R. Mirgazov³, E.R. Osipova⁴, A.I. Panfilov¹, L.V. Pankov³, A.A. Perevalov³, E.N. Pliskovsky², E.V. Rjabov³, M.I. Rozanov⁶, V.Yu. Rubtzov³, B.A. Shaybonov², A.A. Sheifler¹, M.D. Shelepov¹, A.V. Shkurihin⁴, A.A. Smagina², O.V. Suvorova¹, V.A. Tabolenko³, B.A. Tarashansky³, S.A. Yakovlev⁷, A.V. Zagorodnikov³, and V.L. Zurbanov³

¹Institute for Nuclear Research, 60th October Anniversary pr. 7A, Moscow 117312, Russia

²Joint Institute for Nuclear Research, Dubna 141980, Russia

³Irkutsk State University, Irkutsk 664003, Russia

⁴Skobeltsyn Institute of Nuclear Physics MSU, Moscow 119991, Russia

⁵Nizhni Novgorod State Technical University, Nizhni Novgorod 603950, Russia

⁶St. Petersburg State Marine University, St. Petersburg 190008, Russia

⁷EvoLogics GmbH, Berlin

Abstract. The status and perspectives of the feasibility study to detect high energy cosmic neutrinos acoustically in Lake Baikal is presented. The concept of an acoustic array as a part of the Baikal Gigaton Volume Neutrino Telescope GVD based on results of simulation and background measurements is described.

1 Introduction

Markov's suggestion about the creation of big optical detectors in natural reservoirs [1] had a fundamental significance for neutrino astrophysics development. In such a set-up natural water works as a target for neutrinos and as a medium for Cherenkov light. Last year, the IceCube collaboration detected first astrophysical neutrinos with PeV energies. In spite of big advances in the development of optical UHE neutrino detection they still have quite strong limitations. The main problem is the attenuation length in water and ice, even in purest media it can not be longer than tens of meters for Cherenkov light. That imposes considerable restrictions on the minimal density of the optical sensors in a detector. Since the first optical neutrino telescopes were put into operation it became clear that the volume of the detectors to search for UHE astrophysical neutrinos should be probably much more than one cubic kilometer. Thus, with optical sensors, the cost of such a system is very high. On the other hand in 1957 the Soviet physicist Askaryan showed that UHE particles may produce acoustic

*e-mail: nbudnev@api.isu.ru

pulses [2]. It was suggested to use this effect to search for UHE neutrino in the sea or in Lake Baikal. The considerable advantage of this approach is that acoustic signals with frequencies higher than 1 kHz are capable to propagate over very long distances with minimal attenuation due to absorption (attenuation length is two orders higher than for Cherenkov light), so the dominant attenuation factor is the geometrical divergence of the energy of the acoustic pulse. And it should be mentioned that the amplitude of pulses in the near-field zone decreases only as the square root of distance which is due to the cylindrical form of the wave front produced by showers. So in principle an acoustic neutrino telescope may observe a bigger target volume with a lower number of detector units. Research for the feasibility of acoustic UHE neutrino registration in Lake Baikal was started in 2004. Since then substantial technical and methodological experience was gained [3], [4], [5]. It was revealed that the acoustic background in the Lake Baikal provides even better conditions for neutrino registration than the one in the Mediterranean Sea. In this paper we report the current state of research in the scope of the Baikal acoustic neutrino detection project.

2 Acoustic array design

For the development of the project of the neutrino acoustic detector we take into account results of our previous measurements of hydro-physical characteristics and acoustic background at the site of the Baikal neutrino experiment, as well as results of simulations of acoustic pulses produced by ultra-high energy neutrinos and the propagation of the signal in Baikal water [6], [7]. Cascades, generated by neutrino interactions in water, should produce bipolar acoustic transients. The expected bipolar pulse duration is of the order of several tens of microseconds. The amplitudes of such pulses are proportional to the thermal expansion coefficient $\alpha(T)$ [8], which is proportional to the difference $\Delta T(H)$ between the temperature of water $T(H)$ and temperature of its maximum density TMD $T_{MD}(H)$ at the current depth H . In Lake Baikal this difference $\Delta T(H)$ is close to zero at the depths of about 200-400 m and increases with depth, at 1400 m it is about $2C^\circ$ [9]. Thus, it is sensible to optimize the acoustic detector for “listening” of water layers at depths in the range 800 – 1400 m. The earth is not transparent for the ultra-high energy neutrinos, thus, at depths deeper than several hundreds meters the horizontal neutrinos dominate in total flux Fig. (1). Most of the acoustic signal energy is concentrated within a disk, the axis of which coincides with the axis of the cascade. The pulse amplitude varies very rapidly depending on angle from the median plane of the disk. The directions of the axes of cascades coincide with the direction of incoming neutrinos, in our case they are in the range of nadir angles from 80 to 180 degrees, but acoustic signals from that cascades will propagate mainly at the zenith angles 0-75 degrees.

For the search of such signals it is viable to distribute the Acoustic Sensor Modules (ASM) of the detector in the relatively thin layer with thickness of about 100 m at depths about 500-600 m. This distribution of ASMs provides the best signal-to-noise ratio (SNR) for the acoustic search of ultra-high energy neutrinos in Lake Baikal. On the one hand, the ASMs are in relatively close distances from the areas of the most effective generation of acoustic pulses. On the other hand, there is a very small number of the sources which mimic neutrino signals at large depths in Lake Baikal [6]. ASMs placed at depths larger than 500 m are able to detect the background ‘neutrino-like’ signals at zenith angles more than 110 degrees only when produced by near surface sources located at distances of more than 15 km or by signals reflected from the bottom. In both cases signals are significantly suppressed. As a result, acoustic signals from the most part of high energy cascades are distinguished from the background generated by surface sources. Thus, the distribution of the ASM at depths 500-600 m allows to significantly decrease the detection threshold of neutrino acoustic detection in the cold Baikal water and makes it comparable or even smaller than in relatively warm Mediterranean sea water with its higher thermal expansion coefficient”

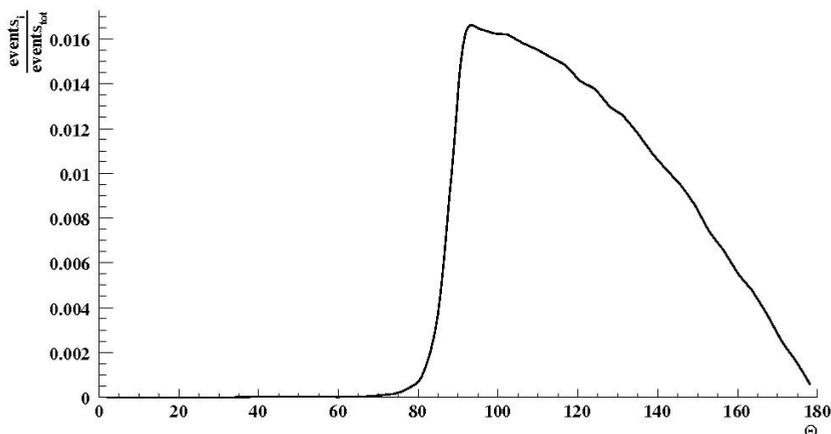


Figure 1. Nadir angle distribution of electron neutrino with energy $10^{17} - 10^{21}$ eV at depth 1 km.

The most realistic plan of the development of such an acoustic detector is to design it as an extension for the Gigaton Volume Detector (GVD) - kilometer-scale Baikal Cherenkov underwater neutrino telescope, which is currently under construction [10]. ASMs will be placed in the quasi-plane layer at the depths 500-600 m. We assume that on every string of GVD we will install up to 8 ASMs with a spacing of about 10 -15 m (Fig. (2)). In this case every acoustic pulse could be detected by several triplets of ASMs placed on the same string. The data about dimensional distribution of amplitudes is important for the suppression of short background signals which could appear as a result of interference of acoustic waves from distributed sources (rain, waves on the surface, etc.), and produced by some quasi-local sources (fish, boats, etc.) at shallow depths. The distribution of amplitudes and wave-factors in the first case will be quasi-random, in the second case we expect a quasi-spherical wave-front. In the both cases the time-dimensional distribution of pulses strongly differs from the pancake pulses from high energy cascades.

3 Baikal Acoustic Sensor Module

The main elementary unit of the Baikal acoustic neutrino detector - the Acoustic Sensor Module - is a device capable of detecting signals of predefined shape and to interpret them in terms of a plane wave, generated by a quasi- local source. To reconstruct the direction of the pulse's source each ASM will be equipped with an antenna with at least 4 hydrophones. The optimum distance between the hydrophones is defined by the condition that it must surely exceed several wave-lengths of the expected signal but, on the other hand, should not be too long in order to minimize the number of background pulses covered by the "time window" [6]. So, we arranged the hydrophones in the shape of a tetrahedron with equal distances of about 1.5 m between the hydrophones. All ASMs of every string are connected to the String Control Module (SCM), which provides acquisition and preprocessing of the data from the ASM, sending the data to the Shore Computer Center (SCC) of the Baikal Neutrino Observatory, operating with control input from SCC to ASM, synchronization and power supply for ASM.

The power supply and communication management within an acoustic string is organized as follows. The supply DC voltage of 300 V for the string is applied to the SCM where it is converted

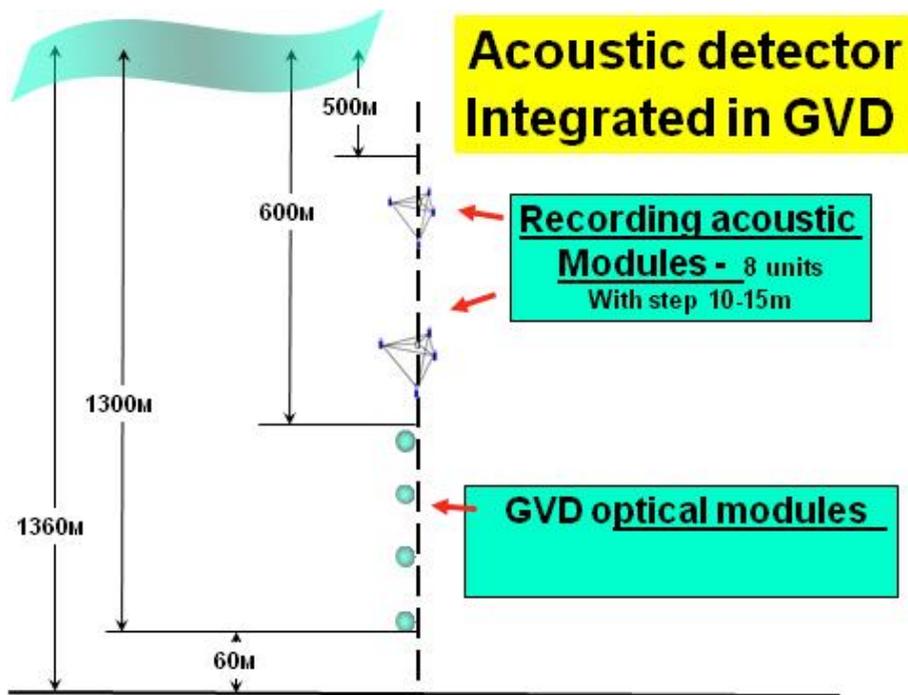


Figure 2. Acoustic Sensor Modules on a string of the Gigaton Volume Detector.

to the level of 48 V and distributed over the all ASM with power supply and synchronization (PSS) board, see Fig. (3). All ASM and power supply board controlling electronics is locally networked with star topology. Communication between acoustic strings and lakeside computer is realized with DSL modems. For electric power transmission to ASM and communication the same Ethernet cable is used.

The all data interchange is realized through a switch-board installed on the SCM. On the PSS board Ethernet traffic from the switch-board is redirected to special RJ-45 connectors manufactured by HALO company specialized on the support of the PoE technologies. In that connector the data flow is joined with the power supply and is transmitted through one net cable to the detection module. The detection module power supply chain is equipped with a resettable fuse designed for a current of 1.5 A. It will switch off the power supply channel of the ASM if a software protection does not switch off the power in case of a short circuit for whatever reason.

There are two parts on the PSS board: a control unit and a unit responsible for monitoring of the power parameters. The control unit performs the controlling of gates of solid state relays PVG612PBF of ASM power supply system. It's central element is the micro-controller STM32F437. The power monitoring unit is used for permanent checking of voltage and currents of acoustic string electronics. In case of identification of any malfunctions it informs the control unit in due time. The central element of the power monitoring unit is the STM32F303 micro-controller. The components belonging to different units are galvanically isolated from each other. As sensors for the hydro-acoustic antennas, piezoelectric hydrophones developed in the Far-East State University are used. They have sufficiently high and homogeneous sensitivity in a cone with opening angle of about 30 degrees in the frequency

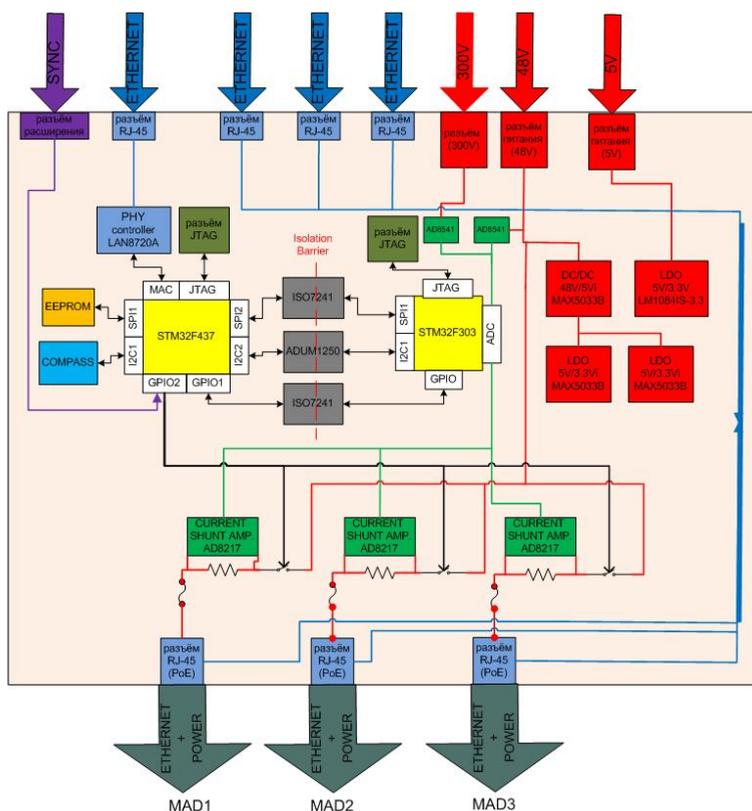


Figure 3. The functional scheme of the power supply and synchronization board.

range 5-30 kHz, from other directions the sensitivity is significantly lower. Such parameters of hydrophones allow to listen deep layers of the lake effectively and significantly suppress the influence of the background from the surface layer. Hydrophones have integrated pre-amplifiers with two amplifier stages. The first cascade is developed as charge amplifier, because the source of the signal has a very high output resistance. The second cascade transforms the asymmetric signal to a differential one, which comes via differential pair to the input of an analog chain of the ASM. Total amplitude amplification factor is 10. Test of the measurement chain in the lab gives the following results: input referred self-noise level of analogous channels is of less than 1 μ V, bandwidth 53 kHz, ripple of amplitude-frequency characteristic in the frequency range of 3 – 38kHz is about ± 3 dB hydrophone sensitivity is about 0.8 mV/Pa, beam width is 90 degrees. Total gain of analog channel is from 20 dB to 80 dB with possibility of setting with step of 3 dB.

The calibration of the acoustic detector was successfully performed in situ at Baikal neutrino observatory site with a specially developed emulator of neutrino acoustic signals.

4 A prototype acoustic string

To test the main technical and methodical solution we constructed a prototype acoustic string consisting of 3 Acoustic Sensor Modules and the String Control Module. This setup was arranged on

the engineering string of Baikal neutrino observatory. The data are in processing. An example of a background neutrino-like pulse detected by one of the ASM is shown in Fig. (4). Its zenith angle is 21 degrees.

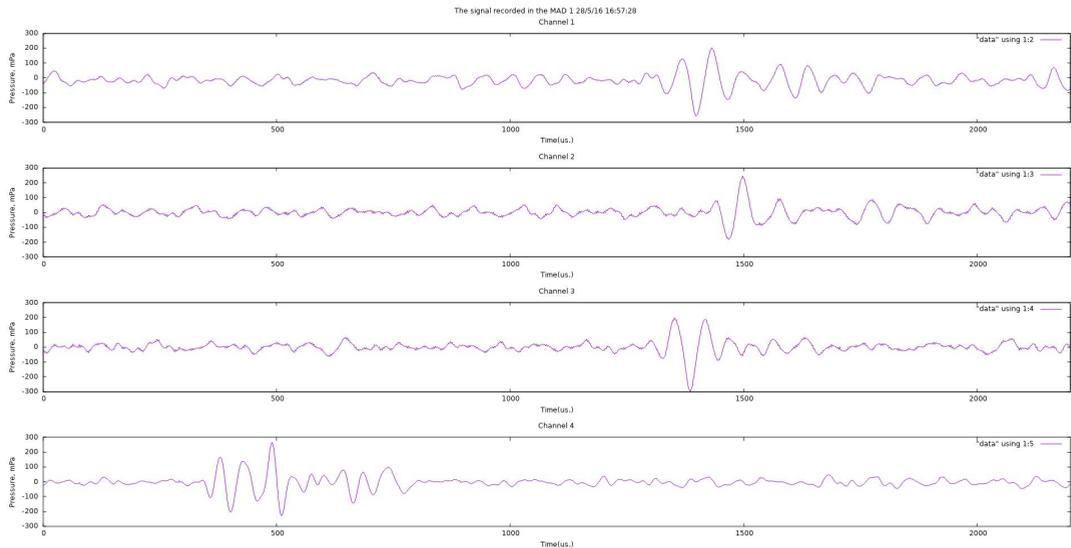


Figure 4. A sample of background neutrino-like pulse detected 28-05-2016.

5 Summary and outlook

Acoustic neutrino detection in Lake Baikal and in other natural reservoirs is far from being trivial due to high level of background noise. Comparison of results of acoustic pulse characteristic calculations and properties of noise in Lake Baikal shows that the energy threshold for neutrino detection in the lake should be of order $10^{19} - 10^{20}$ eV [6]. Taking into account that sources of background including “neutrino-like” short pulses are concentrated in a near-surface zone, we suggest an acoustic detector design that is based on the deployment of a grid of Acoustic Sensor Modules with rather compact antennas arranged at stings of the Gigaton Volume Detector at depths 500–600m at distances of 10-15 m. This configuration is optimized to identify interaction of ultra-high energy neutrino by listening from the top to signals from the deeper zones of Lake Baikal.

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