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Faculty of Mathematics, Physics and Informatics

Mgr. Lukáš Fajt

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Time calibration and Pulse Processing of the Baikal-GVD Neutrino Telescope

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4.1.5. Nuclear and Subnuclear Physics

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Submitter:	Mgr. Lukáš Fajt Department of Nuclear Physics and Biophysics, Faculty of Mathematics, Physics and Informatics, Comenius University, Mlynská dolina F1, 842 48 Bratislava 4, Slovakia
Supervisor:	prof. RNDr. Fedor Šimkovic, CSc.

Study field:	4.1.5. Nuclear and Subnuclear Physics
Study program:	Nuclear and Subnuclear Physics

Chairman of committee:
prof. RNDr. Jozef Masarik, DrSc.
Department of Nuclear Physics and Biophysics,
Faculty of Mathematics, Physics and Informatics,
Comenius University,
Mlynská dolina F1, 842 48 Bratislava 4

Contents

1 Introduction

In the last few decades, the neutrino physics has become the object of interest for many physicists. We witnessed many astonishing discoveries and huge progress in the theoretical as well as experimental neutrino physics where this effort was awarded with multiple Nobel Prizes. One of very promising fields of neutrino physics is the neutrino astronomy which deals with detection of high energy astrophysical neutrinos coming from distant galactic and extragalactic sources thus opening a completely new observation window to the Universe. For detection of such very rare and elusive particles, it is necessary to build detectors of gigantic dimensions ($\sim \mathrm{km}^3$) [1].

The main motivation for the neutrino astronomy is the fact that astrophysical neutrinos, despite their tiny detection probability, are perfect cosmic probes. In contrast to the charged particles they are not influenced by the cosmic electromagnetic fields thus they travel in a straight path from the point of their origin. In addition, neutrinos interact very weakly and thus penetrate enormous distances in contrast with high energy gammas which can be scattered or absorbed. Moreover, neutrinos can without problem escape from very dense regions, i.e. core of the collapsing stars, active galactic nuclei, etc. This means that neutrinos can be used to provide undistorted picture of sources where the unimaginable amount of energy is released. In this way they could shed some light on explanation of origin and propagation of high energy cosmic rays.

The Baikal collaboration, which is currently building the neutrino telescope Baikal-GVD in the largest and deepest lake in the world, was one of the first one in the world that started neutrino telescope program in 1981. In 2019, the Baikal collaboration finished installing the fifth cluster and Baikal-GVD thus became the largest neutrino telescope on the Northern hemisphere and one of the key players on the scene. The first construction phase of the Baikal-GVD is going to be finished in 2021. Where $0.4\,\mathrm{km}^3$ of sensitive volume will be instrumented by 2592 optical modules. However, the increasing number of installed clusters has been taking data since 2015. The data is used to develop a brand new and improve the previously used calibration, analysis and reconstruction techniques. This thesis focuses on the development and improvement of wide range of processing techniques including, pulse processing, double pulse identification and time calibration of the detector. In addition, extensive MC simulations and laboratory measurements of the possible future surface extension of the Baikal-GVD were performed.

2 Thesis Aims

The main aims of the dissertation thesis are as follows:

A. Familiarize with the time calibration systems of the Baikal-GVD telescope. Understand the calibration procedures used to date. Design and implement advanced time calibration techniques with emphasis to the accuracy of the time calibrations and to the complete automation. Verify the obtained precision of the individual steps of the calibration. Study the time walk effect and its influence to the time calibration procedure.

B. Design and perform MC simulation of possible future surface extension of the Baikal-GVD underwater detector with the help of CORSIKA and GEANT4 simulation toolkits in order to optimize the surface extension parameters, i.e., number of stations, distances and dimensions. Study the parameters of the secondary cosmic rays simulated with CORSIKA. Use secondary atmospheric muons simulated in the CORSIKA as the input for the Geant4 simulations. Implement scintillator geometry, composition and scintillation properties to the GEANT4. Simulate response of the scintillator to the secondary atmospheric muons. At the same time, perform the first laboratory test measurements of newly prepared prototypes including scintillators, PMTs, and amplifiers.

C. Improve the present pulse processing procedure used in the off-line processing of the Baikal-GVD data. Focus mainly on the pulse shape analysis. Introduce new pulse processing techniques. Find the best possible analytical formula for the systematic description of the Baikal-GVD pulses. Use this formula to study the effect of finite sampling frequency on the precision of the pulse time estimation and to explain the trigger threshold anomaly. Implement new MC data merging technique based on the analytical formula. Create a MC pulse generator.

D. Find and implement new double pulse detection techniques acting on the measured waveforms. Study their classification efficiencies on the wide range of the double pulses. Use advanced machine learning techniques to achieve optimal classification performance. Determine the limits of the double pulse detection and explore new methods how they can be overcome.

E. Participate in detector construction directly at Lake Baikal during regular winter expeditions. Collaborate with members of expedition to install new detector parts as well as replace malfunctioning detector components.

3 Time Calibration

In the end of Phase-1, the Baikal-GVD will contain almost 2600 Optical Modules (OMs). Every OM holds a 10" Hamamatsu PMT which can detect light coming directly from high energy neutrino interactions in water or from secondary particles created in these interactions. From the positions of OMs, detection times and amplitudes of detected pulses, the direction, position and energy of secondary particles which carry the information about primary neutrinos can be reconstructed. The precise measurements of previously mentioned parameters can also significantly help reject background events.

To allow reconstruction with high accuracy, the time frames of the individual OMs have to be synchronized carefully [2, 3]. The synchronization procedure is called time calibration. The GVD cluster consists of 24 sections where every section consists of 12 OMs. To secure the highest accuracy of time calibration of the whole cluster with respect to this arrangement, the time calibration is performed in two consecutive steps:

- Intra-section calibration - The relative time delays of OMs in one section are obtained. For this type of calibration, the two built-in LEDs installed in every OM are used.
- Inter-section calibration - The time differences between individual sections in the cluster are measured. This calibration can be achieved by means of the electronic calibration runs, regular muon runs and calibration LED matrices.

With this approach, the most suitable time calibration system as well as its operational conditions can be chosen. In the calibration procedure, the time corrections for every individual channel are obtained and applied later on in the offline processing. In the Baikal-GVD, all steps of the time calibration procedure are performed in situ, except the measurement of signal cables delays that are measured in a laboratory. The Baikal-GVD was designed and constructed so that more different calibration systems and methods can be used in individual calibration steps and their results are used to estimate the precision of the obtained calibration corrections.

The brand new completely automated programs for the intra- and inter-section calibration were written and all the calibration runs taken for the last three years were periodically processed. New calibration techniques were incorporated to the both steps of the calibration procedure. Intra-section time corrections of all three installed clusters were obtained and their precision and time stability were verified. The mean intrinsic time resolution given by the electronics, finite sampling and pulse time extraction was obtained for all clusters and in all the cases is below 0.3 ns.

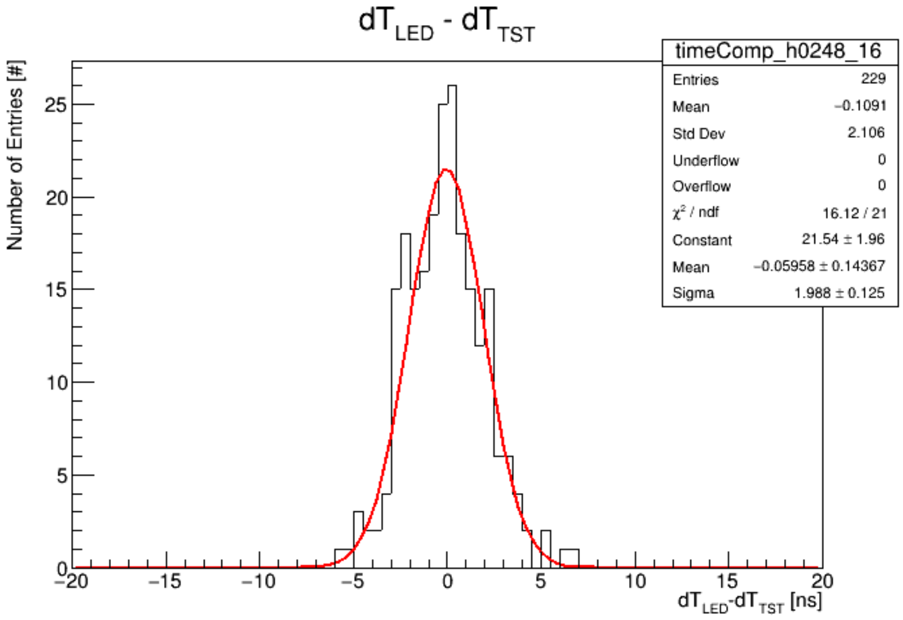

Figure 1: The comparison of the intra-section time corrections obtained by two independent methods, i.e. dT_{TST} and dT_{LED}. The distribution is fitted with Gaussian function. The $\sigma = 1.99\,\mathrm{ns}$ presents the worst case scenario for the time calibration precision.

The accuracy of the individual steps of the time calibration was cross-checked by multiple independent calibration systems and procedures on wide range of distances and intensities. The program for inter-section calibration takes into account the real geometry of the string measured by acoustic modules. The precision of the time inter-section calibration was improved with a two-phases fitting procedure of the measured time distributions. Based on the obtained results, it can be concluded that the achieved precision of the time calibration within individual clusters is below 2 ns (see Fig. 1). The time stability of the calibration was verified with the resulting mean change of calibration parameters safely below 0.5 ns in a time scale of few months.

New extended calibration runs were designed, tested and performed to evaluate the strength of the Time Walk Effect on the pulse time extraction precision for all clusters. It was the first time the time walk effect was measured for all OMs simultaneously *in situ*. In the worst case scenario, the TWE can reach up to 4 ns depending on the charge of the pulse and thus has to been undoubtedly taken into account. To eliminate this effect, two different approaches were used to design the correction function. With general approach, where single time walk correction function is used, the overall calibration precision improves to 1.5 ns. The new time calibration techniques can be readily used in the Baikal-GVD standardized data processing chain. The results of the described time calibration procedure will provide a solid basis for future work in this topic, i.e.

the time calibration with the reconstructed muon tracks and its further improvement.

4 Detector Surface Extension

The neutrino telescopes installed in the water (sea or lake) have many advantages like low light absorption and scattering, possibility to re-arrange the geometry and much more. However, one of their disadvantages is the fact that the surface detector can not be installed above them. This in fact do not apply for the Baikal-GVD detector since the surface of the lake is frozen for the part of the year. The ice thus creates safe solid platform for surface detector. On the other hand, the surface detector can be installed on the lake for only 3 months.

The idea of the detector Surface Extension (SE) which should complement the underwater neutrino telescope is not new [4, 5]. The plan is to use a relatively small plastic scintillators (0.5-1.5 m) with a small (1-2 inch) PMTs however different configurations and parameters of the array and scintillators are being studied. This configuration is much cheaper, simpler and easier to install and maintain than other options. The main purpose of this array of surface scintillation detectors is a detection of secondary cosmic ray showers. The array can thus be used as an atmospheric muon veto as well as a veto of atmospheric neutrinos from zenith. Nevertheless, the surface array can be also used to study many other phenomena like spectrum of secondary cosmic rays, the precision of GVD reconstruction procedures, etc.

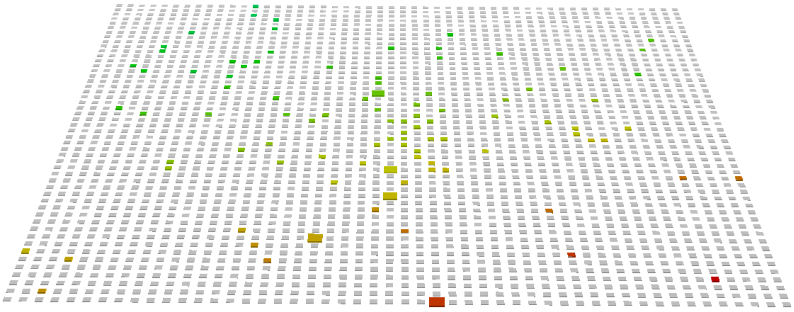

Figure 2: The visualization of the detected secondary cosmic ray with SE detector with 50x50 scintillators with 10 m spacing in square configuration. The energy of primary particle is 10^{15} eV and $\vartheta = 45°$. The color of the station represents time of detection and its size represents the number of muons passing given station.

First of all, the detector design, performance and limits have to be known to evaluate the benefits of the extension with respect to its cost. To achieve that, the multi step extensive MC simulations were developed and performed. Starting with the simulation of the secondary cosmic rays with CORSIKA, followed by the simulation of the energy losses and light propagation in the scintillators in GEANT4 and ending with the reconstruction of the pulse waveforms. The purpose being to study the response to the secondary cosmic rays (see Fig. 2) as well as to optimize its parameters, i.e. number of stations, distances and dimensions. The first results concerning the scintillator configuration and expected strength of the signal in number of photoelectrons were achieved with CORSIKA and GEANT4.

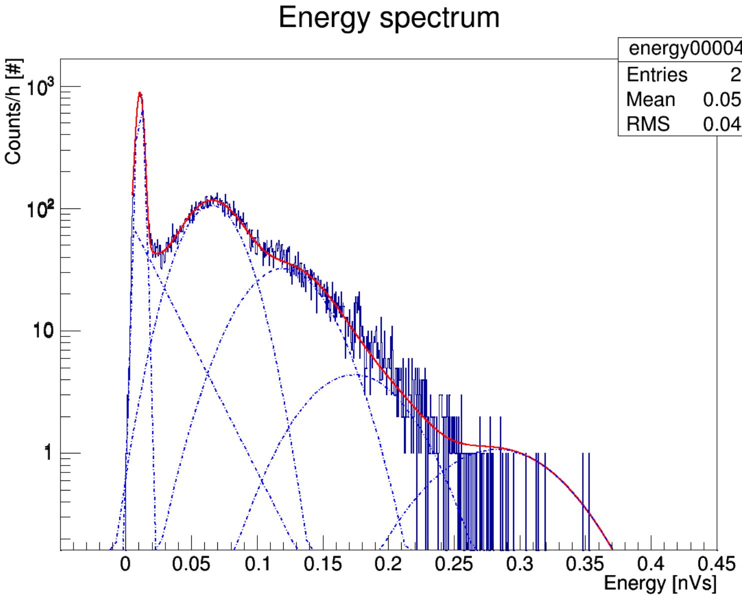

Figure 3: Results of the PMT single photoelectron technique calibration. The pedestal peak as well single, double, triple and quadruple photoelectron peaks and exponential noise component are represented by the blue dashed lines. The red line shows the overall fit result.

In parallel, the first laboratory measurements were performed. The first PMTs were calibrated with a single photoelectron technique for different values of applied high voltage, furthermore the dark noise rates were determined. The new charge sensitive amplifiers were examined and compared with raw unamplified pulses. The first prototype scintillators were tested with atmospheric muons. The results of laboratory measurements, ~ 100 p.e./muon, agree well with the results obtained from the GEANT4 simulations, ~ 80 p.e./muon.

5 Pulse Processing

The possibilities of the new advanced pulse processing were studied in detail. The emphasis was placed on the analytical formula of the pulse shape. The Gumpbel function [6] defined as:

$$f(x) = a \cdot \mathrm{e}^{-(z(x) + \mathrm{e}^{-z(x)})},\ z(x) = \frac{x - \mu}{\beta} \tag{1}$$

where a represents the amplitude of the pulse, β represents the width of the pulse and μ is the position of the pulse maximum, was identified as an ideal candidate describing correctly a wide range of measured pulses (see Fig. 4). It was successfully shown that the analytical formula can be used to extract pulse parameters like charge and time. Next to this success, it was also used to create a MC pulse generator and to improve the agreement between the measured and simulated data.

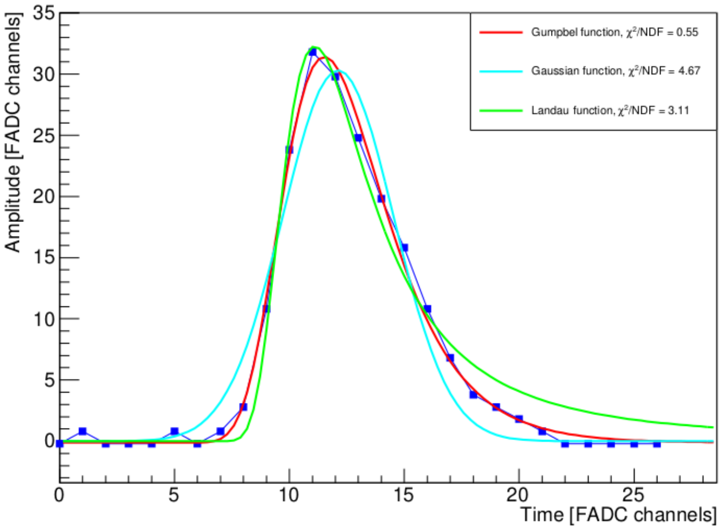

Figure 4: Comparison of three alternative functions aiming to describe the Baikal-GVD pulses: Gauss, Landau and Gumpbel. The best possible candidate is the Gumpbel function with $\chi^2/\mathrm{NDF} = 0.55$.

The MC pulse generator was utilized to study the effect of finite pulse sampling rate and to explain the disagreement of the trigger threshold values. It has been shown that the 5 ns sampling frequency does not significantly affect the pulse time estimation. Regarding the trigger threshold, the re-scaling factor was calculated and after winter expedition in 2019 its value was used to set correct trigger threshold values of two newly installed clusters. The Gumpbel function was adopted to control the quality of the measured pulses and to identify the double pulses. Once the double pulses are found, the Gumpbel function is used to separate them and to reconstruct the original parameters of the constituent single pulses (see Fig. 5). The findings of the new analytical formula were incorporated in the new standard pulse processing method that was implemented to the Baikal-GVD data processing software BARS. The new method improved the charge calibration accuracy and opened new possibilities for suppression of the noise pulses based on the pulse shape analysis. Eventually, this can lead to significant improvements of the muon angular reconstruction precision.

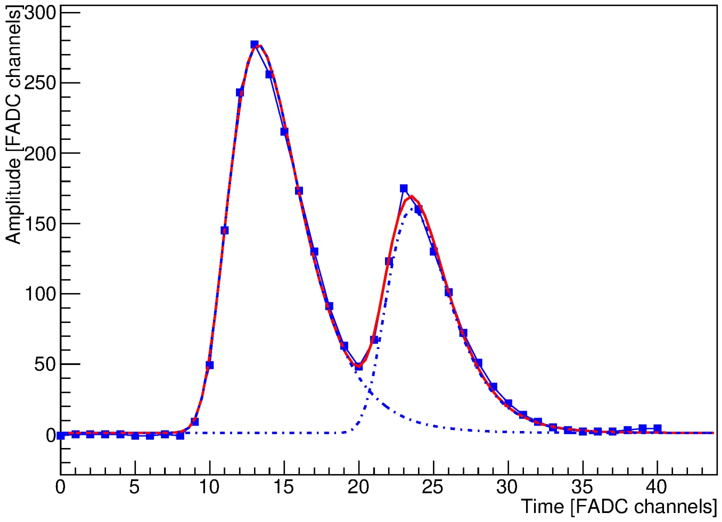

Figure 5: Illustration of the DP separation with the Gumpbel function. The DP waveform is fitted with the sum of two Gumpbel functions. The parameters of the constituent SPs can thus be reconstructed.

6 Double Pulses

The Baikal-GVD is a 3D lattice of PMTs transforming the Cherenkov light produced by relativistic charged particles to electric signals. These signals are sampled and digitized by an FADC thus creating a waveforms. The regular waveforms created as a response of the PMT to a single interaction produced by a single particle are called Single Pulses (SP). The SPs are characterized by distinctive leading and falling edges and by the absence of a local minimum between them. On the contrary, if a PMT is hit in quick succession by light produced by more particles or by light produced in more interactions of the same particle, the individual SPs overlap and the waveform clearly displays a multiple peak structure. Such pulses are called Double Pulses (DP). An example of the usual DP is shown in Fig. 6.

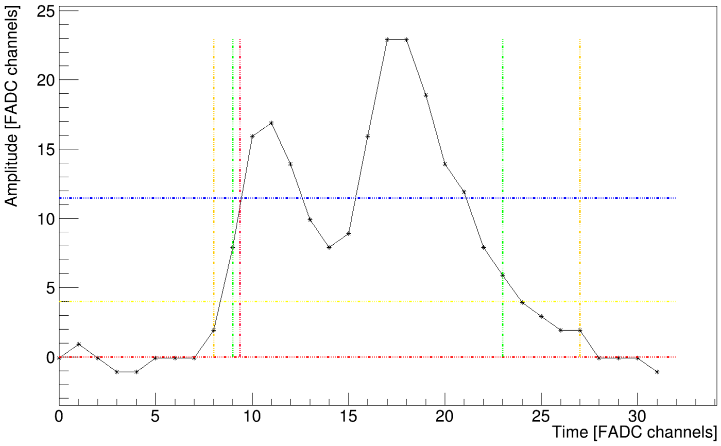

Figure 6: An example of a detected DP.

Until now, all the pulses in the Baikal-GVD were classified as SPs, however the separation of SPs and DPs can have far-reaching impact on the understanding of the detector hardware, on the suppression of the background as well as on the search for astrophysical neutrinos. For these reasons, brand new Double Pulse Detection Techniques (DPDTs) were developed, implemented and tested on real waveforms from the detector. The techniques described in the following text were optimized specifically for the Baikal-GVD nevertheless the pulse overlapping is a general problem affecting a wide range of experiments. The presented techniques can be easily modified to fit needs of other experiments.

Three completely new double pulse detection techniques were designed and tested with real measured double pulses. They have been optimized for the optimal performance with Baikal-GVD data. However, they can be easily implemented by any other experiment with interest for pulse overlap identification. First technique uses the first derivative of the waveform to detect DPs. The second technique exploits the difference in the charge-amplitude ratio for SPs and DPS. The last technique is based on the Gumpbel function described above. The Gumpbel function describes very well the SPs. The large χ^2/NDF of the pulse fit with the Gumpbel function can be an implication of the DP nature of the pulse.

The individual techniques perform well for only limited range of pulses. Thus, more advanced double pulse detection technique including all three simpler techniques was implemented. This advanced technique is based on the machine learning, specifically on the boosted decision trees. Large training datasets of the double pulses from real measured waveforms were created and they were used to train the boosted decision trees to identify the double pulses. The 90.74 % double pulse detection efficiency was reached while the 99.66 % of background events were rejected. The Boosted decision trees double pulse detection technique was implemented to the BARS and for the first time enabled to classify the Baikal-GVD pulses according to their origin. The new double pulse detection technique can be successfully used for a large number of applications. It can be used to separate the atmospheric muon bundles from the single muons created in the neutrino interaction, thus significantly reducing the background. Moreover, completely new fields of research have opened up. Mainly, the search for the high energy tau neutrinos which can serve as a completely independent probe of the extraterrestrial origin of the high energy neutrinos. Clearly, further research will be needed to prove the benefits of the double pulse detection in these applications.

7 Winter Expeditions

The Winter Expeditions (WEs) are very important and serious events for the Baikal-GVD project. Every year during two and half months, usually starting in February, the members of the Baikal collaboration - scientists, technicians, engineers, join the common efforts directly at Lake Baikal. The main goals of the WEs are: a) installation of new clusters, b) replacement of malfunctioning parts, c) deployment of shore cables, and d) installation of the calibration sources.

The author of this thesis was so fortunate that he could attend three consecutive winter expeditions (see Fig. 7) in shorter time periods and cooperate with the real experts and learn a lot from them. It was magnificent experience and excellent opportunity for a newcomer to understand how complicated it is to construct a neutrino telescope and its operation at first hand. The short overview of the tasks that he focused on is given:

1. WE2016 (12 days) - Replacement of the malfunctioning OMs, dismantling and removal of old underwater infrastructure and rearrangement of peripheral strings from original 40 m to a final 60 m distance.

2. WE2017 (20 days) - Installation of the new strings of the second cluster: new OMs, CeMs, AMs, calibration devices etc.

3. WE2018 (22 days) - Repair works of the first and second clusters, deployment of the shore cable.

The winter expeditions are a very crucial period in the year for the Baikal-GVD collaboration. It would not be possible without determined and experienced members of the collaboration, who work hard at the lake during tough conditions (sometimes up to -35 °C), seven days per week, 10 hours per day, 2 months in a row.

Figure 7: Picture of the installation works on the surface of the frozen lake. The author of the thesis is first from right.

Summary

The neutrino astrophysics has undergone tremendous development within the last decade. New neutrino telescopes are being installed on different locations of the world. The high energy astrophysical neutrinos have been discovered. In addition, the first extraterrestrial source of the high energy neutrino was identified with a multi-messenger approach of temporal and spatial coincidences with other types of particles. However, the detector IceCube is still the only one which proved, without doubt, the astrophysical nature of the detected neutrinos. Moreover, the deficit of the detected high energy tau neutrinos is in contradiction with expectations. The muon track detection channel enables detection of neutrinos only from the hemisphere shielded by the Earth itself. Therefore, to cover the whole sky, other km^3 scale neutrino telescopes have to be installed on the Northern hemisphere to complement the IceCube detector located on the South pole.

To tackle these yet unsolved issues, the Baikal-GVD is being installed in Lake Baikal lake since 2015. In 2018 it became the largest neutrino telescope on the Northern hemisphere. In addition, it is going to double its recent volume till 2021. Simultaneously with the detector installation, which is already a well defined and refined procedure improved every year, the development and enhancement of the calibration, data processing and particle reconstruction procedures have to be performed to reach the best possible performance of the detector. Since the high energy neutrino astronomy is trying to detect a very rare events, it should not be forgotten, to search for and develop new possible extensions of the detector that could improve the overall background rejection capabilities.

The work presented in this thesis is devoted to the improvement of the Baikal-GVD performance with results from various topics including time calibrations, pulse processing, double pulse detection, and MC simulations and laboratory measurements of the possible surface extension of the detector. Many of the new techniques, presented in this thesis, were already incorporated to the main Baikal-GVD processing software BARS and used by other members of the collaboration. In addition, the new advanced pulse processing improved the precision of the charge calibration. The implementation of the double pulse classification opened the possibility to search for tau neutrinos and to reduce the atmospheric muon background component. On the level of the detector construction, the author of this thesis joined three winter expeditions and contributed to the construction of the state of the art neutrino telescope.

List of publications

I. A.D. Avrorin et al., *Dark matter constraints from an observation of dSphs and the LMC with the Baikal NT200.* Journal of Experimental and Theoretical Physics 125(1), 2017.

II. A.D. Avrorin et al., *Baikal-GVD.* EPJ Web of Conferences 136, 04007, 2017.

III. B. Shaybonov et al., *Search for cascade events with Baikal-GVD demonstration cluster "Dubna"* . PoS ICRC2017, 962, 2018.

IV. V. Aynutdinov et al., *Status of the Baikal-GVD experiment - 2017* . PoS ICRC2017, 1034, 2018.

V. K. Golubkov et al., *Calibration and monitoring units of the Baikal-GVD neutrino telescope* . PoS ICRC2017, 1032, 2018.

VI. A.D. Avrorin et al., *Hydroacoustic Positioning System for the Baikal-GVD* . PoS ICRC2017, 1033, 2018.

VII. L. Fajt et al., *Baikal-GVD: Time Calibrations in 2016.* PoS ICRC2017, 1036, 2018.

VIII. B. Shaybonov et al., *Data management and processing system for the Baikal-GVD telescope.* PoS ICRC2017, 1046, 2018.

IX. A.D. Avrorin et al., *Gigaton Volume Detector in Lake Baikal: status of the project.* PoS NEUTEL2017, 063, 2018.

X. L. Fajt, *Time calibrations of the GVD neutrino telescope (Extended Abstract).* Proceedings of the Student Science Conference, 2018.

XI. A.D. Avrorin et al., *Baikal-GVD: Status and prospects.* EPJ Web of Conferences 191, 01006, 2018.

XII. A.D. Avrorin et al., *Search for High-Energy Neutrinos from GW170817 with the Baikal-GVD Neutrino Telescope.* JETP Letters, 108(12), 2018.

XIII. A.D. Avrorin et al., *Luminescence of water in Lake Baikal observed with the Baikal-GVD neutrino telescope.* EPJ Web of Conferences 207, 09002, 2019

XIV. A.D. Avrorin et al., *Environmental studies in Lake Baikal: basic facts and perspectives for interdisciplinary research.* EPJ Web of Conferences 207, 09001, 2019.

XV. A.D. Avrorin et al., *Spatial positioning of underwater components for Baikal- GVD* . EPJ Web of Conferences 207, 07004, 2019.

XVI. M.D Shelepov, L. Fajt et al., *Time calibration of the neutrino telescope Baikal-GVD* . EPJ Web of Conferences 207, 07003, 2019.

XVII. A.D. Avrorin et al., *Baikal-GVD: cascades.* EPJ Web of Conferences 207, 05001, 2019.

XVIII. A.D. Avrorin et al., *Status of the Baikal-GVD Neutrino Telescope* . EPJ Web of Conferences 207, 01003, 2019.

XIX. A.D. Avrorin et al., *Baikal-GVD: first results and prospects.* EPJ Web of Conferences 209, 01015, 2019.

List of conferences and workshops

i. Poster: "Baikal-GVD: Time Calibrations is 2016", International Cosmic Ray Conference, Busan, South Korea, 4.- 14. July, 2017.

ii. Poster: "Baikal-GVD: Time calibrations", Internation school of astroparticle physics, Arenzano, Italy, 6. - 17. June, 2017.

iii. Poster: "Baikal-GVD: Time calibrations", Pontecorvo Neutrino School, Prague, Czech Republic, 20. August - 1. September, 2017

iv. Presentation: "Time calibrations of the GVD neutrino telescope at lake Baikal", Student Science Conference, FMFI, Comenius University, Bratislava, Slovakia, 26. April, 2017.

v. Poster: "PhD at Baikal GVD thanks to the Czech ans Slovak membership in JINR Dubna", 5th South Africa - JINR Symposium: Advances and Challeneges in Physics within JINR and South Africa, Somerset West, South Africa, 5. - 9. November, 2018

vi. Poster: "Analytical formula of the pulses in the neutrino telescope Baikal-GVD", Neutrino 2018 conference, Heidelberg, Germany, 4. - 9. June 2018.

vii. Presentation: "Neutrino Telescope Baikal-GVD", TeV Particle Astrophysics 2018 conference, Berlin, Germany, 27.- 31. August 2018.

viii. 5 presentations of the regular Baikal-GVD collaboration workshops.

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