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Method and device for tests of the laser optical calibration system for the Baikal-GVD underwater neutrino Cherenkov telescope

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The large-scale deep underwater Cherenkov neutrino telescopes like Baikal-GVD, ANTARES or KM3NeT, require calibration and testing methods of their optical modules. These methods usually include laser-based systems, which allow to check the telescope responses to the light and for real-time monitoring of the optical parameters of water such as absorption and scattering lengths, which show seasonal changes in natural reservoirs of water. We will present a testing method of a laser calibration system and a set of dedicated tools developed for Baikal-GVD, which includes a specially designed and built, compact, portable, and reconfigurable scanning station. This station is adapted to perform fast quality tests of the underwater laser sets just before their deployment in the telescope structure. The testing procedure includes the energy stability test of the laser device, 3D scan of the light emission from the diffuser and attenuation test of the optical elements of the laser calibration system. The test bench consists primarily of an automatic mechanical scanner with a movable Si detector, beam splitter with a reference Si detector and, optionally, Q-switched diode-pumped solid-state laser used for laboratory scans of the diffusers. The presented test bench enables a three-dimensional scan of the light emission from diffusers, which are designed to obtain the isotropic distribution of photons around the point of emission. The results of the measurement can be easily shown on a 3D plot immediately after the test and may be also implemented to a dedicated program simulating photons propagation in water, which allows to check the quality of the diffuser in the scale of the Baikal-GVD telescope geometry.

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1. Introduction

The Baikal-GVD telescope[1] is located in the south-eastern part of Lake Baikal, about 55 km to the south of Irkutsk. The telescope's clusters are deployed in a distance around 3.6 km from the shore in a depth of 1366 m (anchor). The telescope currently consists of eight clusters, which are the independent telescope units. Clusters are installed every year during Winter Expeditions, thanks to which the continuous development of the telescope is possible. Each cluster consists of 8 instrumented strings, on each of them there are 36 optical modules, grouped into sections of 12 optical modules. Optical modules, inside which there are photomultipliers and necessary electronics, are directed downwards, so they "look" towards the bottom of the lake. A diagram of the clusters distribution is shown in the Fig. 1.

Such a large research infrastructure located in a natural water reservoir is susceptible to damage and position changes of detection elements caused by water flows. A complex system of telescope positioning and calibration is therefore required to ensure the highest possible accuracy and precision, and also to reveal possible system faults. In such a large telescope, it is also necessary to synchronize the time as precisely as possible between individual modules. To ensure this, several methods of optical calibration are used[2]: LEDs placed in the optical modules, which by emitting short flashes of light enable calibration of the optical modules (intra-section callibration), LED matrix used for inter-section calibration, and a laser system used for calibration between clusters. Lasers (marked in the Fig. 1) are placed between the clusters of the telescope at a distance of about 120 m from the nearest instrumented string.

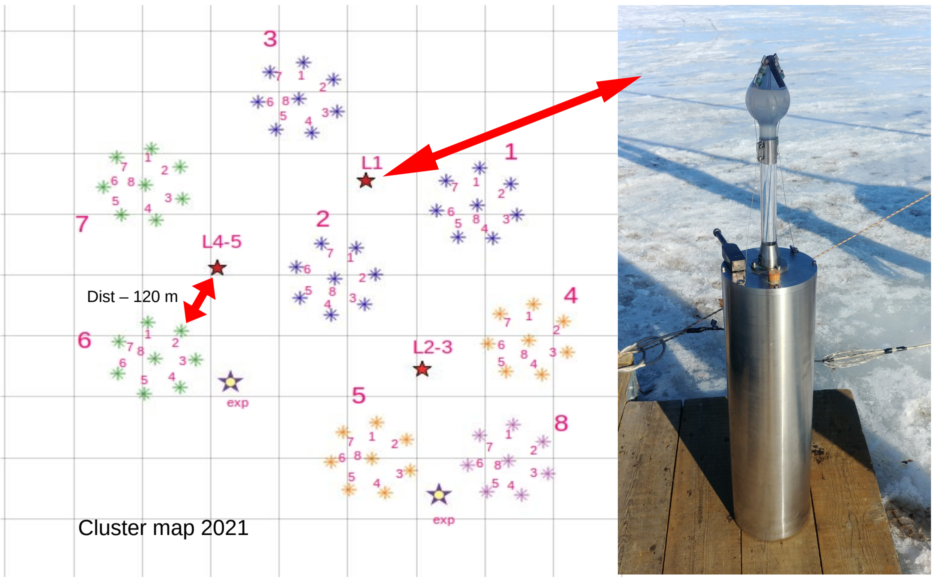


Figure 1: Left: Clusters map for 2021. The positions of the lasers (L1-L5) are marked by red stars. Strings with lasers are placed about 120 m from the nearest instrumented string. Right: Laser in a pressure housing, equipped with a lightguide and a diffuser with a metal hood (reflector) on a top.

The system consists of DPSS, Q-switched lasers[1], emitting a beam on a wavelength of 532 nm and a single flash energy of 370 μJ. The flash duration is about 1 ns (FWHM). Flashes are emitted in series with pulse repetition of 10 Hz. The flash intensity is approximately 2×10^{14} photons.

[1]Diode Pumped Solid State pulse laser

Currently, all lasers are equipped with optical diffusers, enabling a fairly isotropic distribution of light around the laser device. For the proper operation of the entire system, a dedicated simulation is also necessary, to determine both the amount of light registered by the modules, as well as to precisely estimate the time of arrival of subsequent signals. It allows to accurately determine the propagation of light during a real event recorded by the telescope. To increase accuracy of the calibration, a special test bench was developed, allowing not only to precisely examine the distribution of light emission from diffusers, but also to thoroughly examine each of the optical elements, including the lasers themselves, before their deployment in the lake. Such a measurement allows to obtain a data set required to estimate the aging rate of laser devices (lasers and optics as well), but most importantly, it allows actual input data to be obtained for simulation. The method, being the subject of this publication, is a combination of a hardware solution, which is the automatic, reconfigurable test bench, with simulation of light propagation in water. This method is therefore an extremely useful, efficient and accurate tool that allowing for a quick determination of the impact of modification of the laser system on the observed results in the structure of a real telescope. The simulation program was called Pretorian, because it was created, inter alia, to ensure the safety of the Optical Modules during in-situ tests with a laser beam distributed by other method (collimated beam, cone), than by using a diffuser.

2. Method description

2.1 Test bench and scans results

To perform repeatable tests of the laser system components, possible both - in laboratory conditions and during a Winter Expedition on a surface of a frozen lake, it was necessary to design and build an automatic, universal scanner, further called test bench. The device Fig.2 is fully reconfigurable, thanks to which it allows to perform a number of planned tests, as well as to perform any additional measurements necessary to determine the impact of changes in the optical calibration system on the telescope response.

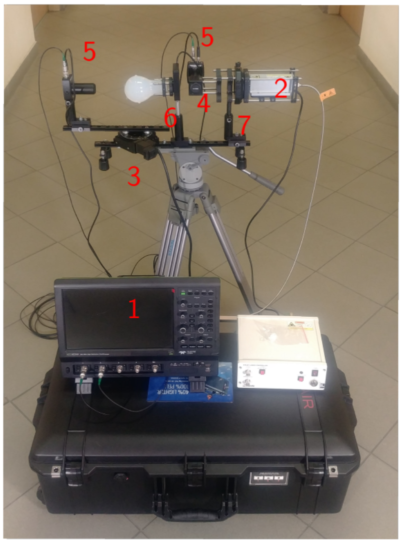
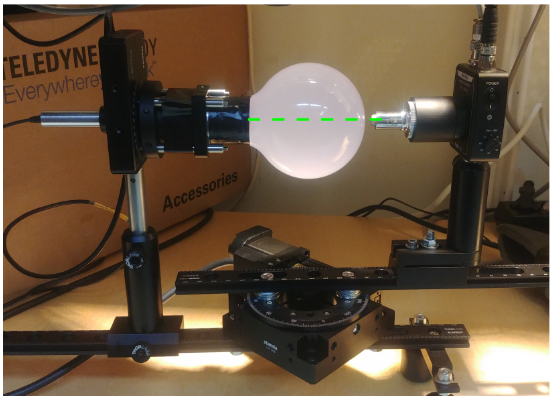


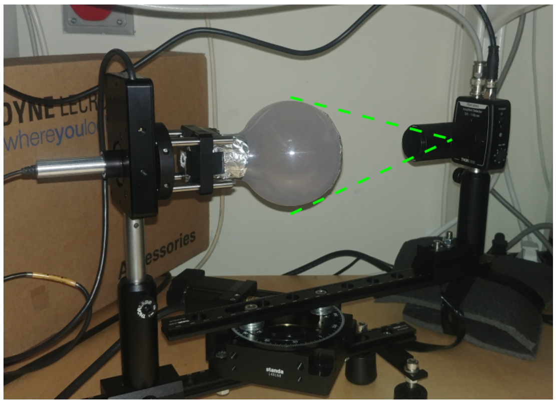
Figure 2: The scanner consists of a test bench (3) equipped with two automatic rotary tables - one placed horizontally (rotation in the horizontal plane) and the other placed vertically (rotation of the tested element around its axis of symmetry in the axis of the laser beam). The test bench is also equipped with reconfigurable component holders (6), laser holder (7), beam splitter with attenuators set (4) and two PDA 100A2 detectors (5) - reference and measurement. The entire test bench, together with the Q-switched DPSS laboratory laser (532 nm, 137 µJ) and the necessary accessories, is housed in a reinforced transportation box, which allows it to be easily moved and transported to perfom the complex tests during a Baikal-GVD Winter Expedition.

Test bench is operated from the Teledyne LeCroy HDO 4034A oscilloscope (1). For this purpose, a special control program has been developed, which also performs data acquisition from the oscilloscope to a file. This allows to easily implement the obtained data from the scan in the dedicated simulation. The program also makes a real time plot from each scanned plane. After making a full scan, program creates a 3D graphic presenting the distribution of light intensity on the surface of the tested diffuser (option available in the diffuser test mode). Along with the test bench, the PM100USB laser beam energy monitor with the ES11C detector is also used to control the stability of the laser parameters. The stand can work with both a laboratory laser and the laser used in the calibration system of the Baikal-GVD telescope. Thanks to use of Q-switched lasers, it is not necessary to use a darkroom – measurements can be made even in the sunlight.

During the research works on the test bench, two scan methods were developed: the so-called "near scan" (a), also called differential scanning, and "far scan" (b), also called integral scanning.



(a) Near diffuser scan example.



(b) Far diffuser scan example.

Near scan allows the examination of a small structural changes in optical elements, mainly in diffusers. It explores the emission of light in a very narrow angle from a point lying on the surface of the tested element. This scan allows, inter alia, to determine the impact of doping of the diffuser material to its attenuation.

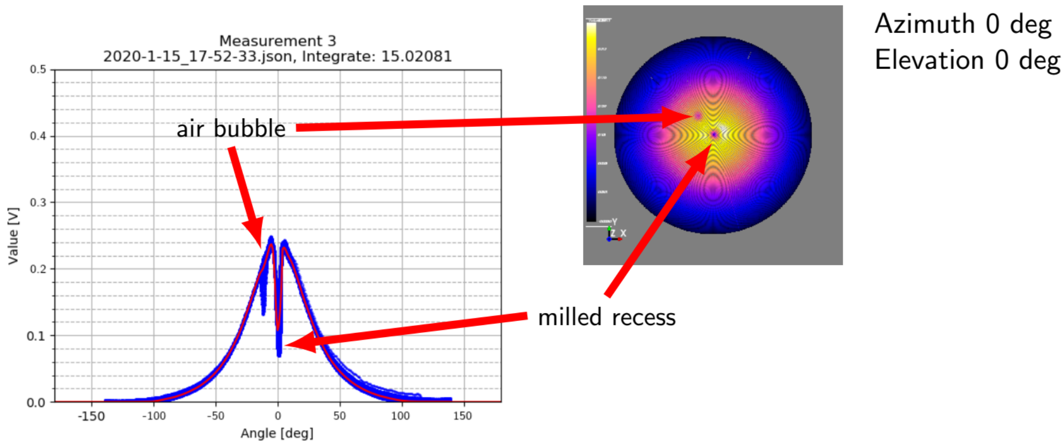


Figure 3: Near scan result. The plot shows averaged measurements from many planes. On the right side the 3D visualization showing the upper part of the diffuser

The far scan allows to determine the actual light distribution at any distance from the diffuser (or other tested element). In the scan configuration, the detector "observes" the entire visible surface of the tested element. Such a scan already taking into account the absorption and scattering coefficients of a medium in which the measurement is performed. The data collected from the far scan performed from a distance of 14 cm (determined experimentally in relation to the diffuser size) were used as an input data for the simulation of light propagation in water.

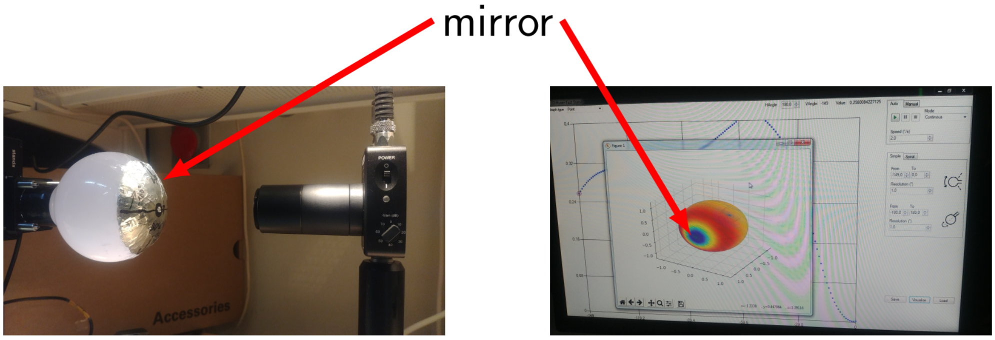


Figure 4: Far scan result. The test was performed with a mirror on the top to improve the isotropy in a backward region. Right: The scanner control interface with scan visualization.

Initial research was carried out on a set of three different diffusers used in the Baikal-GVD experiment till the end of 2020.

The research revealed differences in the light distribution and in the attenuation of individual diffuser materials. A number of tests were also carried out to improve the light distribution to illuminate the Optical Modules below the laser horizon in the Baikal-GVD telescope. As can be seen in the Fig. 1, the lasers are located outside of the clusters, so the desired light distribution should allows to illuminate as many optical modules as possible, which are located on the sides of the laser device.

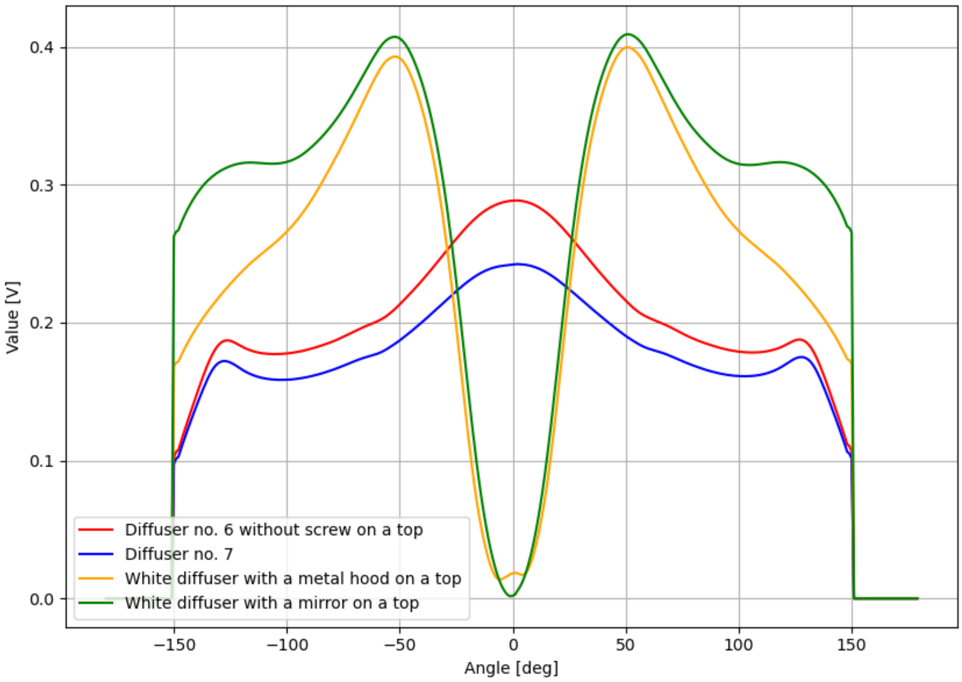


Figure 5: Scans results comparison.

2.2 Simulation - Pretorian[2]

Pretorian can be used before test run using actual parameters of water and position to get telescope response immediately. For small simulations, below 10^{10} initial photons, can be run on modern personal computers (2 GHz, 8 cores) in relatively short time (from few seconds to one day). Output data contains only necessary detection events. Pretorian is multithreaded simulation written in C/C++. For photon propagation is used forward Ray Tracing improved by approximation at scattering points. Simulation is still under development.

2.2.1 Hybrid algorithm

Pretorian is developed for fast approximation of detectors response for light source like laser beam or diffuser. Forward Ray Tracing (RT) method provide good results for big statistic and short distances, but in underwater neutrino telescopes distances are larger than absorption length. Hybrid method use scattering points as new source of photons with scattering distribution. Using this method we can obtain good results for close distance (from RT) and approximation for larger distances.

Forward Ray Tracing is a particle tracking method that can interact with the medium in which they move (scattering, absorption), and detection by the detector is based on a direct hit. The step of the particle tracking is to calculate: probability of the type of event (scattering, absorption), new position and intersection with objects.

Approximation is similar to sending photons directly to detector, but number of photons detected by detector is depend of detector angular size, medium parameters, distance and probability of scattering angle to this direction. Shadowing effect can be suppressed for approximation for faster calculations.

Simulation save each event above selected threshold, thanks that output file, RAM consuming and simulation time are decreased with preserved full time resolution (floating-point precision) or selected time bin (default 1 ns). Events below threshold are saved as cumulative value.

[2]The name Pretorian comes from the ancient bodyguards of the Roman emperors. The program can also be used to support in-situ tests performed with the telescope's laser system. As in the case of the bodyguards, the task of the program will be to ensure optimal attenuation of signals to avoid damage to the Optical Modules resulting from blinding them by the laser beam. The program can also be used to support in-situ tests performed with the telescope's laser system.

2.2.2 Simulation tests and results

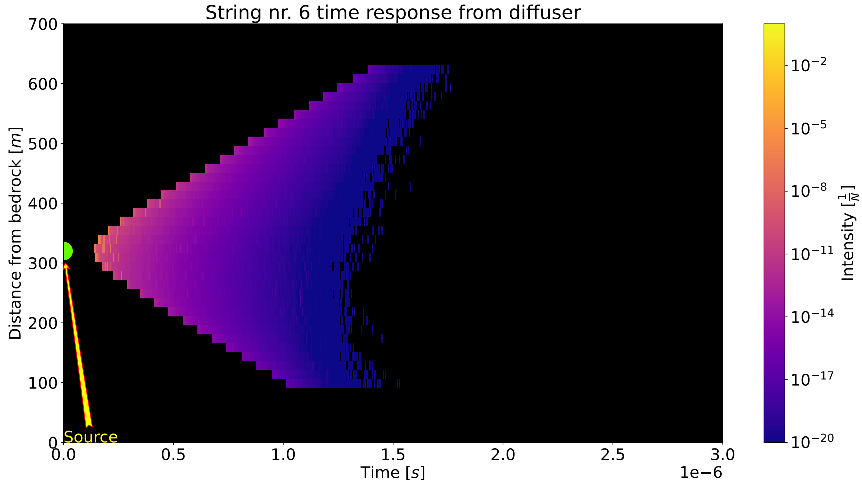
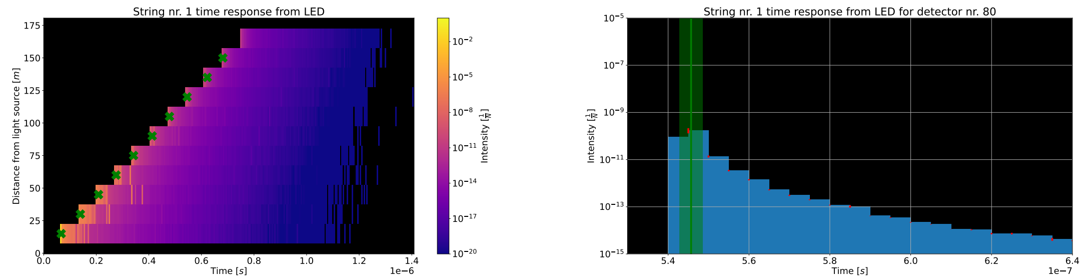


Figure 6: Hybrid method for diffuser, 10^7 initial photons, time bin 5 ns.



(a) Comparison photon intensity to LED test run. Green points are OM acquisition time.

(b) Close up to time versus intensity for single OM located above light source (blue bars). Green line represents detection time from real data from test run.

Figure 7: Compare OMs response with data from telescope. Source is located at point 0, time bin 5 ns.

Fig. 6 shows the simulation result obtained from the diffuser scan presented on Fig. 4 (angular light distribution profile is marked by the green curve on Fig. 5). The graph presents visualizations of light propagation within one cluster string. The laser is located at a distance 30 meters from the string no. 6. The differences in time, visible in the graph are related to the optical path between the light source and the individual optical modules placed every 15 meters on the cluster string. The position of the diffuser on the graph is just for demonstration purpose and does not correspond with the real position of the diffuser in the telescope structure. The presented results take into account the angular response of the optical modules and the approximated water parameters in Baikal Lake. Data from a test run performed on one telescope cluster section using the LED system (intra-section calibration) was compared with a simulation of the same type of event (Fig. 7). There are no significant discrepancies between the experimental data and the simulation results.

3. Conclusion

The new method of testing of the components of the laser system has been designed, along with the automatic test bench and the dedicated simulation of photon propagation in water. The test bench is fully reconfigurable, which in combination with the simulation allows for insertion of tested light sources and study the propagation of light in the Baikal-GVD telescope structure (or any other which geometry and parameters will be provided in the simulation). This allows to test new methods that improves telescope calibration system, including the possibility of in-situ measurement of light scattering and absorption in water. The test bench is fully software independent and allows to work with any oscilloscope in case of its failure and replacement. It is not necessary to use a darkroom to perform the tests, which significantly facilitates the work and increases the functionality of the device. The proposed method and device also allows for the creation of a "map" of the laser system, which will enable the estimation of laser efficiency decrease after a certain time. Pretorian simulation may work on any computer, even on a laptop, which makes it a very useful and fast tool which determines the response of the Optical Modules of the telescope to the emission from any provided light source along with 3D visualizations.

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