

## Hydroacoustic Positioning System for the Baikal-GVD

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The Baikal-GVD neutrino telescope with an km<sup>3</sup> scale detection volume is currently under construction at Lake Baikal. The telescope will be composed of functionally independent setups - clusters of strings of optical modules based on photomultiplier tubes (with eight strings in each cluster). First cluster of GVD in its baseline configuration was deployed in 2016. Spatial positions of light sensors are controlled by dedicated acoustic positioning system. The basic elements and the layout of the acoustic positioning system for the Baikal-GVD neutrino telescope are described, and selected results of system operation are presented.

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## 1. Introduction

Baikal-GVD [1] is a project for a kilometer scale underwater neutrino telescope in lake Baikal, designed primarily for the study of astrophysical neutrino fluxes. The telescope consists of clusters - functionally independent detectors comprised of eight strings of optical modules (OMs) each. Photomultipliers located in optical modules register Cerenkov radiation emitted by secondary particles produced by neutrino interactions with the observed medium, allowing for reconstruction of direction and energy of the primary particle. The first cluster in baseline configuration was completed in 2016, followed by another one this year; both clusters are currently acquiring data.

In Baikal-GVD the optical modules are attached to flexible strings. Each string stretches from a fixed anchor point on the lakebed upwards to subsurface buoys 20-30 meters below the surface. The underwater currents of lake Baikal affect string dynamics and change spatial configuration of the detector, sometimes moving OMs tens of meters from their immediate position. A one meter error in OM position is equivalent to 4.5 ns error in time calibration, so accurate estimates of OM coordinates are necessary for a successful reconstruction effort. In order to track OM coordinates, an acoustic positioning system (APS) has been developed [2] by EvoLogics GmbH (Germany) and deployed at the site of the experiment.

## 2. The acoustic positioning system

The Baikal-GVD acoustic positioning system is an array of acoustic modems (EvoLogics S2C R 42/65) installed along the strings of the detector. Acoustic modems (AMs) are connected to the data acquisition system of the telescope via RS-485 interface. It is facilitated by a 2-channel Ethernet to RS-485 converter (serial device driver NPort IA-5250), installed in the string control module. One channel is used to communicate with the topmost AM, and another one with the lower ones. While the modems are functionally identical, they can be separated into two classes: beacons and nodes. Beacons are installed along optical modules of the string as shown on Fig. 1 and are oriented downwards. Nodes are oriented upwards and are installed near the anchor, few meters above the lake floor, comprising a long baseline acoustic antenna. While each string is supposed to have all four beacons, nodes are optional.

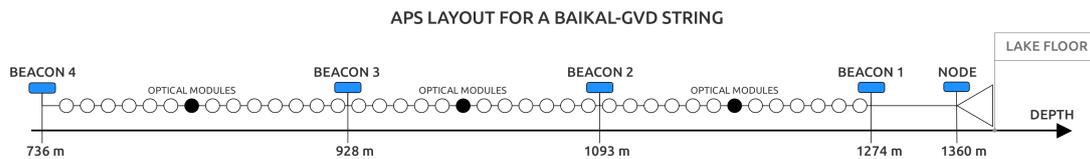


Figure 1: APS layout for Baikal-GVD string

The APS regularly polls beacons for the acoustic signal delays from nodes and uses this data to triangulate beacon coordinates. Communication between AMs is facilitated by D-MAC protocol [3]. The polling period depends on APS configuration, but for one cluster it is typically 40-60 seconds. This process is controlled by the APS software operating from the shore station. While APS operations are fully automated, it is possible to remotely access APS software for maintenance. The acquired data is buffered at the shore and then transferred to the primary data storage in Dubna

for preprocessing and further use. Under the assumption of constant sound speed field (seasonal variations of sound speed at a given depth are presumed to be below 0.1 m/s) estimated beacon positioning accuracy is 5 mm at the elevation of 160 m [4], and several centimeters at the elevation of 420 meters [2]. Accuracy estimates are subject to the node antenna configuration.

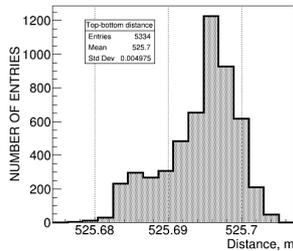


Figure 2: Distance between topmost and lowermost beacons string #1, cluster #2, 2017

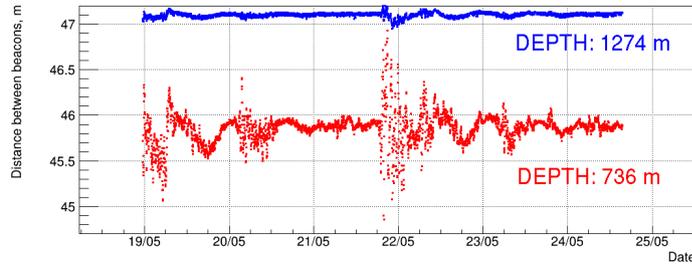


Figure 3: Distance between parallel beacons on strings 4 and 5, cluster 2, 2017

### 3. Acoustic data processing

The APS output is a list of timestamped coordinates for each beacon. By itself this data cannot be used for reconstruction and needs to be preprocessed. First, each beacon's position is linearly interpolated at regular intervals (usually an average APS polling period for the provided data). This process produces an aligned set of interpolated spatial beacon configurations called aligned configurations. If some of the beacons malfunctioned within the observed period, then its coordinates can be guessed from its initial position and coordinates of an operational beacon located on the same depth. This is due to the observed correlation between coordinates of parallel beacons (see Fig. 3).

Next step is data quality control. A number of metrics have been devised in order to estimate the quality of acoustic records. The primary ones are beacon record density, distances between beacons on the same string and distances between parallel beacons on neighboring strings. Beacon record density is the proportion of interpolated beacon positions that lie within a specified time window (ten minutes) from physical measurements. It is used to monitor APS performance and to detect hardware malfunctions. Distance between beacons is used to determine hydrodynamic modes of the medium and to estimate statistical error of acoustic measurements.

Once preprocessing is complete, the data is ready to be used in reconstruction with BARS (Baikal Analysis And Reconstruction Software, see [5]). OM coordinates are calculated for each event by fitting string model to the beacon coordinates and then interpolating OM positions. Utilising a physically realistic string model can be computationally taxing, so BARS architecture permits picking a less precise model for, e.g., on-line reconstruction. In this mode the string is represented as a piecewise linear function and OM coordinates are obtained by linear interpolation of beacon coordinates. This approach is possible because the strings are nearly vertical - as shown on Fig. 4, average XY distance between beacons located at the depths of 928 and 1274 meters is 3.5 meters.

Given that beacon depth deviations are within 10 cm (see Fig. 8), it puts position uncertainty for OMs at the depth below 928 m, on average, at 15 cm (assuming that beacon coordinates error is insignificant). OM coordinates reconstructed in this mode are shown on Fig. 5.

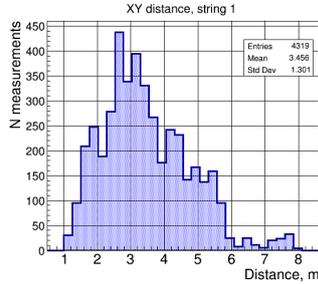


Figure 4: XY distance between beacons at the depths of 928 m and 1274 m, 2015

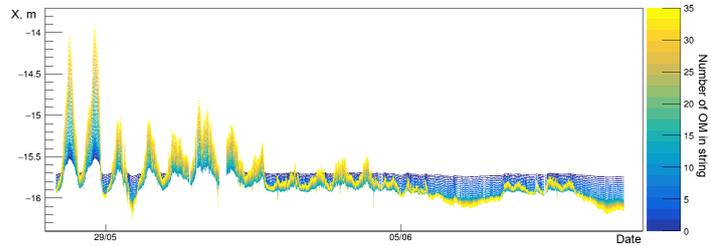


Figure 5: Interpolated X coordinates for OMs on string #1, cluster 1, May-June 2016

#### 4. Performance

The recorded beacon behavior shows that main coordinate variance is observed within XY plane, while beacon depth remains relatively stable. As can be seen on Fig. 6a, beacon depth range at 736 m is several centimeters, while XY range of the same depth is of the order of meters. The coordinate variance in XY plane also decreases with depth (Fig. 6 and Fig. 7). The range of XY coordinates increases from about 1 meter at 1274 m to ten meters and more at 736 m.

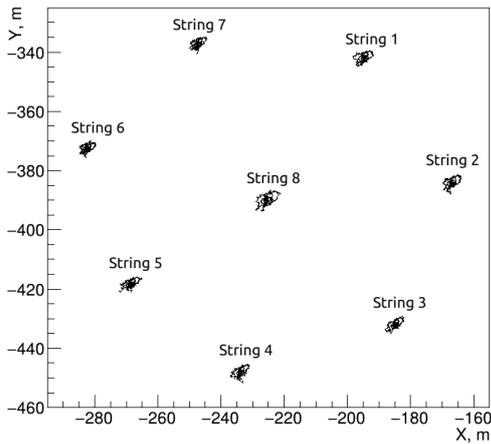


Figure 6: Beacon XY coordinates for cluster #2 at the depth of 736 m, May 18-25th 2017

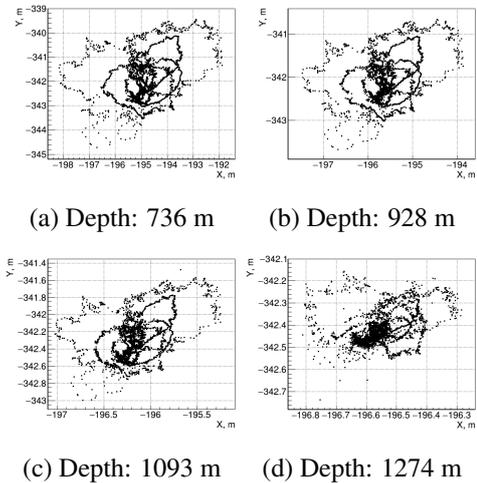


Figure 7: XY coordinates of beacons on string #1, cluster #2, May 18-25th 2017

Depending on seasonal variations and short-term changes in hydrodynamic conditions (e.g. storms), beacons can move up to 40-60 cm between adjacent measurements. This distance decreases to about 3 cm for lower beacons and periods of hydrodynamic stability. This puts geometric

POS (ICRC2017) 1033

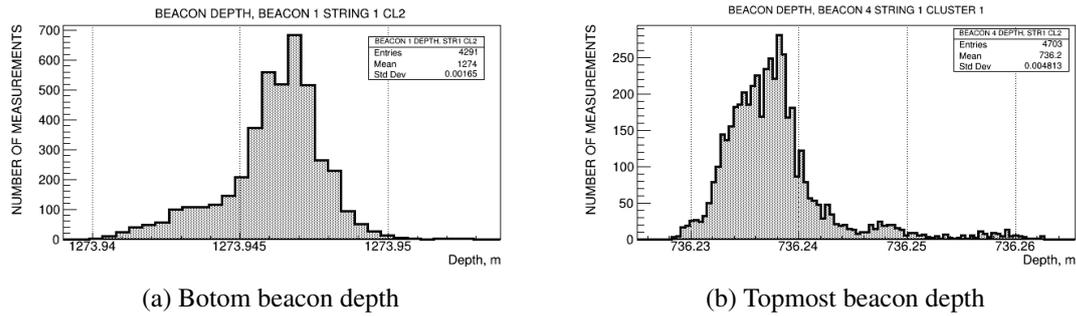


Figure 8: Beacon depth for beacons on string #1, cluster #2, May 18-25th 2017

signal delay uncertainty within 2 ns resolution of time calibration for topmost (and, therefore, most volatile) OMs even for simplified piecewise linear model of the string.

## 5. Summary

For a large scale underwater neutrino telescope like Baikal-GVD precision of the positioning system directly affects reconstruction accuracy. A long baseline acoustic positioning system has been developed and deployed on the two existing clusters of the detector. The system is currently operational and is integrated with the BARS data analysis framework. Preliminary analysis indicates that the performance of acoustic positioning provides timing accuracy within 2ns.

## 6. Acknowledgements

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## References

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