# Status of the early construction phase of Baikal-GVD

A. D. Avrorin[a], A. V. Avrorin[a], V. Aynutdinov[a], R. Bannasch[g], I. Belolaptikov[b], D. Bogorodsky[c], V. Brudanin[b], N. Budnev[c], I. Danilchenko[a], G. Domogatsky[a], A. Doroshenko[a], A. Dyachok[c], Zh. Dzhilkibaev[a], S. Fialkovsky[e], A. Gafarov[c], O. Gaponenko[a], K. Golubkov[a], T. Gress[c], Z. Honz[b], K. Kebkal[g], O. Kebkal[g], K. Konishchev[b], E. Konstantinov[c], A. Korobchenko[c], A. Koshechkin[a], F. Koshel[a], V. Kozhin[d], V. Kulepov[e], D. Kuleshov[a], V. Ljashuk[a], M. Milenin[e], R. Mirgazov[c], E. Osipova[d], A. Panfilov[a], L. Pan'kov[c], A. Perevalov[c], E. Pliskovsky[b], V. Poleschuk[c], M. Rozanov[f], V. Rubtsov[c], E. Rjabov[c], B. Shaibonov[a,b,·], A. Sheifler[a], A. Skurikhin[d], A. Smagina[b], O. Suvorova[a], B. Tarashchansky[c], S. Yakovlev[g], A. Zagorodnikov[c], V. Zhukov[a], V. Zurbanov[c]

[a] *Institute for Nuclear Research, 60th October Anniversary pr. 7a, Moscow 117312, Russia*
[b] *Joint Institute for Nuclear Research, Dubna 141980, Russia*
[c] *Irkutsk State University, Irkutsk 664003, Russia*
[d] *Skobeltsyn Institute of Nuclear Physics MSU, Moscow 119991, Russia*
[e] *Nizhni Novgorod State Technical University, Nizhni Novgorod 603950, Russia*
[f] *St. Petersburg State Marine University, St. Petersburg 190008, Russia*
[g] *EvoLogics GmbH, Berlin, Germany*

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**Abstract**

The second-stage neutrino telescope BAIKAL-GVD in Lake Baikal will be a research infrastructure aimed mainly at studying astrophysical neutrino fluxes by recording the Cherenkov radiation of the secondary muons and showers generated in neutrino interactions. The prototyping/early construction phase of the BAIKAL-GVD project which is directed towards deployment and operation of the first demonstration cluster has been started in April 2011. An important step on realization of the GVD project was made in 2014 by the deployment of the second stage of the demonstration cluster which contains 112 OMs arranged on five strings, as well as equipment of an acoustic positioning system and instrumentation string with an array calibration and environment monitoring equipment. Deployment of the demonstration cluster will be completed in 2015.

*Keywords*: Neutrino telescopes, Lake Baikal;

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## 1. Introduction

The next generation neutrino telescope BAIKAL-GVD in Lake Baikal will be a research infrastructure aimed primarily at studying astrophysical neutrino fluxes and particularly at mapping the high-energy neutrino sky in the Southern Hemisphere including the region of the galactic center. The detector will utilize Lake Baikal water instrumented at depth with light sensors that detect the Cherenkov radiation from secondary particles produced in interactions of high-energy neutrinos inside or near the instrumented water volume. The configuration of the telescope consists of clusters of strings - functionally independent sub-arrays, which are connected to shore by individual electro-optical cables. The site chosen for the experiment is in the southern basin of Lake Baikal. Here, the combination of hydrological, hydro-physical,

· Corresponding author. Tel.: +7-985-298-8733; fax: +7-496-216-6666; e-mail: bair@yandex.ru.

and landscape factors is optimal for deployment and operation of the neutrino telescope. The water depth is about 1360 m at distances beginning from about of three kilometers from the shore. The flat lake bed throughout several tens of kilometers from the shore provides a practically unlimited water volume for a deep underwater Cherenkov detector. An up to 1 m thick ice cover from February to the middle of April allows the deployment of the telescope, as well as maintenance and research works directly from the ice surface, using it like a solid and fixed assembling platform. The light propagation in the Baikal water is characterized by an absorption length of about 20 - 25 m and a scattering length of 30 - 50 m [1]. The water luminescence is moderate at the detector site.

The first prototype of the GVD electronics was installed in Lake Baikal in April 2008 [2]. It was a reduced-size section with 6 optical modules (OMs). This detection unit provided the possibility to study basic elements of the future detector: new optical modules and a Flash Analog-to-Digital Converter (FADC) based measuring system. During the next two years different versions of a prototype string were tested as a part of the NT200+ detector. The 2009 prototype string consisted of 12 optical modules with six photomultiplier tubes (PMTs) R8055 and six XP1807 [3]. In April 2010, a string with 8 PMTs R7081HQE and 4 PMTs R8055 was deployed. . The operation of these prototype strings in 2009 and 2010 allows a first assessment of the DAQ performance [4,5].

The prototyping/early construction phase of the BAIKAL-GVD project which aims at construction and operation of the first demonstration cluster has been started in 2011. In April 2011 the first autonomous engineering array which includes preproduction modules of all elements, measuring and communication systems, as well as a prototype of acoustic positioning system of GVD-cluster was installed and commissioned [6,7,8]. The array was connected to shore by an electro-optical cable which was also deployed in 2011. In April 2012 an extended version of the engineering array which comprises 36 OMs was deployed [9]. This array consists of two short strings and the first full-scale string of the GVD demonstration cluster with 24 OMs.

The next important step in the realization of the GVD project was made in 2013 by deployment of an enlarged engineering array - the first stage of the demonstration cluster, which comprises 72 OMs arranged on three 345 m long strings, as well as an instrumentation string with an array calibration and environment monitoring equipment [10]. The first stage of the demonstration cluster was successfully operated from April 2013 to February 2014 in several testing and data taking modes. A total of $5.5 \cdot 10^7$ events has been recorded which corresponds to 216 days of array live time.

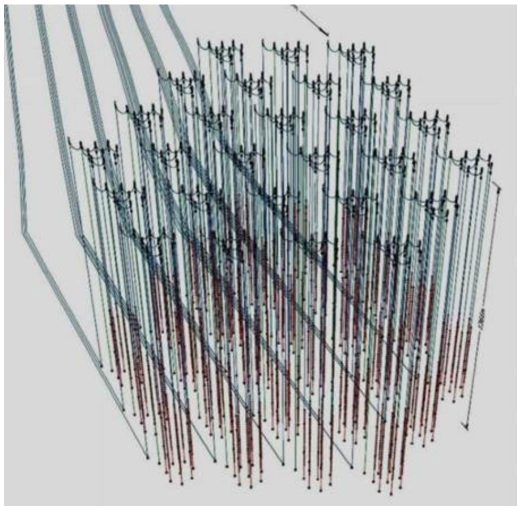

Figure 1: Artistic view of the GVD-telescope.

## 2. GVD design

The BAIKAL-GVD is a 3-dimensional lattice of optical modules (OMs) – photomultiplier tubes enclosed in transparent pressure spheres. The OMs are arranged on vertical load-carrying cables to form strings. The telescope will consist of clusters of strings - functionally independent sub-arrays, which are connected to shore by individual electro-optical cables (see figure 1). Each cluster comprises eight strings – seven peripheral strings uniformly arranged at a 60 m distance around a central one. The OMs are spaced by 15 m along each string and face downward. The OMs along a string are combined in sections – the functional detection unit of the telescope. The distances between the central strings of neighboring clusters are 300 m.

The muon effective areas for two optimized GVD configurations are shown in figure 2. The curves labeled GVD*4 and GVD correspond to configurations with 10368 OMs and 2304 OMs, respectively. The muon effective area for GVD*4 (6/3 event selection requirement – at least 6 hit channels on at least 3 strings) rises from 0.3 $km^2$ at 1 TeV to about of 1.8 $km^2$ asymptotically. The muon angular resolution (median mismatch angle between generated and reconstructed muon directions) is about 0.25 degree.

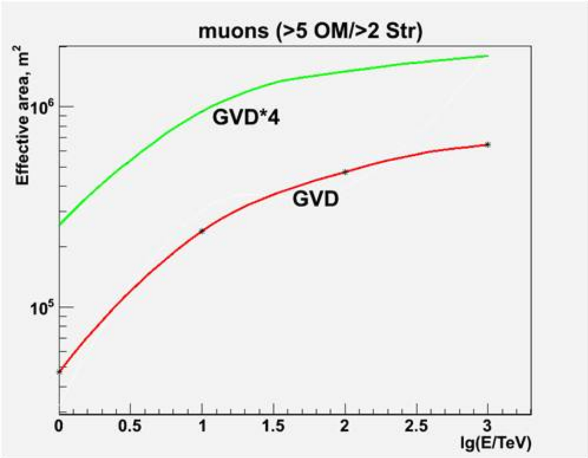


Figure 2: Muon effective area. The curves labeled by GVD*4 and GVD correspond to configurations with 10368 OMs and 2304 OMs, respectively.

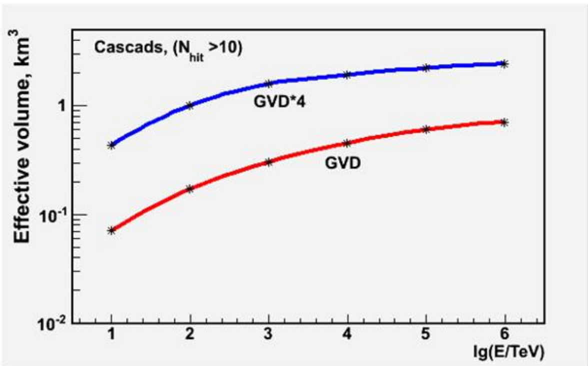


Figure 3: Effective volume of cascade detection. The curves labeled by GVD*4 and GVD correspond to configurations with 10368 OMs and 2304 OMs, respectively.

Shower effective volumes for two configurations are shown in figure 3. Effective volumes (11/3 condition – at least 11 hit channels on at least 3 strings) for GVD*4 above 10 TeV range from 0.4 to 2.4 km$^3$. The accuracy of shower energy reconstruction is about 20-35% depending on shower energy. The angular resolution is about 3.5-6.5 degrees (median value).

## 3. Demonstration cluster

The demonstration cluster will comprise a total of 192 optical modules arranged on eight 345 m long strings (7 side strings located at 60 m distances from a central one). Each string comprises 24 OMs spaced by 15 m at depths of 900 m to 1250 m below the surface. Each OM consists of a pressure-resistant glass sphere with 43.2 cm diameter which holds the OM electronics and the PMT which is surrounded by a high permittivity alloy cage for shielding it against the Earth magnetic field. A large photomultiplier tube Hamamatsu R7081-100 with a 10-inch hemispherical photocathode and a quantum efficiency up to 35% has been selected as light sensor. Besides the PMT, an OM comprises a high voltage power supply unit (HV), a fast two-channel preamplifier, and a controller. The tube gain has been adjusted to about $10^7$. Additional signal amplification by a factor of 10 is provided by the first channel of the preamplifier. This gain value results in a spectrometric channel linearity ranging up to about 100 photoelectrons. The second preamplifier output with factor 20 is intended for PMT noise monitoring. For temporal and amplitude calibration of the measuring channel, two LEDs are installed in the optical module. The OM controller is intended for HV control and monitoring, for PMT noise measurements, and for time and amplitude calibration. Slow control data to and from the OMs are transferred via an underwater RS-485 bus.

The optical modules are grouped into sections - the detection units of the array [11]. Each section includes 12 OMs and the central module (CeM). PMTs signals from all OMs are transmitted through 90 m long coaxial cables to the CeM of the section, where they are digitized by custom-made ADC boards with 200 MHz sampling rate. The waveform information from all measuring channels of the section is transferred to the Master board located in the CeM. The Master board provides readout of the ADC data, connection via local Ethernet to the cluster DAQ-center, control of the section operation and the section trigger logic [11]. A request of the section trigger is transferred from the Master board to the cluster DAQ-center, where a global trigger for all sections is generated. The global trigger initiates data transmission from all sections to shore.

The data transmission between the cluster DAQ-center and the shore station is provided through a 6 km long electro-optical cable with a bandwidth up to 10 Gbit/s. The rate of data transmission to shore is limited by the bandwidth of a connection channel between string communication module and the cluster DAQ-center which is about of 8 Mbit/s. To provide the required data rate (not less than 100 Hz), on-line data processing in each section is performed. The raw data sample is reduced by more than 50 times by the Master electronic cards located in CeMs.

The demonstration cluster will comprise an acoustic positioning system [8] and an instrumentation string with equipment for array calibration and monitoring of environmental parameters.

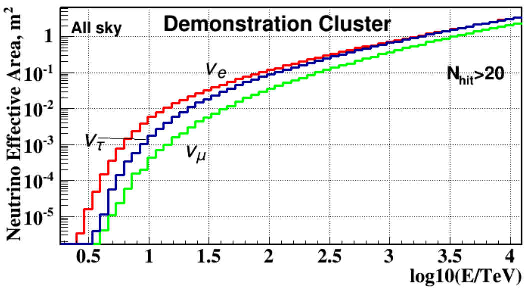


Figure 4: Neutrino effective areas for each flavor averaged over all arrival angles. The effective area includes effects from attenuation of neutrinos in Earth.

Recently, IceCube found evidence for a diffuse signal of astrophysical neutrinos in an energy range of ~60TeV to 2 PeV [12,13]. In this search events were selected by the requirement that they display a vertex (shower pattern) contained within the inner part of the instrumented ice volume. The Baikal collaboration has a long-term experience on studies of muons and neutrinos by detection and reconstruction of secondary high-energy cascades. Limits on the all-flavour astrophysical diffuse neutrino flux were derived from data taken with the NT200 neutrino telescope [14, 15]. The demonstration cluster of GVD has the potential to detect astrophysical neutrinos with a flux measured by IceCube. The search for high-energy neutrinos is based on the selection of cascade events generated by neutrino interactions in the sensitive volume of array.
After applying an iterative procedure of vertex reconstruction followed by the rejection of hits contradicting the cascade hypothesis on each iteration stage [14], events with a final multiplicity of hit OMs $N_{hit}$ > 20 are selected as high-energy neutrino events. With this event selection, the neutrino effective areas for each flavor assuming an equal flux of neutrinos and antineutrinos and averaged over all arrival angles have been derived and are shown in figure 4. These areas are about ten times smaller than the corresponding areas of IceCube [12]. The accuracy of shower direction reconstruction is about 4 degree (median value), which is substantially better than the 10-15 degree accuracy for IceCube [12]. The fraction of shower events ($E_{sh}$ = 100 TeV) with mismatch angles between generated and reconstructed muon directions less than a given value is shown in figure 5.
Energy distributions of the expected number of shower events per year for IceCube astrophysical fluxes for different flavours and all-flavour, as well as the distribution of expected background events from

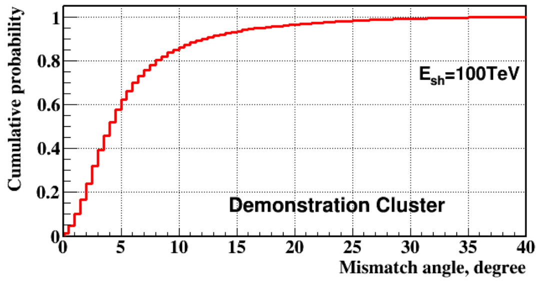


Figure 5: The fraction of shower events with mismatch angle less than a given value.

atmospheric neutrinos are shown in figure 6. The expected background events from atmospheric neutrinos are strongly suppressed for energies higher than 100 TeV.

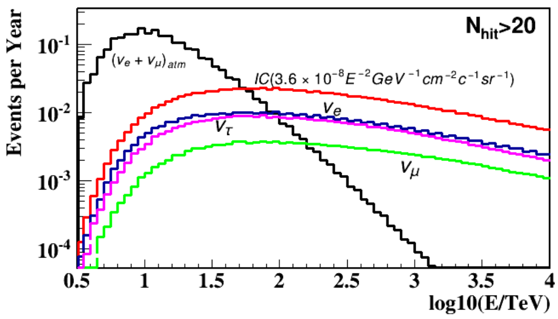


Figure 6: Expected distributions of events per year from astrophysical fluxes obtained by IceCube. Also shown is the expected distribution of background events from atmospheric neutrinos.

We expect about one event per year with $E_{sh}$>100 TeV from an all-flavour astrophysical flux with the normalization $E^2F=3.6 \cdot 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ [12] in the demonstration cluster, compared to about 10 events in IceCube.

## 4. Current stage of the demonstration cluster

The next important step in the realization of the GVD project was made in 2014 by deployment of the second stage of the demonstration cluster, which comprises 112 OMs arranged on five strings, as well as an instrumentation string with array calibration and environment monitoring equipment. The schematic view of this array is shown in figure 7. The vertical spacing of OMs is 15 m and the horizontal distance between strings is about 40 m. In addition to the OMs, each string comprises the communication module (CoM), and the two central modules (CeM) of the two sections of the string. Also each string comprises four transceivers of the acoustic positioning system (AM). The modified cluster DAQ-center is located at the central string of the demonstration cluster and is connected to shore by the electro-optical cable. The instrumentation string is located at 60-100 m away from the measuring strings with the OMs. It comprises the calibration laser source, eight optical modules, as well as 10 acoustic sensors of the positioning system. The calibration laser source [12] is located at 1215 m depth and is used for time synchronization between the OMs on different strings. The high intensity of the laser source (up to $6 \cdot 10^{13}$ photons/pulse) allows the illumination of OMs at distances more than 200 m away from the source. The acoustic

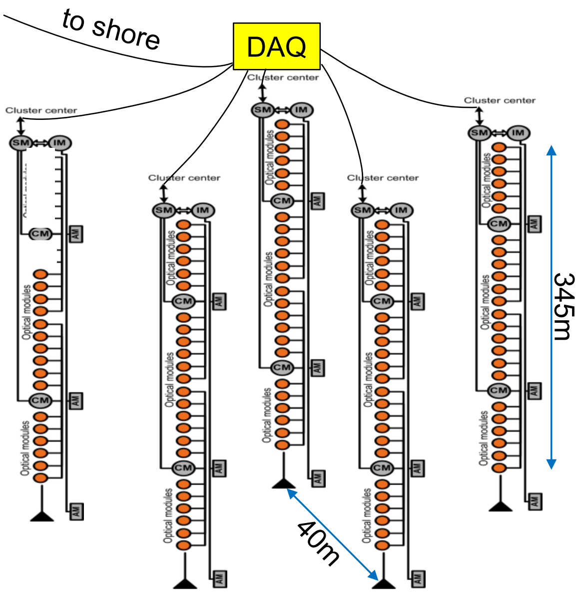


Figure 7: Schematic drawing of the second stage of the demonstration cluster.

sensors are arranged along the instrumentation string starting from 50 m depth to the bottom of the string and perform monitoring of the string displacements at different depths caused by deep or/and surface water currents. Eight optical modules housing two R8055 and six XP1807 PMTs are arranged at depths from 600 m to 900 m on the instrumentation string and aim at monitoring of the light background at these depths.

The second stage of the demonstration cluster is successfully operating since April 2014 in several testing and data taking modes. In data taking mode a total of $1.6 \cdot 10^{8}$ events has been recorded which relates to 123 days of live time from April 10 till September 27. Long-term control and monitoring of the array measuring system behaviour, as well as background conditions during the array operation in 2014 have been performed. In figure 8 the PMTs counting rates in 2014 are shown. The main contribution to the recorded counting rates comes from radiation produced by

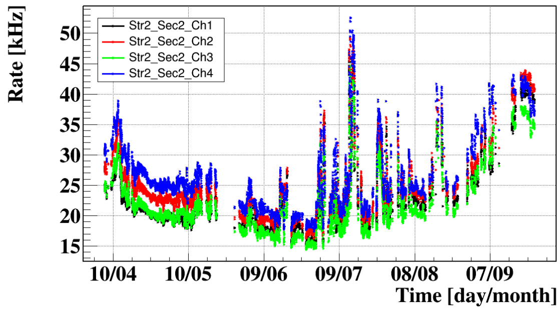


Figure 8: Counting rates of four OMs on the top section of the second string which were observed in 2014.

chemiluminescence in the deep water. During April - September 2014 the PMTs counting rates are about of 15-40 kHz, which are comparable with values obtained in 2012-2013.

One of the main goals of the array operation in testing modes is the estimation of the ability of in-situ calibration procedures. Calibration of the array recording system includes charge and timing calibrations of the measuring channels and time synchronization of OMs on different sections. All these calibration procedures are based on the usage of the OM's internal calibration LEDs and the external laser light source.

The charge calibration allows translating the signal amplitudes into numbers of photo-electrons (p.e.), which is the relevant information for muon and shower energy reconstruction. For the charge calibration of PMTs a standard procedure based on an analysis of a single photoelectron spectrum (s.p.e.) has been applied. In this calibration mode the pulses of the two LEDs of an OM are used. The intensity of the first LED is fitted to provide a detection of s.p.e. signals with a detection probability about 10%. These pulses are used to measure the s.p.e. distribution of the PMT signals. Pulses of the second LED with intensities corresponding to about 50 p.e. of the PMT signal are delayed by 500 ns and are used as a trigger to suppress background signals with small amplitudes initiated by the PMT dark current, as well as the light background of the lake water.

The timing calibration of the measuring channels aims at control the relative time offsets between the PMTs, which are due to the PMT internal delays and delays caused by the signal transmission through about 90 m cables connecting OMs and CeM. The intensities of LEDs light bursts are high enough to illuminate the neighboring PMTs on the string. It allows synchronization between OMs of different sections, as well as the measurement of relative time offsets between channels inside one section. The time synchronization of different sections was performed and relative offsets between PMTs were derived by means of LEDs, using the known locations of strings and OMs which have been obtained from the analysis of data accumulated by the acoustic positioning system.

The performance and quality of the calibration procedures have been verified by the reconstruction of position and intensity of the calibration laser. An external calibration laser provides five series of 480 nm light pulses at five fixed intensity levels ranging from approximately $10^{12}$ to $6{\cdot}10^{13}$ photons/pulse [12], which roughly corresponds to shower energies from 10 PeV to 600 PeV. This allows

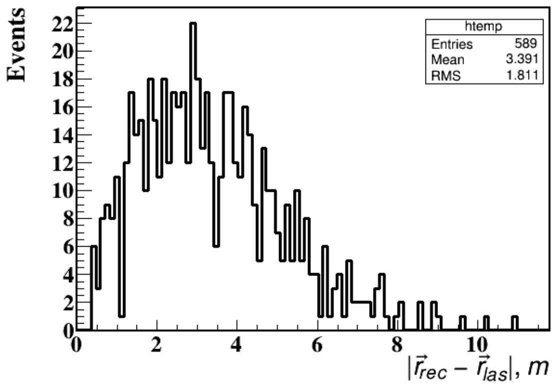


Figure 9: Deviation of reconstructed laser coordinates from those obtained by the acoustic positioning system.

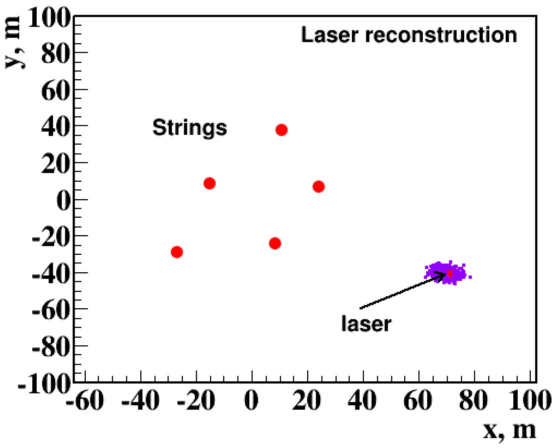


Figure 10: Top view of reconstructed laser positions. The star indicates the laser position obtained by the acoustic system.

to test the array capability for high-energy cascade reconstruction. The position of the laser source was reconstructed using the arrival times of photons detected by the PMTs, taking into account the timing calibration of the PMTs by LEDs. Results of the reconstruction were compared with the laser coordinates obtained by the acoustic positioning system. Differences between reconstructed coordinates and those obtained by the acoustic system are shown in figure 9. The reconstruction accuracy (median value) is about 3 m. Shown in figure 10 are strings and laser positions obtained by the acoustic system, as well as reconstructed laser positions. The obtained results demonstrate the expected quality of the array calibration procedures.

## 5. Conclusion

The ambition of the Baikal collaboration is the construction of a km3-scale neutrino telescope - the Gigaton Volume Detector in Lake Baikal. . During the R&D phase of the GVD project in 2008-2010, its basic elements - new optical modules, FADC readout units, underwater communications and trigger systems - have been developed, produced and tested in situ by long-term operating prototype strings.. The prototyping phase of the GVD project has been started since April 2011 and aims at completion of the first demonstration cluster of GVD in spring 2015. The first stage of the GVD-cluster comprising three strings was deployed and successfully operated in 2013. In 2014 the second stage of the demonstration cluster with 112 OMs at 5 strings has been deployed and is presently taking data.

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