The BAIKAL Neutrino Experiment: From NT200 to NT200+

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Abstract

The Baikal Neutrino Telescope has been operating in its NT200 configuration since April, 1998. The telescope has been upgraded in April, 2005 to the 10 Mton scale detector NT200+. It’s main physics goal is the detection of signals from high energy neutrino cascades. NT200+ reaches a 3-year sensitivity of $2 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}$ for an all-flavor diffuse cosmic $E^{-2}$ neutrino flux for energies $10^2 \text{TeV} \div 10^5 \text{TeV}$.

Design and sensitivity of NT200+ are described. NT200+ is forming the basic building block of a future km3-scale (Gigaton-Volume) Baikal Telescope. Research and development work on that next stage detector has started.

Key words: Neutrino telescope, Neutrino astronomy, UHE neutrinos, BAIKAL
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1. Introduction

The Baikal Neutrino Telescope is operated in Lake Baikal, Siberia, at a depth of 1.1 km. Deep Baikal water is characterized by an absorption length of $L_{\text{abs}}(480\text{nm}) = 20 \div 24 \text{ m}$, a scattering length of $L_s = 30 \div 70 \text{ m}$ and a strongly anisotropic scattering function with a mean cosine of scattering angle $0.85 \div 0.9$ [1].

The first stage telescope configuration NT200 [1] was put into permanent operation on April 6th, 1998 and consists of 192 optical modules (OMs). An umbrella-like frame carries 8 strings, each with
The upgraded Baikal Telescope NT200+ consists of the old NT200 surrounded by three new, external strings placed 100 m away from NT200 (see Fig. 1). Four underwater electrical cables connect the detector with the shore station. Each optical module contains a 37-cm diameter QUASAR - photomultiplier (PM) which has been developed specially for this project [2]. The two PMs of a pair are switched in local coincidence in order to suppress background from bioluminescence and PM noise; each pair defines a channel.

The upgraded telescope NT200+ was put into operation on April 9th, 2005. This configuration consists of the old NT200 telescope, surrounded by three new, external strings placed 100 m away from NT200 (see Fig. 1). With these new strings, the sensitivity of the Baikal telescope for very high energy neutrinos increases by a factor 4.

With the NT200 telescope, a number of relevant physics results has been obtained so far: searches for WIMPs, high energy atmospheric muon neutrinos and muons, relativistic and slow magnetic monopoles and diffuse extraterrestrial high energy neutrinos. Reviews were given at this conference [3], and in refs. [4,5,6,7]. The NT200 all-flavor limit for a steady diffuse neutrino flux with $E^{-2}$ shape, $E^2 \Phi = 8.1 \times 10^{-7} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}$ (20 TeV $< E < 50$ PeV), is among the most sensitive limits published so far by neutrino telescopes [8].

For NT200, the detection strategy for high energy neutrino events is based on a search for Cherenkov light from pointlike cascades in a Mton-scale sensitive volume below the detector, which is much exceeding the instrumented geometric volume ($V_{\text{geo}}(\text{NT200}) \sim 0.1$ Mton).

With the upgrade to NT200+, the effective volume is now “fenced” by 3 distant, long outer strings with only 36 OMs in total, which will give physics information on high energy showers well exceeding that of NT200: The long baseline allows to localize the shower position, and hence the shower energy. This significantly improves the rejection capability against the physics background (mainly high energy atmospheric muons with em-showers, passing not far below NT200). A measurement of the shower energy will be possible. Fig. 2 gives the detection volume for NT200+ as function of neutrino energy for $\nu_e$ and $\nu_\mu$ events between 10 TeV and 1 EeV. The sensitivity to an $E^{-2}$-diffuse all-flavor neutrino flux is $2 \times 10^{-7} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}$ ($E > 10^2$ TeV, 3 years) [8].

In this paper, we describe the new NT200+ telescope, being the natural extension of NT200, and its data acquisition, control and calibration sys-
tems. NT200+ will be used as the basic cell of a future km3-scale detector (Gigaton Volume Detector) in Lake Baikal, which is briefly sketched.

2. The NT200+ Telescope

The upgraded telescope NT200+ was commissioned in April, 2005. This new configuration consists of a central part (the old telescope NT200) and three new, external strings (NT+), see Fig. 1. The external strings are 200 m long (140 m instrumented) and are placed at 100 meter distance from the center of NT200. Each string contains 12 OMs, grouped in channels (OM pairs) like in NT200. The upper channels are at approximately the same depth as the bottom OMs of NT200, adjacent channel distances are 20,50, 20, 30 and 20 m from top to bottom (for depths of upper, 3rd and lower channels see Fig.1). All channels are down-looking, except the lower two on each string (up-looking).

Two basic tasks had to be solved, in order to integrate NT200 and the external string subsystems into a united NT200+ detector: creation of a data acquisition and control system for the external strings, and providing a time synchronisation between the two subsystems and a tagging of common events (see also [9]). Since a simple doubling of the data acquisition and control system for NT200 and NT+ was compatible neither with the number of available cable connections to shore, nor with future upgrades, we decided to significantly modernize the system by introducing for the first time embedded PCs with reliable industrial Ethernet infrastructure underwater. For NT200+, all data and control cable connections of NT200 and the outer strings go to a new central control and readout unit (DAQ center) about 20 m below surface (see Fig. 1), where they are multiplexed to a single line to shore.

All information necessary to combine NT200 and NT+ sub-events, is provided by the common electronics module (CEM) specially designed for NT200+. CEM is located at the DAQ center and connected through coaxial cables with the NT200 and NT+ DAQ subsystems. This module contains TDC units that measure time differences between NT200 and NT+ triggers with a resolution of about 2 ns. Also, all NT200 trigger pulses...
are counted and added to the NT+ data stream. Figure 3 sketches the DAQ and control system of NT200+, composed of the two subsystems for NT200 and NT+. String electronics modules (SEM) form the lower level of NT200+ DAQ system. NT200 and NT+ strings (Str) contain two and one SEM, respectively. These units translate trigger request signals from string channels to the detector electronics module (DEM) or to CEM for NT+, and provide time and amplitude measurements for all triggered channels. A NT200 trigger is formed when the number of fired channels \( N_{\text{hit}} \) is at least \( N_{\text{min}} \) within 500 ns at DEM. \( N_{\text{min}} \) is typically set to 3 or 4. The trigger signal is used as a common stop for the TDCs of NT200 channels. For common operation with the external strings, the signal of the NT200 trigger is sent through 1.2 km coaxial cable to CEM. The number of NT200 triggers within an experimental run is recorded by a counter in CEM. On each external NT+ string, triggers are formed as independent string-triggers, in case of at least 2 fired channels within 1000 ns. String triggers are sent to CEM, where the time difference between string trigger and the trigger of NT200 is measured. This information is used to relate within an event the times of OMs in NT200 and the externals strings.

NT200 and NT+ experimental data are transferred to the shore center through two underwater PCs located in pressure glass spheres. Both underwater PC spheres are nearly identical, their content is detailed in Fig. 4: a single board PC/104 (PC104: Advantech-PCM9340), a DSL-modem (DSL-M: FlexDSL-PAM-SAN, with hub and router), a managed Ethernet switch (SwRSTP: RS2-4R, running RSTP protocols for the two-fold redundant ethernet network between the PC spheres), an Ethernet-ComServer (CSrv: WUT-58211, for PC-terminal emulation), two mediaconverters (Mc: for coaxial connection to external control units) and the experiment data and slow-control modems (D-Mod and C-Mod). The connection to shore is by a single DSL-Modem at a speed of up to 2 Mbit/s. This full multiplexing of all data and control streams through a single DSL-channel reduces the number of shore wires to two. Both PC spheres are interconnected via two twisted pair ethernet cables (main and hot spare). This underwater system works stable since its first installation in 2004. Using Linux throughout the system (for underwater PCs and shore station PCs) allows for easy remote maintenance and control from home institutions.

3. NT200+ Laser Calibration

Large volume underwater Cherenkov detectors need calibration of the relative time-offsets between all light-sensors to a precision of a few nsecs, since event reconstruction and classification are based on the precise light arrival times. For NT200+, calibration is done with a powerful external laser light source with up to \( 5 \times 10^{13} \) photons per pulse and nsec-pulse duration [9], which is located between two outer strings, see Fig.1. This ensures amplitudes of \(~100\) photoelectrons on a few PMTs on each external string and on NT200. High amplitudes minimize uncertainties due to light scattering.

![Fig. 5. Measured NT200+ time resolution as function of PMT amplitudes for laser calibration pulses.](image-url)

The NT200+ laser calibration unit is made of a powerful short-pulse Nitrogen laser (\( \lambda = 337 \) nm) with about \( 100 \mu J \) for <1 nsec pulse duration, which is pumping a Coumarin dye laser at 480 nm. After passing through a computer-controlled attenuator disc, the light is isotropized by a light diffuser ball, made of a round-bottom flask filled with Silicone Gel (RTV-6156) admixed with hollow micro-glass spheres at about 5%-volume ratio.
(S32 from 3M, with \( \approx 40\mu m \) diameter; following an idea developed for the SNO detector [10]). The total loss of this isotropizing sphere is \(< 25\%\). All components are mounted into a 1 m-long cylindrical glass pressure housing, which gives isotropic emission for more than the upper hemisphere. The unit is installed at a depth of 1290 m below surface and operated in autonomous mode: after power-on from shore, a series of pulses at various intensities is conducted.

The final light output ranges from approximately \( 10^{12} \) to \( 5 \times 10^{13} \) photons/pulse, corresponding to shower energies from 10 PeV to 500 PeV. The laser unit is used, varying the total intensity, to calibrate pointlike shower vertex and energy reconstruction algorithms for energies up to 500 PeV.

This laser unit allows for an independent performance check of the key elements of the NT200+ timing system. We performed the relative time synchronization of all news strings and NT200, and find the jitter of this to be less than 3 nsec. This jitter is due mainly to the significant length (1.2 km) of synchronisation line between NT200 and external strings. The measured dependence of the relative time jitter on PMT amplitudes is presented in Fig. 5 for several pairs of channels of NT200 and external strings.

4. A Gigaton Volume Detector at Baikal

MC simulations have shown that the detection volume of NT200+ for PeV cascades would vary only moderately, if NT200 as the central part of NT200+ is replaced by a single string of OMs. Figure 6 gives the detection volume for different configurations as a function of cascade energy. The standard configuration of NT200+ is marked by empty rectangles. The other configurations comprise a single string instead of NT200: a standard string of 70 m length and 24 OMs (filled rectangles), a half string with 12 OMs covering 35 m (dots), and a 70 m long string sparsely equipped with 12 OMs (triangles). The configuration with the long 12-OM string shows an energy behavior very close to the one of NT200+.

For neutrino energies above 100 TeV, such a configuration could be used as a basic building block of a km³-scale or Gigaton Volume Detector (GVD). Rough estimations show that 0.7 \( \div 0.9 \) Gton detection volume for neutrino induced high energy cascades may be achieved with about 1300 OMs arranged at 91 strings. A top view of GVD as well as a sketch of one basic subarray are shown in Fig. 7. The shower energy reconstruction capability is illustrated in Fig. 8. The physics program of this detector at very high energies covers the typical spectrum of cubic kilometer arrays.

5. Conclusions and Outlook

The deep underwater neutrino telescope NT200 in Lake Baikal has been taking data since April 1998. A number of interesting results have been obtained, based on the first years of NT200-operation.

The Baikal telescope has been significantly upgraded in 2005. The new telescope configuration NT200+ has a sensitivity better than \( 10^{-7} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV} \) for a diffuse \( E^{-2} \) electron neutrino flux within the energy range \( 10^2 \text{ TeV} \div 10^5 \text{ TeV} \). NT200+ will search for neutrinos from AGNs, GRBs and other extraterrestrial...
sources, neutrinos from cosmic ray interactions in the Galaxy as well as high energy atmospheric muons with $E_\mu > 10$ TeV.

For the planned km3-detector in lake Baikal, R&D-activities have recently been started. Technical and physics experience with the new NT200+ detector will be an important part of this program. With a Technical Design Report for the km3-detector scheduled for 2008, deployment will start in 2010.

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