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Hydroacoustic Coordinate-Measuring System of the NT-200 Baikal Neutrino Telescope

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Abstract—The hydroacoustic coordinate-measuring system of the NT-200 Baikal neutrino telescope is described. It is a ranging long-base hydroacoustic system constantly operating in an automated or interactive mode and capable of measuring the coordinates of the detecting modules of the NT-200 to within 20 cm. Special attention is given to the justification of the estimate of the coordinate measurement errors. As an illustration, some results of measuring the coordinates of the elements of the NT-200 and the hydrophysical characteristics of lake Baikal are presented. © *2005 Pleiades Publishing, Inc.*

1. INTRODUCTION

The idea of developing large deep-water systems for detecting elementary particles in natural water basins was put forward by M.A. Markov 40 years ago [1]. The essence of the idea consists in using an array of photodetectors deployed in a deep natural water basin to detect the Cherenkov radiation of relativistic particles moving in water, specifically, the particles produced by the interaction of high-energy neutrinos with the medium. Such systems were expected to allow the scientists to solve a variety of problems of high-energy neutrino astrophysics, high-energy physics, and elementary particle physics [2].

The first deep-water neutrino detector was the NT-200 Baikal neutrino telescope, which was put into full operation in April 1998 [3]. Today, the ANTARES neutrino detector is at the stage of realization in the Tulon bay [4] and two more deep-water neutrino detectors, NEMO [5] and NESTOR [6], are under development in the Mediterranean Sea. All of these systems are intended for the detection of Cherenkov radiation of the relativistic charged particles produced by the interaction of neutrinos with the medium. Today, the possibility to study high-energy neutrinos by detecting the acoustic signals from cascade showers [7] is at the initial stage of investigation.

In all the deep-water neutrino detector projects, the detecting modules are mounted on submerged buoy stations of different configurations with the distances between them being much smaller than their lengths. However, the buoy stations, whose lower ends are anchored to the bottom, move in space under the effect

† Deceased.

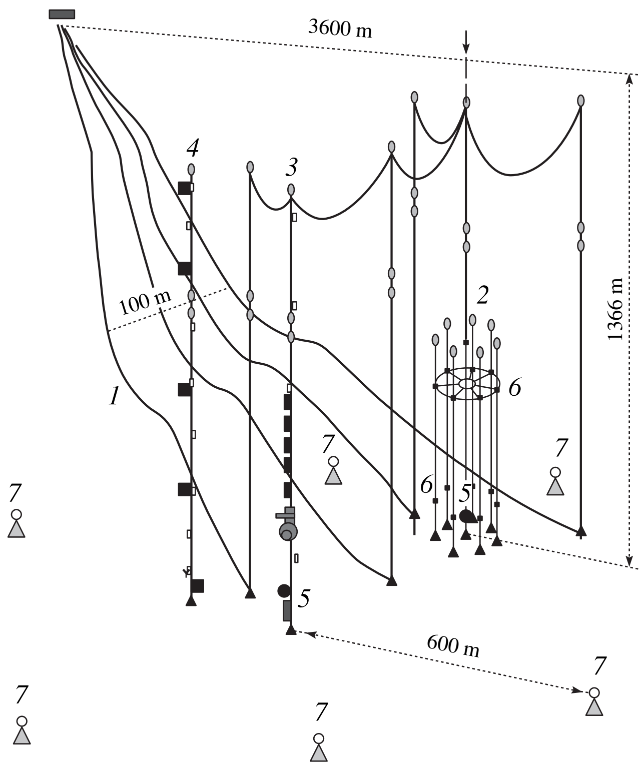

Fig. 1. The NT-200 deep-water Baikal neutrino telescope system: (*1*) cable communication lines, (*2*) NT-200 neutrino telescope, (*3*) hydrological string, (*4*) sedimentological string, (*5*) master modules, (*6*) acoustic receivers, and (*7*) acoustic beacons.

of currents, which occur in large natural water basins at any depth. Therefore, two problems arise:

(i) the determination of the possible evolution of the buoy stations forming the deep-water system of the detector and the consideration of the probability of their confusion due to the inhomogeneity of currents and the differences in buoy-station configurations;

(ii) the determination of the actual spatial positions of all detecting modules of the neutrino detector after their placement and the realization of the long-term monitoring of their coordinates to provide an adequate reconstruction of the events.

The problem of determining the spatial position of an object in the water medium is a common problem of practical oceanology. As a rule, it is solved using acoustic systems that determine the coordinates of objects with respect to a certain number of reference points—acoustic beacons [8, 9]. A specific feature of the case of a deep-water neutrino telescope is the necessity to provide long-term permanent measurement of the coordinates of many objects distributed over a large water volume (about one cubic kilometer).

In this paper, we describe the hydroacoustic coordinate-measuring system (HCMS) of the NT-200 neutrino telescope. This system is capable of permanent operation in an automated or interactive mode; it has a long base and allows one to measure the coordinates of the detecting modules of the NT-200 with an accuracy of 20 cm or better. We give special attention to the evaluation of the coordinate measurement errors. We also present some results obtained by measuring the coordinates of the modules of NT-200 and the results of measuring the velocity of sound in the Baikal water.

In the HCMS of NT-200, acoustic signals propagate over several tens of trajectories in a volume on the order of one cubic kilometer, which makes it possible to use this system for studying hydrophysical processes. In particular, it is possible to monitor the variations of the mean water temperature in different layers of the lake over a long period of time. This is an important alternative method for studying the variations in the heat store of the lake, the water-exchange processes, and other phenomena characterized by different space and time scales.

2. STRUCTURE OF THE HYDROACOUSTIC COORDINATE-MEASURING SYSTEM OF NT-200

The general view of the NT-200 deep-water neutrino telescope and its HCMS is shown in Fig. 1. The HCMS includes:

—a shore station consisting of a control computer, a communication modem, and a power supply unit;

—a cable communication line about 7 km in length;

—transceivers (master modules) and ultrasonic receivers (acoustic receivers);

—self-contained transponders—bottom beacons.

2.1. Master Modules and Acoustic Receivers

Durable cylindrical casings of the master modules and acoustic receivers are made of the AMG-6 aluminum alloy. Crates with electronics are fixed to the upper covers of the instruments. A cover has two holes for the modular parts of pressure-seal connectors. One of the connectors is used for the power supply and for communication with the shore station, and the other, for the connection to the hydrophone. As electroacoustic transducers the HCMS uses hydrophones made on the basis of piezoceramic spheres 50 mm in diameter. Their maximum sensitivity at a frequency of 30 kHz is 250–300 μV/Pa.

The HCMS contains more than twenty acoustic receivers and master modules placed on nine buoy stations, and all of them are connected in parallel to one conductor of the KG7-70-90 geophysical cable, which serves for the power supply and communication with the shore station. To ensure the performance of the system in the case of a leak or shortage in one of the instruments, each of the casings contains a sealed optronic switch through which high voltage arrives at the power supply unit. In the initial state, all switches are in the open-circuit position. At the initiation of the system, according to the commands from the shore station, all the optronic switches are sequentially closed by individual codes. If the current consumption in one of the instruments exceeds the allowed limit, this instrument is excluded from the configuration and is not turned on at the next initiation. The electronics of an acoustic receiver is assembled on the basis of low-consumption components and includes a power-supply unit, which transforms the input dc voltage of 300 V to low voltages, and a receiving channel, which contains a selective amplifier, an envelope detector, a threshold device, and a signal duration check circuit. A master module additionally contains an ultrasonic signal generator.

The control over the measurement process and the communication of the acoustic receivers and master modules with the shore station occur through K1821BM85-microprocessor-based controllers. The latter provide for

—the execution of measurements according to a preset program,

—the preliminary data processing and the compaction of data,

—the data communication through the cable, and, finally,

—the data being saved in the internal solid memory.

2.2. Hydroacoustic Beacons

Six beacons of the HCMS are uniformly distributed over a circle with a radius of 600 m and with the center at the point of the hydrological string location (Fig. 1). This number of beacons makes it possible to enhance the robustness of the system and to improve the measurement accuracy, as well as to obtain additional information on the hydrophysical parameters of the water medium. Figure 2 shows the general view of a short buoy station with an acoustic beacon. On platform *7* made of pieces of rails welded together, a durable sealed casing *6* with electronics and power cells and a rigid arc with a rod *5* are mounted. At the upper end of the rod, a hydrophone *4* is fixed in the middle of a safety frame. The distance from the hydrophone to the bottom is 4 m (here, the fact that the lower layer of the rails is immersed in bottom sediments is taken into account). A kapron cord *3* with a length of 30–40 m is tied to the rod. The cord is held in the vertical position by a bundle of 20 aluminum floats *1*. One meter away from the floats, the so-called collar *2* is fixed, which serves for lifting the beacon: in this case, the collar is hooked by the crabs of a device [10] rotating in the course of its motion in water because of asymmetry. The instants when the beacon is hooked and when the bottom is touched in the process of beacon placement are determined from the dynamometer readings. The weight of the beacon in water is about 100 kg.

The electronics of a beacon consists of analog channels for reception and transmission, a decoder for coded signals, and a device analyzing the received code

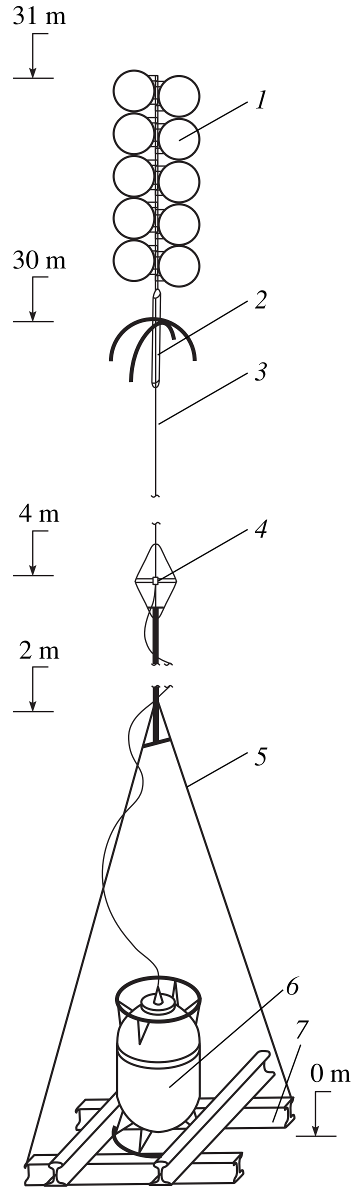

Fig. 2. Deep-water buoy station with an acoustic beacon: (*1*) aluminum floats, (*2*) collar, (*3*) kapron cord, (*4*) hydrophone, (*5*) rod, (*6*) casing, and (*7*) platform.

and generating the beacon response. The beacons are powered by galvanic cells, whose service life is 2–3 years.

2.3. The Shore Station

The shore station includes a computer, a communication modem providing the communication between the shore computer and the underwater equipment of the HCMS, and a high-voltage source. The output voltage of the power source is automatically controlled with allowance for the value of the consumption current so that, independently of the voltage drop in the 7-km-long cable line, the input voltage of the underwater instruments of the HCMS is 300 V.

The software makes it possible to measure the coordinates of the buoy stations in both automated and hand-operated modes of the sequential beacon data acquisition and data selection from certain master modules and acoustic receivers or from their group. The software supports the communication line protocol, remote program loading, and running the program. It is possible to set the necessary gating times for the input receivers of instruments positioned at different sites and to change the thresholds of comparators in the receiving channels of the master modules and acoustic receivers.

2.4. The Coordinate Measurement Cycle of the Neutrino Telescope

The coordinate measurement cycle is initiated by the shore control computer, which sends a sync pulse (a group start) via cable communication lines to the controllers of all or selected groups of master modules and acoustic receivers. The controllers of the instruments execute the preset programs. One of the master modules sequentially transmits coded interrogation signals to each of the beacons. The HCMS uses a time–pulse coding of beacon interrogation at a frequency of 28 kHz. All the necessary carrier frequencies and signal durations are obtained from a single quartz oscillator, which is included in the controller.

The beacon acquisition code contains a 2-ms-long pulse, which is common to all beacons, and a three-position code of the beacon number with a bit duration of 1 ms. The interval between the wave trains is equal to 2 ms. Thus, the length of the whole ultrasonic transmission packet is 10 ms.

To save battery power, all the electronics of a beacon, except for the receiving amplifier, comparator, and range meter, is usually in "sleep" mode. If a train of received signals arrives without discontinuities longer than one period of the carrier frequency and with a train length exceeding 1.75 ms, the timer unit of the beacon is turned on. Then, the beacon interrogation code fills the sequential register of the comparison circuit, and, at the coincidence of the proper code of the beacon with the code arriving to the comparison circuit, the beacon response signal is generated with a duration of 1 ms and a carrier frequency of 32 768 Hz. The controllers of the acoustic receivers and master modules measure the travel times of an ultrasonic signal from the instant of interrogation to the instant of reception of the beacon response signal. The counters of the master modules fix the time of sound propagation from the master module to the beacon and back to the master module. The acoustic receivers are able to measure the time of sound propagation along the master module–beacon–acoustic receiver path and also (by measuring the gating time, see below) the time of sound propagation from the master module to the acoustic receiver. To increase the noise robustness, a discriminator is used to test the duration of each packet of the pulse transmission. An additional measure for increasing the noise robustness is the gating circuit, which opens the receiving channels in a master module and an acoustic receiver 20 ms before the expected arrival time of the response pulse.

Thus, the following times of sound propagation can be measured: $\tau_k^k(i)$, from the kth master module to the ith beacon and back; $\tau_k^j(i)$, along the master module (k)–beacon (i)–acoustic receiver (j) path; and $\tau_k^j(0)$, from the master module (k) to the acoustic receiver (j).

The distance from the point at which the hydrophone of the acoustic receiver(j) is located to the hydrophone of the beacon(i), i.e., the slant range R_{ij}, is calculated by the formula

$$R_{ij} = (\tau_k^j(i) - \tau_k^k(i)/2)C^s(z),$$

where $C^s(z) = z/\int_0^z dz/C(z)$ is the harmonic mean velocity of sound and $C(z)$ is the velocity of sound at a depth z.

The spatial position of the hydrophone of the acoustic receiver is determined as the point of intersection of the spheres whose centers are at the points of the beacon locations and radii are equal to the slant ranges from the beacons to the given hydrophone.

3. ERRORS IN MEASURING THE COORDINATES OF THE DETECTING MODULES

The error in the determination of the coordinates of the detecting modules depends on the accuracy achieved in measuring the slant ranges and the beacon coordinates.

3.1. Instrument Errors

Primarily, these are errors in measuring the travel times of acoustic signals. They consist of the following components:

—the error due to the asynchronous arrival of the initiation pulse from the shore station to the instruments distributed over the buoy stations;

—errors due to the threshold variations in the comparators included in the ultrasonic receiving circuits of the beacons and acoustic receivers; and

—errors due to the discreteness of the coded signal detection channel of a beacon.

The estimates of the maximum values of these errors yield 20, 18, and 36 μs, respectively. To determine the actual accuracy of the time interval measurements by the HCMS, the distribution of the experimental errors in measuring the signal travel times (1200 measurements) along one of the master module–beacon–acoustic receiver paths was obtained. The distribution half-width proved to be about 10 μs, which makes a contribution of about 2 cm to the error in the determination of the coordinates of a detecting module.

3.2. Errors Due to the Uncertainty in the Parameters of the Medium

The main source of errors associated with the properties of the medium is the inaccuracy in the determination of the absolute value of the sound velocity along the signal propagation paths [11]. An analysis has shown that, to measure the coordinates of the detecting modules with a required accuracy of 20 cm, the absolute value of sound velocity should in our case be determined to within 50 cm/s.

The value of the sound velocity can be measured directly [12, 13] or calculated from the data on the temperature *T*, salinity *S*, and pressure *P* with the use of empirical formulas [14–17]. Although the authors in some publications believe that the systematic errors in their formulas are small (e.g., 4 cm/s in [13]), the difference between the values obtained with these formulas for the sound velocity in the Baikal water at the telescope depth reaches 2 m/s.

To perform a direct experimental measurement of sound velocity and to test different empirical formulas for calculating *C*, we measured the time of sound propagation with an acoustic base 100 m in length, which was determined to within ±2 cm (with allowance for the extension of the cable in water). In this experiment, we measured the integral sound velocity over the base length, but the linearity of the depth dependence of *C* (see below) allowed us to determine the sound velocity at given depths by shifting the measuring system in depth within the interval from 800 to 1300 m. Simultaneously, we performed temperature and pressure measurements with an SBE 25-01 probe. As a result, we found that the data of the direct measurements performed as described above with an error no greater than 30 cm/s agree well with the results of calculation by the formulas taken from [13] with the use of the temperature data obtained from the SBE 25-01 probe, which were accurate to within 0.002 deg (the corresponding contribution to the error in calculating $C(z)$ is 1 cm/s). Figure 3 shows the results of calculating the vertical distribution of sound velocity according to [13] and according to the temperature data from [18] for the region where NT-200 was deployed; the distributions are given for different seasons. The greatest sound velocity variations associated with temperature variations are observed near the surface of the lake and reach 40 m/s. At large depths, where the temperature variations are very small, the depth dependence of sound velocity is mainly determined by pressure and can be approximated by the formula

$$C(z) = 1418.96 + 0.0153645z \text{ m s}^{-1},$$

where *z* is the depth in meters.

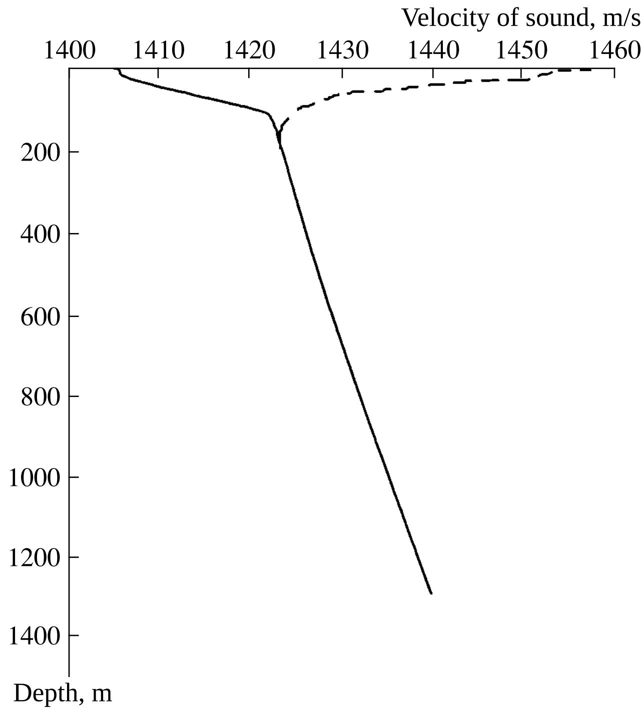

Fig. 3. Vertical sound velocity distribution in Baikal in March (the solid line) and in August (the dashed line).

According to long-term temperature observations [19], at the telescope depth, only slight temperature variations within several hundredths of a degree are possible. Therefore, we can use the sound-velocity profile shown in Fig. 3 as a reference in the HCMS data processing. At the same time, we observe relatively short temperature variations (Figs. 7 and 8) that should be taken into account in calculating the harmonic-mean sound velocity used in the computations. For this purpose, the temperature variations were monitored over a period of one year with the use of a series of TR-1000 termistors spaced at 100 m in depth and placed at the hydrological and neighboring sedimentological buoy stations (Fig. 1).

The average mineralization of Baikal water is about 96 mg/l [20], and its variations do not exceed 30%, which makes a contribution to sound velocity on the order of 12 cm/s with possible variations of about 4 cm/s. Thus, in our case, salinity variations can be ignored.

The currents that occur at the telescope depth in the southern part of Baikal usually do not exceed 20 cm/s [21] and practically do not affect the accuracy of coordinate measurements.

3.3. Errors in the Determination of the Beacon Positions

The beacons are placed at the sites of their operation in winter, by lowering them from the ice cover of the lake. The positions of the points of beacon submer-

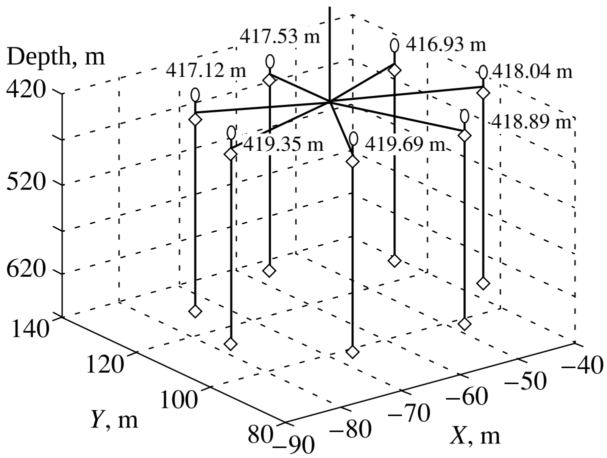

Fig. 4. Positions of the buoy stations of the NT-200 neutrino telescope in the course of their lowering. The numbers near the buoy stations indicate the depths of the upper acoustic receivers.

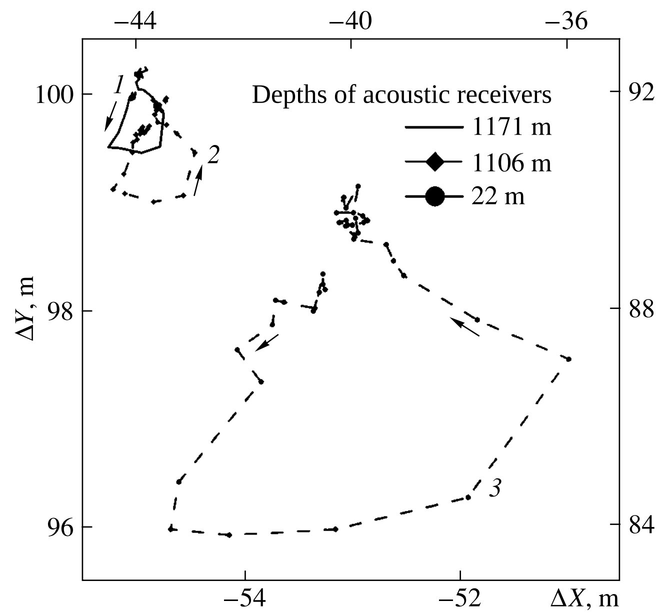

Fig. 5. Fragment of motion of a buoy station of the NT-200 neutrino telescope between June 28, 1994, and July 18, 1994: (*1, 2*) acoustic receivers at depth of 1171 and 1106 m (the left and bottom axes); (*3*) an acoustic receiver at a depth of 22 m (right and top axes).

gence are determined by a laser ranger and a theodolite to within 0.2 m. In winter, when the system is deployed, the currents in the upper layer of Baikal usually do not exceed 2 cm/s and logarithmically decrease with depth [21]. According to our estimates, in the presence of these currents, the points where beacons of the given configuration are placed on the bottom deviate from the corresponding points on the surface by no more than several tens of centimeters.

An independent determination of the beacon positions was performed with the use of an acoustic array consisting of four master modules, whose hydrophones were fixed on two vertical cables at distances of 4 and 104 m from the bottom. The distance between the cables was 336 m. An analysis has shown that the accuracy achieved by us in these measurements was 40 cm, and the average values of the beacon coordinates agreed well with the results of geodetic measurements.

The relative depths of the beacon placement were measured using a contact switch, which was closed at the instant of touching the bottom. This closure was detected by the ohmmeter positioned on the lake surface. The measurement accuracy was 1 cm. The scatter in the sea depths at the beacon sites was 5.69 m. With allowance for the uncertainty in the depth of anchor submergence in the silty bottom, the error in the relative depths does not exceed 5 cm.

3.4. Conclusions

—The main sources of errors in the HCMS are the errors in the determination of the sound velocity profile and the beacon coordinates.

—The HCMS provides the possibility to carry out long-term measurements of the coordinates of the detecting modules of the NT-200 to an accuracy of 20 cm or better.

4. RESULTS OF MEASURING THE COORDINATES OF THE NEUTRINO TELESCOPE

The first measurements of the coordinates of the detecting modules by the HCMS were performed in 1994. These measurements are in progress at the present time. As a rule, they are carried out in four cycles with a periodicity of 10–12 h (or more often, if necessary). The HCMS also allows one to observe the variations that occur in the positions of the telescope strings as the telescope is submerged and placed on the bottom (Fig. 4). It is of interest that, from year to year, after the placement of the system, the strings prove to be almost at the same points. The distances between the hydrophones of the lower and upper acoustic receivers that are fixed on the same string are also retained. They usually differ by no more than 10 cm from the distances measured with a measuring reel before the placement.

During the year, the coordinate motion of the NT-200 as a whole was observed (Fig. 5). The maximum deviations of the buoy stations are observed in the period of autumn storms, in September and October. For the upper buoy (a depth of about 20 m), they exceed 50 m (Fig. 6), while the upper detecting modules deviate by no more than 1.3 m and the lower modules, by 1 m. In all cases, the telescope deviates from the vertical posi-

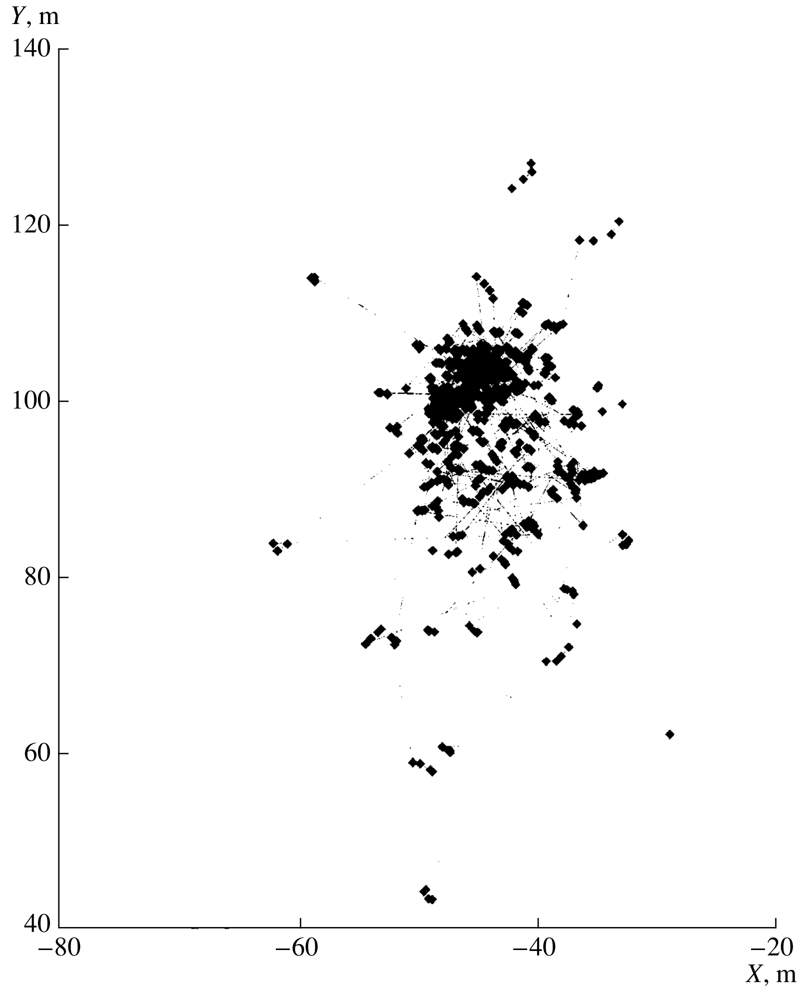

Fig. 6. Motion of an acoustic receiver located at a depth of 22 m under the upper float at a buoy station of NT-200 in 1994. The *Y* axis is directed along the coast to the west.

tion by no more than 1 deg, and the relative coordinates of the detecting modules vary by no more than 10 cm.

5. INVESTIGATION OF THE WATER MEDIUM BY THE HYDROACOUSTIC SYSTEM OF NT-200

The data obtained from the HCMS can also be used to study the hydrophysical processes in the lake. The simplest information of this kind is obtained by observing the behavior of the buoy stations of the telescope. The predominant displacement of the submerged buoy stations to the west confirms the concept concerning the global water circulation in the Southern trench of the lake [21]. Fourier analysis of the buoy station deviations revealed, e.g., the presence of oscillations with periods close to the periods of seiche oscillations in Lake Baikal [22, 23].

A much greater amount of information on the hydrophysical fields can be obtained by analyzing the data on the times of sound propagation between different points in the water medium. For this purpose, it is especially convenient to use paths with a fixed length. Such paths primarily are the paths along the bottom, from the master module to each of the beacons. With the accuracy of time measurements in the HCMS being $\Delta\tau = 10$ μs, the resolution of the observation of mean temperature variations on a path of length L is

$$\Delta T\ (\text{deg}) = \frac{\Delta\tau C^2}{\alpha L} = 0.004/L\ (\text{km}), \qquad (1)$$

where $\alpha = 5.0371$ is the proportionality coefficient in the formula determining the relation between the sound velocity and temperature [13].

The accuracy achieved in measuring the absolute value of the mean temperature also depends on the accuracy of determining the distance ΔL between the transmitting and receiving hydrophones. For the master module–beacon–master module path with $\Delta L = 40$ cm and $L = 1.2$ km, this accuracy is not high (about 0.1 deg), and, therefore, we compare the results with the absolute reference measurements by a TR-1000 termistor. Figure 7 compares the results of temperature

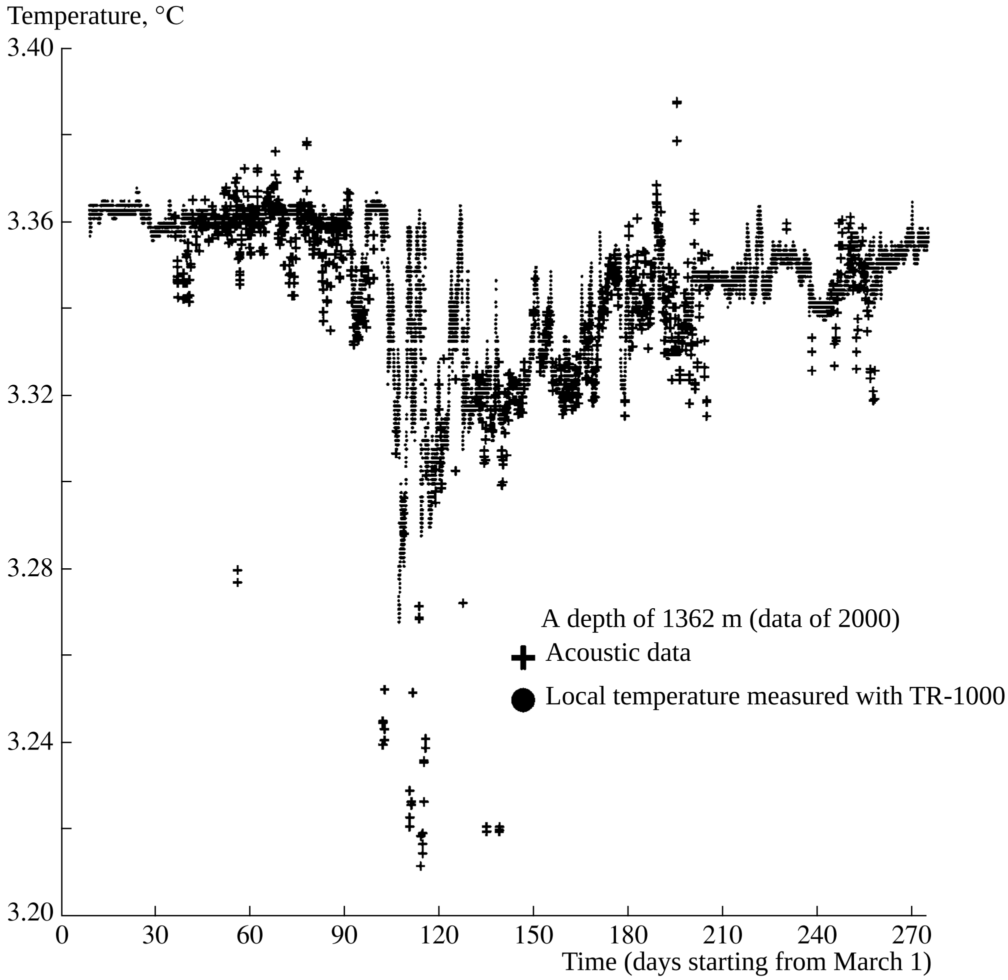

Fig. 7. Results of temperature measurements carried out in 2000 on the master module–beacon path by the HCMS (crosses) and by a TR-1000 termistor positioned 4 m above the bottom (full circles). The errors are not shown in the plot.

measurements on the master module–beacon path with the help of the HCMS and a TR-1000 termistor placed at a distance of 4 m from the bottom. On the whole, a qualitative agreement is observed between the temperature behavior at a point (the TR-1000 data) and the mean temperature of the layer (the HCMS data). After the period characterized by an almost constant temperature in March–May, both methods reliably detected a considerable temperature decrease in mid June and the subsequent decaying temperature variations, which testify to a considerable intrusion of cold waters into the near-bottom region in the homothermal period [18]. For clarity, the errors are not shown in Fig. 7. For the data obtained with TR-1000, the errors are on the order of the dots, and for the HCMS data, according to Eq. (1), they are about ±0.004°C in the given case. The spikes in the HCMS data may presumably be related to failures in the system's operation, for example, because of acoustic noise.

For tracing the hydrophysical characteristics of the water mass, in addition to the horizontal paths along the lake bottom, it is possible to use the vertical paths of sound propagation between the instruments positioned on the hydrological buoy station. As an example, in Fig. 8, we show the temperature variation in the deep 300-m-thick near-bottom layer with time starting from October 13, 1995. In the first part of the period of measurements, the data were taken at a step of 20 s. The large temperature variations (up to 0.4°C, the measurement error is about ±0.015°C), which are observed at large depths in the southern part of Lake Baikal, where, as a rule, a stable stratification of water temperature is observed in the layer from 300 to 1300 m during the whole year [19], may be related to the incursion of warmer near-surface waters due to the storm that occurred at the beginning of this period. Observations of this kind are very important for the understanding of the water-exchange processes in Lake Baikal and testify to the fact that the role of dynamic factors (such as atmospheric pressure variations or wind) should be taken into account in studying the hydrophysical processes in the lake.

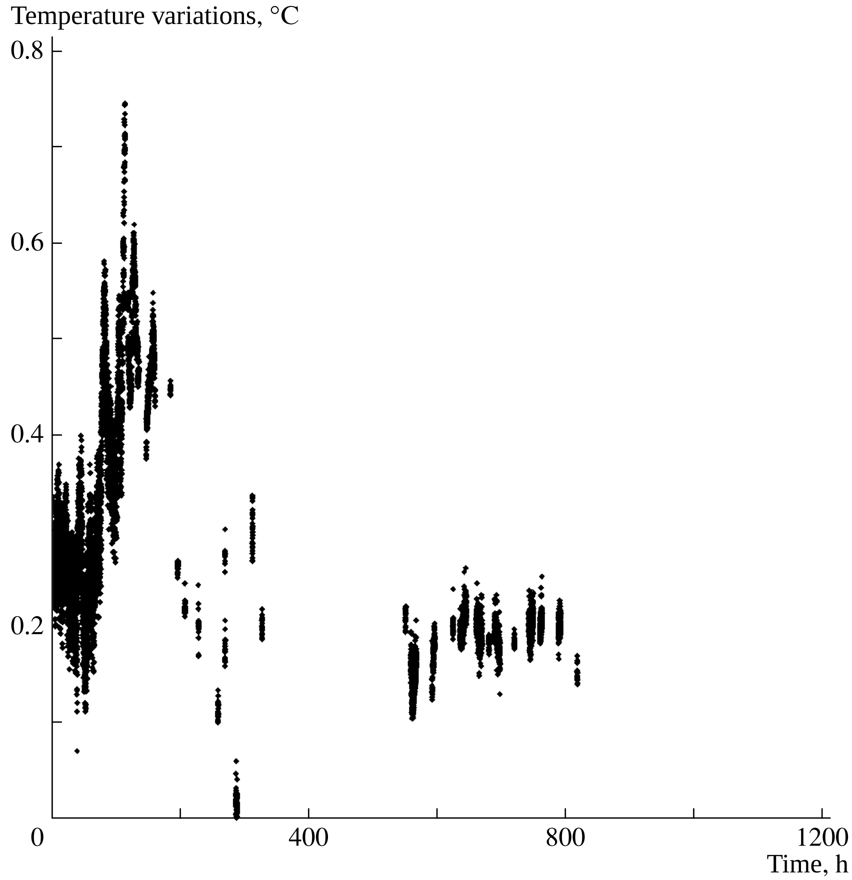

Fig. 8. Measurements of the mean temperature of water in the 300-m-thick near-bottom layer starting from October 13, 1995. Each of the points is a result of a cycle of measurements. The errors are not shown.

6. CONCLUSIONS

The HCMS of the NT-200 makes it possible to monitor the spatial positions of the elements of the neutrino telescope during a long period of time with an accuracy of 20 cm (or better). The architecture of the HCMS allows its further development with the expansion of the NT-200. The methodical and engineering solutions found in developing the HCMS of NT-200 can be used for designing other distributed acoustic systems intended for positioning various objects and for studying the hydrophysical processes in the water medium.

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