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Autonomous Internal Wave Measurer based on Temperature Transmitters for Shelf Studies

A. N. Serebryany [1, 2] ***, D. M. Denisov** [2]**, E. E. Khimchenko** [1]

[1] *Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia*
[2] *Andreyev Acoustics Institute JSC, Moscow, Russia*
* *e-mail: serebryany53@list.ru*

Abstract

The paper describes a device for measuring internal waves, which is made on the basis of a line temperature sensor. This sensor measures the average temperature of the water layer it covers, which makes it possible to avoid registration of fine-structural distortions. The device works offline with the possibility of long-term accumulation of a large amount of information (with an interval of 1 minute – within 1 year). The measurement resolution is set from 1 to 1200 s. The average temperature measurement error is 0.1 °C, temperature resolution is not worse than 0.03 °C. The working depth is up to 200 m. The autonomous measurer is compact and easy to use. The device connects to a computer or smartphone via Bluetooth wireless technology. The paper presents the results of comparative simultaneous measurements carried out by the device and a chain of point temperature sensors on the Black Sea shelf in summer 2018 and autumn 2019. The paper gives examples of the use of an autonomous measurer for recording short-period and inertial internal waves. The comparison of the obtained series shows their close similarity. The conducted frequency spectral analysis also demonstrates a good match and identification of the main peaks of registered phenomena. The device proved to be a reliable and promising tool for measuring internal waves on the shelf.

Key words: internal wave measurer, measuring device, line temperature sensor, short-period internal waves, sensor chain, point temperature sensor, temperature sensor

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Автономный измеритель внутренних волн на базе измерительных преобразователей температуры для исследований на шельфе

А. Н. Серебряный [1, 2] *, Д. М. Денисов [2], Е. Е. Химченко [1]

[1] *Институт океанологии имени П. П. Ширшова РАН, Москва, Россия*
[2] *АО «Акустический институт имени академика Н.Н. Андреева», Москва, Россия*
* *e-mail: serebryany53@list.ru*

Аннотация

Описывается устройство для измерений внутренних волн, выполненное на основе распределенного датчика температуры. Этот датчик измеряет среднюю температуру охватываемого им слоя водной толщи, что позволяет избегать регистрации тонкоструктурных искажений. Устройство работает в автономном режиме с возможностью долговременного накопления большого количества информации (при интервале 1 мин в течение 1 года). Дискретность измерений устанавливается от 1 до 1200 с. Погрешность измерения средней температуры составляет 0.1 °C, разрешение по температуре не хуже 0.03 °C. Рабочая глубина до 200 м. Автономный измеритель отличается компактностью и простотой использования. Устройство подключается к компьютеру или смартфону посредством беспроводной связи *Bluetooth*. Приводятся результаты сравнения одновременных измерений устройства с гирляндой точечных датчиков температуры. Измерения проведены на шельфе Черного моря летом 2018 г. и осенью 2019 г. Представлены примеры использования автономного измерителя для регистрации короткопериодных и инерционных внутренних волн. Сопоставление полученных рядов показывает их близкое сходство. Проведенный частотный спектральный анализ также демонстрирует хорошее совпадение данных распределенного датчика температуры с данными, полученными искусственным распределенным датчиком температуры на основе осреднения измерений гирляндой термодатчиков путем выявления основных пиков регистрируемых явлений. Устройство показало себя надежным и перспективным инструментом для проведения измерений внутренних волн на шельфе.

Ключевые слова: измеритель внутренних волн, измерительные приборы, распределенный датчик температуры, короткопериодные внутренние волны, гирлянда датчиков, точечные датчики температуры, датчик температуры

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Introduction

Measurement of internal waves in oceans and seas has always been a difficult task due to the complexity of this phenomenon and the inaccessibility of its observations in the water layer. To measure internal waves in the oceanic and marine environment, both contact and non-contact (remote) methods are used, which have recently become widespread. The most commonly used are contact measurement methods based on registering changes in the temperature of the water column by vertical chains of point temperature sensors. The widespread use of clusters of chains of point temperature sensors is typical for large-scale experiments conducted in recent decades to study internal waves on the shelves [1–3]. In these experiments, the chains are formed on the basis of a set of autonomous point temperature measurers of a proprietary design. Thermistor chains are also developed as a one-piece measuring tool [4].

An alternative to chains of temperature sensors for measuring internal waves is the line temperature sensor (LTS) proposed in [5]. The LTS measures the average temperature of the layer it covers, adequately tracking temperature fluctuations caused by internal waves. Its main advantage over a point sensor is that the LTS recording is free of the distortion introduced by the fine structure of the vertical temperature profile commonly found in real oceanic or marine conditions. LTS have proven themselves well in measurements on the shelves from stationary platforms [6, 7] and in measurements in the ocean from a vessel in the drift mode or on the move when towing [8].

The disadvantage of measurements based on LTS, which were placed in the aquatic environment, was the need to connect them with bonding wires to recorders located at a distance. The recently developed internal wave measurer [9] does not have this disadvantage, since the LTS is directly connected to a small-sized recording equipment (information storage device) made in a compact case, which, together with the sensor, is lowered into the aquatic environment for the time necessary for measurements. Here it is necessary to call back to the fact that 40 years ago, Marine Hydrophysical Institute developed an autonomous device MGI 1304 (RITM), which performed similar functions [10, 11]. The main difference between the device described in this paper and RITM is that the former is based on modern electronic technology, which makes it possible to reduce dimensions and improve data recording and reading.

This paper presents a modified version of such an autonomous internal wave measurer and presents comparative results of observations obtained when using it.

Technical details of internal wave measurer design

An autonomous internal wave measurer, the general view of which is shown in Fig. 1, structurally consists of a recording device (*1*) and a 20 m long line temperature sensor (*2*). The LTS is made of copper-covered steel wire protected from water by insulating coating. Resistance per unit length of wire is 5 Ohm/m, temperature coefficient of resistance is 0.36 Ohm/K, time constant is 20 s.

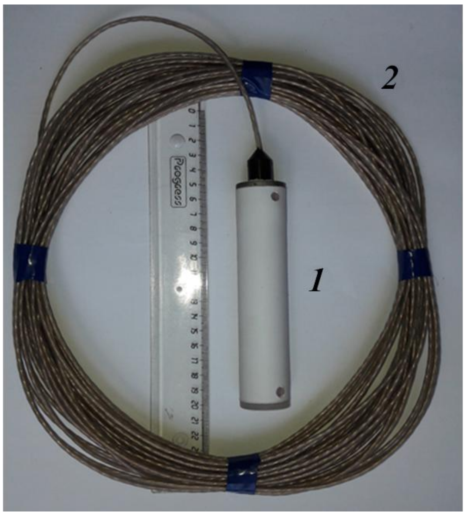


Fig. 1. Autonomous internal wave measurer: recording device – *1*; line temperature sensor (LTS) 20 m long – *2*

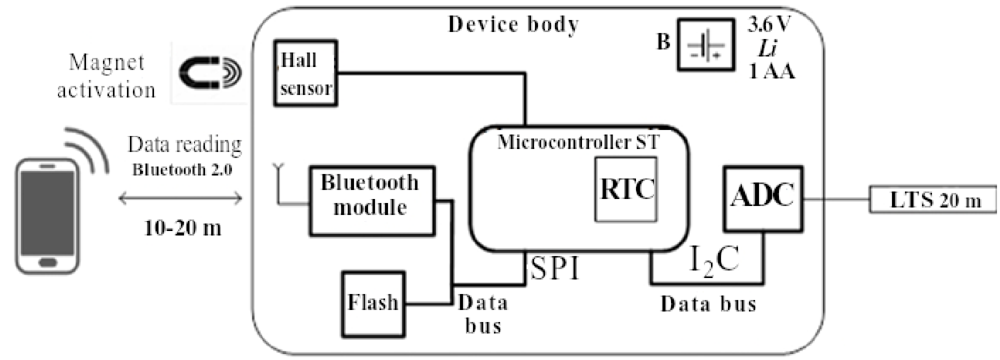
The recording device is designed for periodic recording of temperature values obtained from the LTS. The registration period can be set from 1 to 1200 s. The average temperature measurement error is 0.1 °C, temperature resolution is 0.03 °C. The working depth is up to 200 m.

The body of the device is a sealed cylinder made of a piece of polypropylene pipe with an outer diameter of 32 mm. The LTS is connected to the housing through a cable entry in the lower metal cover of the housing. The top cover is made of transparent organic glass, which makes it possible to observe the status of the device, displayed by the internal LED indicator flashes. Bluetooth radio communication is used to configure the device and read the temperature data archive. To enter the setup mode and read the data, it is necessary to bring a small permanent magnet to the top cover of the device for a short period of time. In this case, the device activates the Bluetooth module, which makes it possible for a computer or smartphone to connect to the device within 20 seconds. An AA-type 3.6 V lithium battery with a capacity of 2400 mAh ensures the operation of the device in the registration mode with an interval of 1 min within 1 year [9].

The recording device consists of a microcontroller with a real-time controller, a 16-bit analog-to-digital converter (ADC) microcircuit, a non-volatile Flash memory microcircuit, a Bluetooth wireless communication module, a proximity switch (a Hall sensor), and a lithium battery B (Fig. 2). The electronic circuit converts the sensor resistance into voltage, which is converted into an ADC code stored in memory.

Comparative results of measurements of internal waves by an autonomous measurer and a chain of temperature sensors

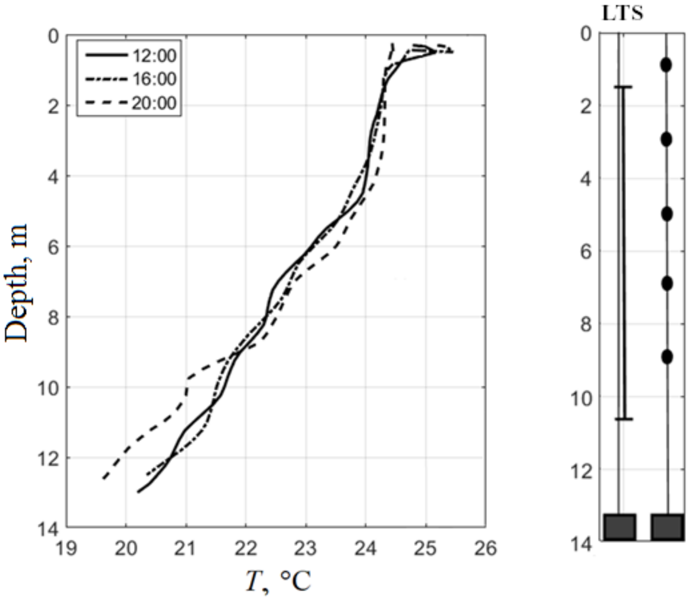
In June 2018, we carried out comparative measurements with an autonomous internal wave sensor (LTS) and a chain of five point temperature sensors in the Black Sea. The chain included autonomous DST centi-TD temperature measurers manufactured by *Star Oddi* company. The point measurers were located vertically with a spacing of 2 m, the time recording was carried out with an interval of 30 s. Both measurers were lowered from the service ramp of the Institute of Ecology of the Academy of Sciences of Abkhazia (IE of ASA) at the point where the sea depth is about 13 m. The horizontal distance between the measurers was about one meter, they were in almost the same conditions, covering a 10-meter water layer.



F i g . 2 . Structural diagram of the internal wave measurer. RTC – real time controller; ADC – analog-to-digital converter; SPI – serial peripheral interface; I_2C – inter-integrated circuit

Fig. 3 shows the position of the LTS and temperature sensor chains at depth and vertical temperature profiles at the beginning of measurements. Temperature profiles were measured with a *Valeport* miniSVP probe.

The recording of the thermistor sensors at all five horizons for the entire observation time (45 h) are shown in Fig. 4. The entire water layer, with the exception of the near-surface area, is characterized by temperature fluctuations with a range



F i g . 3 . Vertical temperature profile on June 15 at different time points (*left*); the position of the LTS and temperature sensor strings at depth (*right*)

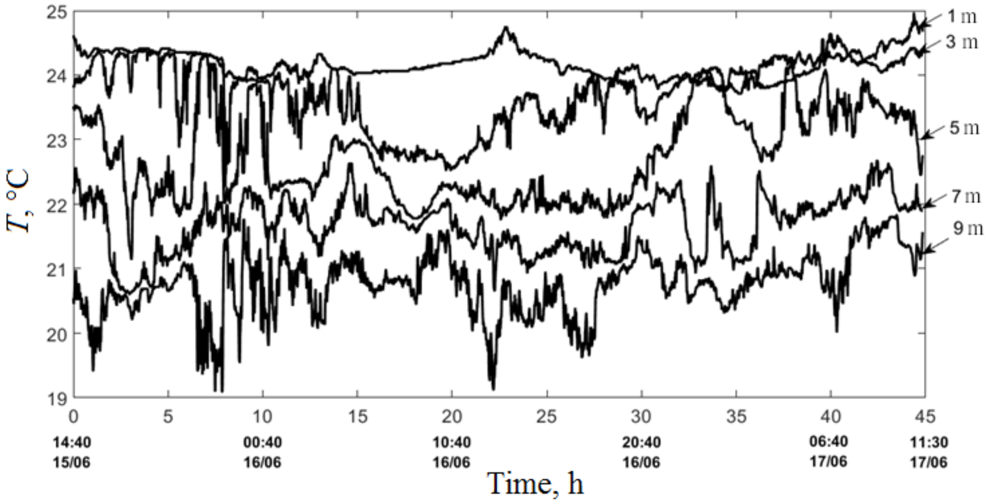


Fig. 4. Recording of thermistor sensors demonstrating temperature fluctuations at five horizons

of 1–2 °C with periods of several minutes or more. In the upper layer, temperature fluctuations are insignificant, but after 30 hours of observations, an inversion occurs.

Fig. 5 shows the implementation recorded by the LTS and the record of the thermistor sensors averaged over five horizons where the sensors were located. To convert the recording of the thermistor sensors into vertical displacements, it was normalized to the measured vertical temperature gradient within the length of the chain. The resulting series represented an artificially modeled LTS based

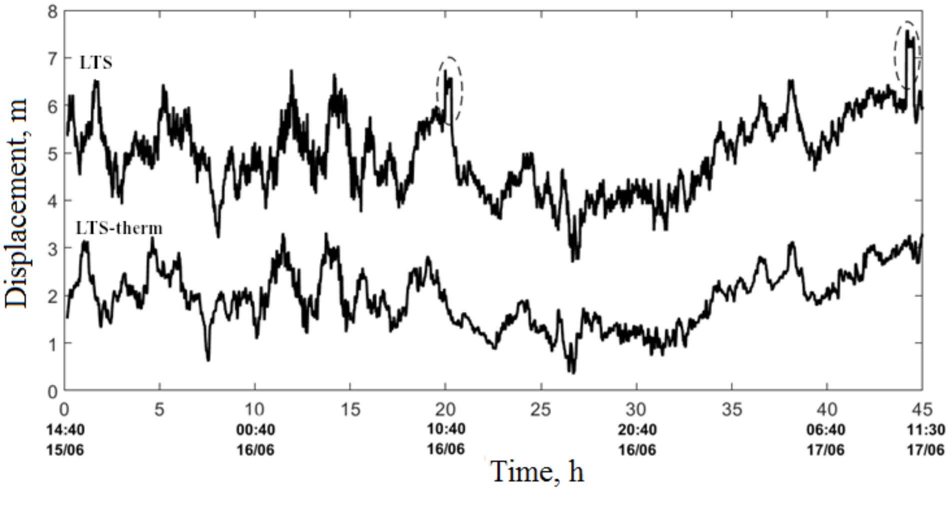


Fig. 5. Comparison of the LTS recording (*top*) and the averaged signal of the five point temperature sensors (*bottom*). The ellipses indicate the moments of measurement of the response of the LTS to a vertical displacement of 1 m

on a chain of point temperature sensors. The LTS recording was converted into vertical displacements of the water column using the measured responses obtained with a short-term (20-minute) vertical displacement of the sensor by 1 m. The conversion of the LTS average temperature recording into vertical thermocline displacements in meters by measuring the sensor response to a given vertical displacement is a well-known method when working with LTS [12, 13].

Simple visual comparison of two obtained series shows their close similarity. Both series demonstrate synchronous thermocline fluctuations with a vertical range of 2–3 m (Fig. 5). To further compare the data and to determine the period of prevailing fluctuations, the spectra of the obtained series were calculated (Fig. 6). The frequency spectra of thermocline fluctuations calculated within the measured series show peaks corresponding to the periods of 2–2.4 h, 30–40 min, 18 min, and 4 min. The spectral tilt, which is close to the Garrett–Munk model spectrum [14], and the spectral energy level, which is underestimated compared to the model one, can also be noted. The Garrett–Munk spectrum developed for internal waves in the ocean, is used here for comparison with waves in shallow water. All the above features are characteristic of the tideless Black Sea spectra [15, 16], and the thermocline fluctuations with such parameters are typical for short-period internal waves in the Black Sea.

Registration of inertial internal waves using autonomous LTS

In addition to short-period internal waves, long-period inertial internal waves, which play an important role in water dynamics, often occur in the sea shelf zone.

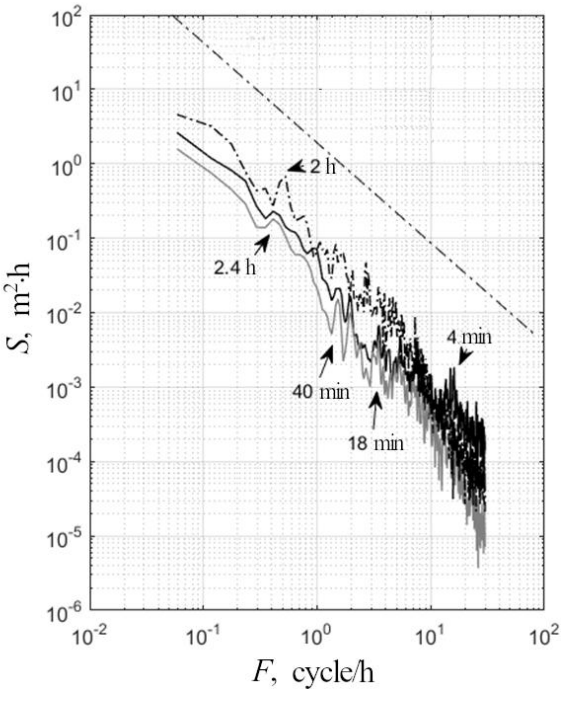


Fig. 6. Frequency spectra calculated from records of the LTS (black curve), temperature sensors chain (grey curve), and point sensor (dashed-dotted curve) at a depth of 9 m. The dash-dotted straight line shows the Garrett–Munk spectrum

They are reliably recorded using current measurers [17, 18], but LTS also makes it possible to track them reliably by the thermocline vertical displacements.

In the autumn of 2019, we conducted studies of internal waves in the Black Sea near the city of Sukhum, the area of which is characterized by a narrow shelf edge. In these measurements, we used an autonomous LTS described in this paper. An experimental batch of sensors was manufactured by Acoustics Institute. The results of this work are published in [19], but here we want to give a clear example of internal wave registration with a period close to the inertial one, registered by this autonomous LTS located on the Abkhazian shelf at a depth of about 50 m, at a distance of about 150 m from the coast.

An inertial internal wave with a period close to 17 h (see Fig. 7) causes the thermocline shear 2.5 m upwards and then, after passing through the crest, on which there are packets of short-period internal waves, it descends almost to its original position. Most probably, the vertical gradient of the shear flow increases in the region of the wave crest causing the formation of a set of short-period internal waves. The packets of short-period internal waves are shown in the inset of Fig. 7.

The inertial internal wave shown in Fig. 7 refers to the lowest (first) mode. In this case, the entire water layer synchronously shifts up and down in turn. This is the most common type of inertial motion in the marine environment. But there are also inertial internal waves of the second mode. They were also registered in the Black Sea [16, 20], and the second mode internal waves have also recently been recorded on the ocean shelf [21]. In order to detect internal waves

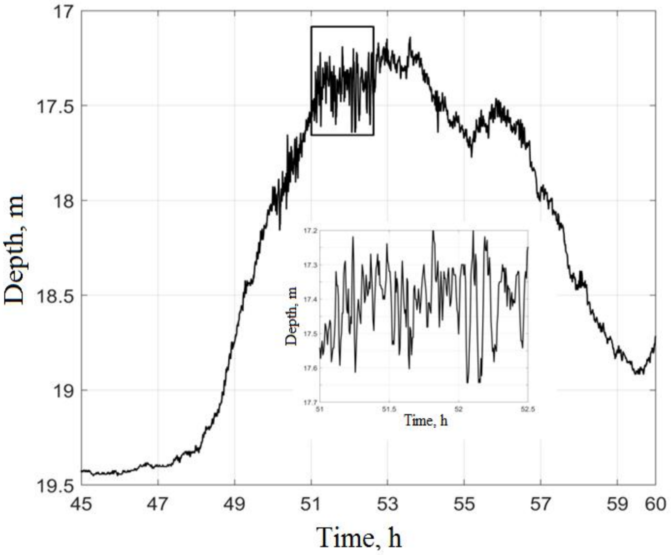


Fig. 7. Record of an inertial internal wave made by an autonomous LTS on the Black Sea shelf

above the first mode, it is necessary to design sensors in stages consisting of a set of several LTS located vertically, by analogy with the point thermistor sensors.

Conclusion

Both the proposed autonomous LTS-based measurer and chain of point temperature sensors are necessary means of contact measurements of internal waves in the marine environment with their own advantages. As for LTS, this is the ability to better transmit the thermocline wave fluctuations, its relative ease of fabrication and calibration. LTS-based records make it possible to reveal the nonlinear nature of internal waves, as well as to compare the profiles of the recorded waves with theoretical models. In addition, the use of several spatially separated LTS forming antennas makes it possible to measure reliably the spatial spectra of internal waves, which is hardly achievable by other contact means. The only drawback of the LTS is its filtering of wave fluctuations above the first mode. This drawback can be overcome by designing sensors in stage consisting of a set of several LTS located vertically.

The tests of the developed autonomous internal wave LTS-based measurer demonstrated its applicability for marine experiments. The use of several corresponding measurers in the shelf zone of the seas will make it possible to design spatial antennas and measure spatial spectra of internal waves, as well as to determine the wavelength, direction, and speed of their propagation.

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About the authors:

Andrey N. Serebryany, Chief Research Associate, Shirshov Institute of Oceanology, RAS (36 Nakhimov Av., Moscow, 117997, Russian Federation), Dr.Sci. (Phys-Math.), **ORCID 0000-0001-6449-8002, ResearcherID: F-9009-2014, Scopus Author ID: 6604015592**, *serebryany53@list.ru*

Dmitriy M. Denisov, Senior Research Associate, Andreyev Acoustics Institute (4 Shvernika St., Moscow, 117036, Russian Federation), *denisov.dimitry@gmail.com*

Elizaveta E. Khimchenko, Research Associate, Shirshov Institute of Oceanology, RAS (36 Nakhimov Av., Moscow, 117997, Russian Federation), Ph.D. (Geogr.), *ekhym@ocean.ru*

Contribution of the authors:

Andrey N. Serebryany – problem statement, participation in the construction of the internal wave measurer, analysis and description of the study results, preparation of the graphic materials, preparation of the article text

Dmitriy M. Denisov – design and development of the autonomous internal wave measurer, software development, analysis of the measurement data, preparation of the graphic materials, revision of the article text

Elizaveta E. Khimchenko – performance of *in situ* measurements, data processing, discussion of the results, preparation of the graphic materials, revision of the article text

All the authors have read and approved the final manuscript.