



Seawater Salinity Estimating Module Based on the Sound Velocity Measurements

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Purpose. Reliability of knowledge about the ocean dynamics and climate variability is largely limited for lack of systematic *in situ* observations of the sea surface layer salinity, which is one of the basic hydrological parameters determining circulation and stratification of the water masses. The study is aimed at developing an autonomous device for long-term monitoring of salinity in the seawater upper layer.

Methods and Results. One of the most effective tools for *in situ* observations of the ocean upper layer is the global network of surface drifting buoys – drifters. At present, the network consists of more than 1500 buoys, but only a few of them provide sea surface salinity observations within the framework of a limited number of pilot experiments. In the drifters, salinity is calculated by the traditional method using the results of the electrical conductivity and temperature measurements. There are a few problems related both to the principle of determining salinity by this method and to providing long-term stable running of conductivity sensors under the conditions of pollution and biological fouling. A drifter equipped with the module for the sound velocity and temperature measurements used for calculating salinity by an alternative method just aboard the drifter, was developed in Marine Hydrophysical Institute, Russian Academy of Sciences. The sound velocity and temperature module includes a specially designed time-of-flight sound velocity sensor with the fixed base and a quartz temperature sensor. In course of two years, numerous laboratory and *in situ* tests of several prototypes of the sound velocity and temperature module were performed. The laboratory tests showed that the repeatability limits for the results of the sound velocity measurements in the distilled water were ± 0.02 m/s. According to the data of the long-term *in situ* tests performed at intensive biological fouling, the error of salinity estimation resulted from of the sound velocity and temperature measurements were within ± 0.05 %. This result permits to expect that the sound velocity and temperature module parameters will remain stable in real conditions of long-term autonomous operation.

Conclusions. The obtained results make it possible to recommend application of the drifters equipped with the modules for the sound velocity and temperature measurements as an effective tool for regular operational monitoring of the salinity field of the upper sea layer.

Key words: drifting buoy, seawater, sound velocity, temperature, salinity

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Introduction. In the last twenty years, the main source of systematic operational contact information about the state of the ocean upper layer and the near-surface atmosphere has become autonomous drifting data collection platforms –

surface drifters [1, 2]. Monitoring data is delivered to users via *Argos* or *Iridium* satellite communication systems. Currently, one of the most urgent problems of improving the drifter observation network is to create a drifter with the function of salinity calculation. The difficulty in solving this problem lies in the specifics of drifter observations. In order for monitoring to be economically feasible, the drifters, at a relatively low cost, must ensure operability for at least 1 year, maintaining the metrological characteristics of the measuring channels in the conditions of pollution, biological fouling and other affecting factors.

The papers (see, for example, [3–6] and others) present the results of salinity monitoring by several dozen drifters that were deployed in the Atlantic Ocean in 2007–2014. The authors of these papers give the estimates of the data quality for only a small number of drifters, whose lifetime provided the acquirement of statistically significant amounts of information. In most cases, the data from the drifters were compared with the data of remote sensing or *Argo* profiling buoys located at a considerable distance from the drifters, less often with the data of soundings by ship means. The deviations of the salinity calculation results in comparison with the data of *Argo* profiling buoys are on average estimated within ± 0.2 ‰, in comparison with the sounding data by ship means – ± 0.1 ‰. In the warm season, the deviation limits increase to ± 0.5 ‰. Depending on the drift conditions, deviations begin to appear in terms of several weeks to several months. A significant amount of drifter data, according to the authors, contains failures and requires preliminary filtering, which excludes their rapid assimilation.

Salinity in all drifters is calculated by the traditional method based on direct measurements of electrical conductivity and temperature, which are carried out using *SBE 37* module (*Sea-Bird Electronics*, USA). The characteristics of the module make it possible to calculate salinity with an error under 0.003 ‰. However, as follows from the abovementioned estimates, the real error in determining salinity turns out to be tens of times greater. One of the main causes for this is the contamination and biological fouling of the conductivity sensor measuring cell. Taking into account the specifics of operating an autonomous drifter, the use of existing methods of protection against the influence of these factors turns out to be either ineffective or economically and (or) too expensive from the point of view of energy consumption. The analysis results of the experience of salinity drifters application with the modules for measuring electrical conductivity and temperature explain the fact that, despite the obvious urgency of the problem of establishing systematic contact monitoring of salinity fields in the upper ocean layer, experiments with the salinity drifters are still at the pilot stage. Thus, as for May 2020, out of 1581 drifters deployed in the World Ocean, only two salinity drifters¹ are functioning, while, according to [7], the monitoring of the upper ocean layer salinity must be performed with a resolution in horizontal coordinates no worse than 250×250 km. Along with this, there are alternative methods for calculating the sea water salinity (by the sound velocity, refractive index), the implementation of which, for a number of reasons, has not found wide application in practice. The paper discusses the development results of a module for calculating salinity from data from direct measurements of the sound velocity and temperature.

¹ *Status of Global Drifter Array*. 2020. Available at: https://www.aoml.noaa.gov/phod/graphics/dacdata/may20_globpop.gif [Accessed: 25 May 2020].

Sound velocity and temperature measurement module. The sound velocity is a directly measured physical quantity, but most often it is calculated as a derivative of the characteristic from the equation of the sea water state. Until recently, working instruments for measuring the sound velocity provided errors of several tens of centimeters per second. Such errors make it possible to effectively solve the problems of applied hydroacoustics, but are completely unacceptable for obtaining reliable estimates of secondary hydrological parameters.

Due to low accuracy of the methods and instruments for measuring the sound velocity, the relationships proposed by a number of authors for calculating the salinity, density, Brunt – Väisälä frequency based on the data on the sound velocity have not found practical application. These parameters are traditionally calculated from measurements of electrical conductivity, temperature and pressure. In this case, within the framework of the hypothesis of the of the seawater relative chemical composition constancy, the binary model “distilled water + quasi-homogeneous salt” is used. The sound velocity, in contrast to electrical conductivity, characterizes the concentration of all substances dissolved in water, and, therefore, using it to calculate secondary hydrological parameters would allow one to overcome this limitation. However, neither the appearance of high-precision sound velocity meters (for example, *UV-SVP* sensors manufactured by *Valeport*, USA) on the market nor the improvement of the equations for calculating the secondary parameters from the sound velocity data [8] have led to a change in the established observation practice. The lack of information on the methods and results of field experiments aimed at evaluating alternative methods for monitoring secondary hydrological parameters is evident from the publications. As a part of solving the problem of establishing systematic monitoring of salinity fields in the upper layer of the sea, the Marine Hydrophysical Institute of the Russian Academy of Sciences developed a module for calculating salinity based on the results of measuring the sound velocity and temperature – *SVT* module, the design and characteristics of which are oriented towards operation as part of a drifter (Fig. 1).

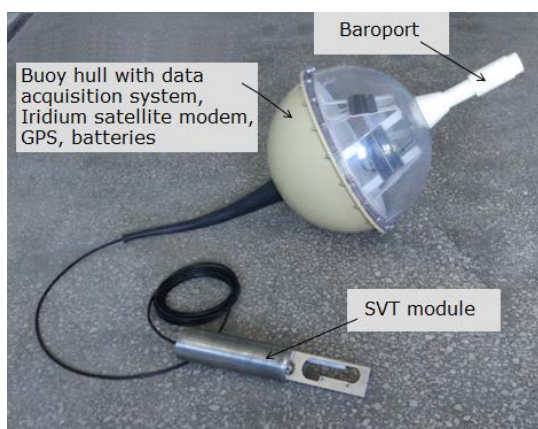


Fig. 1. Appearance of the drifter with the sound velocity and temperature module

The sound velocity meter (SVM) of *SVT* module is implemented according to the time-of-flight method (see, for example, [9] and others), according to which the sound velocity is calculated from the propagation time of an ultrasonic pulse on a fixed measuring base. Despite the simplicity of the method, for its correct implementation in practice it is necessary to overcome significant difficulties associated with minimizing the instrumental and methodological errors.

The instrumental error in measuring the sound velocity is determined by the instability of the measuring base length, the error in the timing of the received echo signals, the error in measuring the time interval, and the diffraction error; methodical error – by the error of the calibration method.

In the SVM a two-base acoustic sensor [10], which consists of an acoustic transceiver and a measuring base, is used. This sensor design allows it to be protected from biological fouling by simple passive methods.

The sensor measuring base of ~ 70 mm long is made of sital CO-115M (Astrosital) with a linear thermal expansion coefficient of $\pm 1.5 \cdot 10^{-7}$ 1/deg. Due to this, in the operating temperature range the relative change in the length of the base does not exceed $3 \cdot 10^{-6}$, which corresponds to the introduction of an additional error of ~ 0.005 m/s.

In the sensor, when excitation by an acoustic transducer pulse occurs, an acoustic signal is emitted into the medium and, propagating, reaches the first and second reflectors. The reflected echo signals are received by the acoustic transducer and converted into electrical signals, the binding of which to the time of receiving the echo signals is carried out at the zero crossing moments of corresponding half periods. With this method, a time interval is formed, the duration of which does not depend on fluctuations in the amplitudes of acoustic echo signals and additional delays [11], but is determined only by the sound velocity in the medium.

Estimating the errors in measuring the time interval, the following should be noted. Advances in the creation of modern high-accuracy sound measuring instruments are directly related to the appearance on the market of new inexpensive time-to-digital converters and highly stable generators. In the converters, for quantizing time intervals the signal propagation delays in logical elements are used. At intervals of hundreds of microseconds, this allows obtaining a resolution of several tens of picoseconds. Delay instability problems due to interfering factors are solved by calibration procedures using a highly stable reference generator.

In SVM, the propagation time of echo signals is measured using *TDC7200* time-to-digital converter (*Texas Instruments*, USA) and *FOX924* temperature-compensated generator (*FOX Electronics*, USA). The converter resolution is $55 \cdot 10^{-12}$ s, the long-term instability of the generator frequency in the range of influencing factors variability is below $3 \cdot 10^{-6}$. At a measuring base length of ~ 70 mm, such characteristics correspond to an error in measuring the sound velocity of no more than 0.005 m/s with a resolution of no worse than 0.001 m/s.

The diffraction component of the error is due to the difference between the real sound wave and the plane one due to the finite dimensions of the acoustic transducer and reflectors of the SVM sensor measuring base. Quantitative estimates of the diffraction effect are rather complex and are based on numerous assumptions [12]. In the SVM under consideration, this component of the error is eliminated during the calibration in the operating range of sound velocities.

A PTK-3M² quartz temperature transducer was used as a temperature sensor in the SVT module, the characteristics of which are discussed in the next section.

It should be noted that the authors of a number of publications devoted to the development of high-accuracy SVM provide the error estimates, which are often comparable with the error of the State primary standard of the unit of sound

² SCTB ELPA, 2020. *Quartz Temperature Converter PTK-3M*. Available at: <https://sktbelpa.ru/preobrazovatel-temperatury-kvartsevyy-ptk-3m.html> [Accessed: 25 May 2020].

velocity in liquid media³. At the same time, the calibration methods are not specified and there is no information about the long-term stability of characteristics, which creates uncertainty in assessing the possibilities of SVM practical application. Also considering the fact that at present there is no single calibration scheme for high-accuracy SVM, quantitative estimates of the characteristics of the developed SVM are preceded by brief descriptions of the procedures for their production. For the same reason, the term “error” is further used only in relation to the instrumental components of the SVM error. As a characteristic of the accuracy of the sound velocity measurements, we will use the term “repeatability”⁴.

Methodology and results of studies of the SVT module characteristics.

The characteristics of the salinity calculation module were studied under laboratory and field conditions. The studies were aimed at assessing the random component of the error and the repeatability of the results of sound velocity measuring in distilled water, the error of measuring the temperature, the repeatability of the results of calculating the sea water salinity from the sound velocity data and temperature. One of the main objectives of the research was evaluating the long-term stability of the characteristics of the measuring channels.

The SVM characteristic was estimated using a method in which the values of the sound velocity are reproduced by changing the temperature of distilled water. In this case, the values of the sound velocity calculated by the Del Grosso formula [13] for distilled water are taken as reference values. Since, as already mentioned, there are problems of metrological assurance of sound velocity measurements, some clarifications should be made regarding the method for determining the SVM characteristics.

In the SVT module the temperature of the medium T_{SV} is measured simultaneously with the measurement of the propagation time τ_{SV} of the acoustic signal on the measuring base. This makes it possible, based on the results of calibration in the operating range of temperatures and sound velocities, to take into account the total contribution of additional error components (instability of the length of the measuring base, the frequency of the reference generator, diffraction error, etc.) without determining the degree of influence of each of them. In practice, the calibration procedure was as follows:

– in the distilled water⁵ within the temperature range from 5 to 25 °C with an interval of 5 °C the measured values of the propagation time τ_{SV} of the acoustic signal on the measuring base and the temperature T_{SV} were recorded;

– for each temperature value the effective length of the measuring base $L_e(T_{SV})=0,5 \cdot C_{REF}(T_{SV}) \cdot \tau_{SV}$, where $C_{REF}(T_{SV})$ is the value of sound velocity calculated by the Del Grosso formula for distilled water at T_{SV} temperature was estimated.

³ State Standard, 2014. *State System for Ensuring the Uniformity of Measurements. State Verification Schedule for Instruments Measuring of Sound Velocity in Liquids within the Velocity Range 800 to 2000 m/s*. Available at: <http://docs.cntd.ru/document/1200110968> [Accessed: 25 May 2020].

⁴ State Standard, 2013. *State System for Ensuring the Uniformity of Measurements. Metrology. Basic Terms and Definitions*. Available at: <http://docs.cntd.ru/document/1200115154> [Accessed: 25 May 2020].

⁵ State Standard, 2018. *Distilled Water. Specifications*. Available at: <http://docs.cntd.ru/document/1200159410> [Accessed: 25 May 2020].

The data series obtained in this way were approximated by a linear function $L_e(T_{SV})_{ap} = a_0 + a_1 \cdot T_{SV}$, where a_0, a_1 are the coefficients;

– the measured values of sound velocity were calculated by the formula

$$C_{SV} = 2 \cdot (a_0 + a_1 \cdot T_{SV}) / \tau_{SV}. \quad (1)$$

The error of the approximation by the function (1) is no more than 0.01 m/s.

During the calibration process at a fixed water temperature the random component of the time τ_{SV} measurement error was also estimated. As can be seen from the histogram in Fig. 2, *a*, deviations $\Delta\tau_{SV}$ of the measurement results are distributed within $\pm 160 \cdot 10^{-12}$ s range, which corresponds to ± 0.0025 m/s in the sound velocity units.

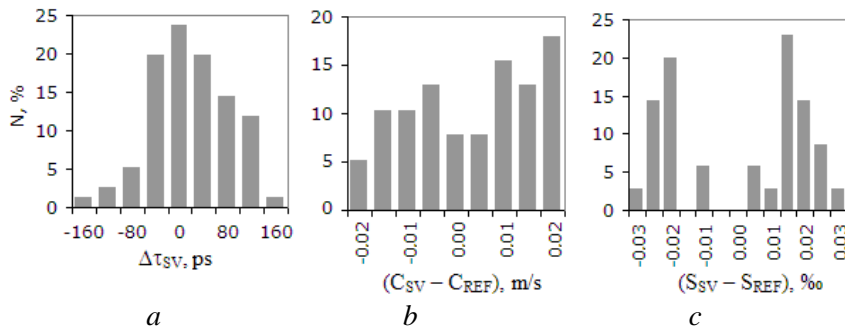


Fig. 2. Distribution of deviations $\Delta\tau_{SV}$ (*a*); repeatability of the results of the sound velocity measurements (*b*) and the salinity calculations (*c*) based on the long-term laboratory tests of the sound velocity and temperature module. N is a number of readings, %

The long-term stability of characteristics of the sound velocity and temperature meters was investigated in laboratory conditions and *in situ*. The tests were carried out for several months in distilled water and seawater.

Laboratory tests were carried out in the same distilled water in which the calibration was performed. In the tests, the error of temperature measurements ΔT_{SV} by PTK-3M and the repeatability of the measurement results of sound velocity $C_{SV} - C_{REF}$, where C_{SV} are the results of sound velocity measurements calculated according to expression (1); C_{REF} are reference values of the sound velocity, calculated using Del Grosso formula for distilled water, were evaluated. In contrast to the calibration procedure, the water temperature was measured with PTS-10 platinum resistance thermometer with an error of no more than 0.002 °C. As a result of the tests, which were carried out for several months at various water temperatures, the fluctuation range of the deviations $C_{SV} - C_{REF}$ was ± 0.02 m/s (Fig. 2, *b*), and the temperature measurement error was no more than 0.004 °C. Assuming that the salinity changes by approximately 0.75 ‰ when the sound velocity changes by 1 m/s and by 3.3 ‰ when the temperature changes by 1 °C, the obtained estimates correspond to ~ 0.02 ‰ error in salinity calculation.

In the laboratory and *in situ* tests in the seawater, the salinity as a function of the sound velocity and temperature was calculated using the equation proposed in [8, p. 813–817]. Note that this is one of the most significant, in our opinion, works where the problem of salinity calculation is considered taking into account the capabilities of modern means of sound velocity measuring.

In the laboratory tests, the results of calculating the salinity from the measured values of the sound velocity and temperature S_{SVT} were compared with the data of a laboratory salinometer S_{REF} , the error of which was not more than 0.002 ‰. Taking into account the fact that the drifter with SVT module was developed for observing the physical fields of the upper layer of the Black Sea open regions, the tests were carried out in the temperature ranges from 5 to 25 °C and salinity from 10 to 25 ‰. As a result of long-term tests, the range of deviations $S_{SV} - S_{REF}$ was ± 0.03 ‰ (Fig. 2, c).

The resistance of the SVT module characteristics to the effects of biological fouling and pollution was assessed in field tests, which were carried out in the Black Sea coastal zone. In these tests, the salinity S_{SV} values from the SVT module data were compared with the salinity S_{4319} from the data of *Sensor 4319B* meter (*Aanderaa*, Norway). The salinity calculation error based on the results of the additional calibration of *Sensor 4319B* conductivity and temperature sensors is below 0.02 ‰. Both instruments were mounted on a bracket fixed to the rock (Fig. 3, a). The tests were carried out for more than four months in the spring-summer period under conditions of intense fouling, the consequences of which are shown in Fig. 3, b. *Sensor 4319B* was placed in the test environment only for the duration of the comparisons to eliminate the fouling and contamination. As a result of tests, the range of deviations $S_{SV} - S_{4319}$ was ± 0.05 ‰ (Fig. 3, c). Relatively large discrepancies are associated with the methodological error due to the spatial arrangement of the devices – according to the manufacturer’s recommendations for correct measurements of electric conductivity, there should be no foreign objects within ~ 0.5 m radius from the *Sensor 4319B* meter. Despite this circumstance, the test results indicate good long-term stability of the SVT module characteristics in natural conditions.

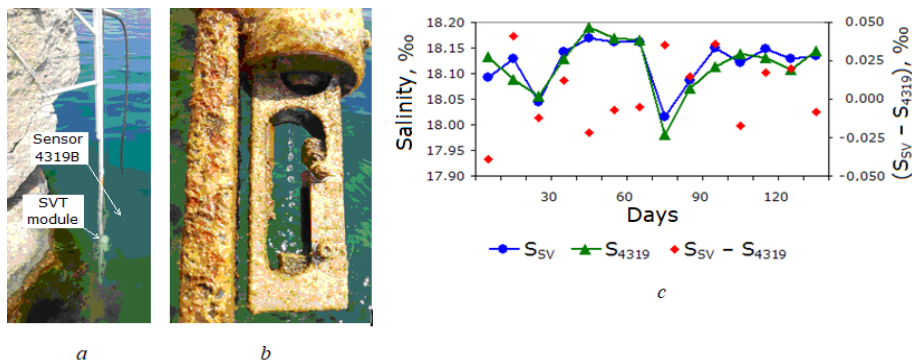


Fig. 3. Location of the sound velocity and temperature module and the *Sensor 4319B* during the comparative in situ tests (a); appearance of the sound velocity sensor in 60 days after the tests began (b); results of comparison of the salinity S_{SV} from the sound velocity and temperature module with salinity S_{4319} from the *Sensor 4319B* (c)

We should clarify that during the tests we did not use any measures to protect the module from biological fouling and contamination for the following reasons based on the analysis results given in [14]. The use of active protection methods by means of ultraviolet irradiation of the sound velocity sensor, its mechanical or acoustic cleaning is excluded, since the module is intended for use as part of a drifter with an autonomous power supply, and the implementation of these methods requires significant energy consumption. Passive protection methods are applicable to almost all external surfaces of the sound velocity sensor, however, the possibility of using these methods is limited by the fact that we currently do not have objective information on the results of long-term use of various protectors and coatings and their effect on the chemical composition of the studied medium, and therefore, on the sound velocity in the medium. The results of our research also do not yet allow us to definitely judge the possibility of using passive protection methods.

We cited the limiting estimates of the uncertainty of the measured parameters obtained during testing as the SVT module characteristics. This, along with descriptions of research methods, gives an idea of the actual characteristics of the module and their long-term stability. Similar estimates were obtained when testing five SVT modules.

Conclusion. The results of the development and study of the SVT module characteristics, oriented to use in an autonomous drifter for long-term monitoring of salinity fields in the upper sea layer, were obtained. The salinity is calculated from the sound velocity and temperature measurements (as opposed to the traditional method of calculation salinity by electrical conductivity and temperature). The SVT module used a sound velocity meter specially designed for the maintenance-free long-term operation as part of a drifter. Quantitative estimates of the SVT module characteristics were obtained as a result of many months of laboratory and field tests. According to the results of laboratory tests, the deviation range of the results of the sound velocity measurements was ± 0.02 m/s, the error of temperature measurements was below 0.004 °C; the range of deviations of the salinity calculation results in the seawater ± 0.03 ‰.

With regard to the main aim of the performed studies – the creation of an autonomous drifter for monitoring the salinity fields of the upper sea layer – the long-term stability of the characteristics of the drifter's measuring channels is essential. According to the results of the performed *in situ* studies in the conditions of pollution and biological fouling, the repeatability of the salinity values calculated from the SVT module data was within ± 0.05 ‰ range, which makes it possible to count on the stability of characteristics of the developed sound velocity meter in real conditions of long-term maintenance-free operation as part of a drifter.

We assess the obtained results as preliminary ones. Nevertheless, they provide grounds for further research aimed at improving the method for determining secondary hydrological parameters from the data acquired from direct sound velocity measurements. The creation of high-accuracy sound velocity meters and methods for the adequate estimation of their characteristics will provide the study of the seawater properties without the limitations inherent in the traditional method

of calculating these parameters from the results of electrical conductivity measurements.

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Sergey V. Motyzhev – problem statement, updating the paper text, discussion of the results, formulation of conclusions

Evgeniy G. Lunev – carrying out the experimental studies, development and debugging of the computer program for solving the problem, updating the paper text, discussion of the results, formulation of conclusions

Vladimir Z. Dukman – development of research tools, discussion of the results, editing and supplementing the paper text

All the authors have read and approved the final manuscript.

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