ISSN 0001-4370, Oceanology, 2013, Vol. 53, No. 2, pp. 233–242. © Pleiades Publishing, Inc., 2013.
Original Russian Text © A.G. Ostrovskii, A.G. Zatsepin, V.A. Soloviev, A.L. Tsibulsky, D.A. Shvoev, 2013, published in Okeanologiya, 2013, Vol. 53, No. 2, pp. 259–268.

INSTRUMENTS AND METHODS

Autonomous System for Vertical Profiling of the Marine Environment at a Moored Station

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Received April 10, 2012

Abstract—This paper presents new results of the research and development project on the moored profiler Aqualog aimed at multidisciplinary studies and ecological monitoring of the marine environment. The data on the profiler's operation are summarized based upon the field experiments in the northeastern Black Sea in 2011. An important scientific result obtained by using the profiler during the experiments was the discovery of the countercurrent below the Black Sea Rim Current in the layer between the 500 m and 900 m depth.

DOI: 10.1134/S0001437013020124

1. INTRODUCTION

The probes that are periodically raised and lowered by anchored bottom or surface winches, as well as the profilers following along the cables taut vertically by the subsurface flotations [2], belong to the self-contained mobile apparatuses of vertical profiling of the marine environment of the moored type. In the latter case, two versions of the system's propulsion were developed: devices with variable buoyancy and the devices sliding along a mooring line by means of an electric motordrive.

The development of self-contained mobile oceanological profilers began in the 1970s. At that time, the small-scale production of the MK-I/II Cyclosonde profilers [14] started. Those profilers allowed oceanographers to obtain about 30.000 vertical profiles of the sea temperature and salinity in the upper layers of the oceans around the North American continent. Since the late 1990s, the oceanological profilers moving up and down on a cable by their motordrives or by means of the winches have been considered a promising component of the global ocean observing system. In the last 20 years, at least 19 devices have been developed and tested under field conditions. Some of the devices have been produced in small series (see [2]). In January of 2011, the Woods Hole Oceanographic Institution with the support of the National Scientific Foundation of the USA opened a new call concerning the development of two types of profilers (coastal and deep-water) that move along a cable (so called coastal and global wire following profilers). That project is complies with the tasks of the most comprehensive US program known as the Ocean Observatories Initiative.

A Russian oceanological mobile profiler is being under development since 2006. This system is called Aqualog, and it is equipped with an electric motordrive and intended for moored buoy stations [3, 4, 11]. We develop this profiler as a mobile carrier of oceanological sensors for multidisciplinary scientific research and environmental monitoring. In this article, we report new results of this development and describe our experience in applying the Aqualog for research under various climatic conditions.

2. APPLICATIONS OF MOBILE PROFILERS AT MOORED BUOY STATIONS

2.1. Scientific research. The Necessity to accumulate long time series of vertical distributions of the parameters of the ocean at specified sites in key water areas worth monitoring lies at the heart of the scientific projects with the use of profilers. The basic purpose of profilers is in the regular acquisition of vertical fine-structure profiles of various characteristics of the marine environment at time intervals sufficient to discriminate the energy-bearing diurnal fluctuations throughout several seasons or even years. Profilers are necessary also for diagnosing the incidental in-water anomalies with a lifetime of a few hours. It is important that one sensor suit at a profiler acquires data in the throught the water column from the near-surface layer to the bottom, thereby allowing one to obtain homogeneous data with uniform accuracy.

The use of profilers should help to answer the question of how the physical and chemical characteristics of the seawater, the dynamics of the currents, the structure of the marine environment and its biota evolve under the impact of the changing climate. These natural transformations influence the fluxes of the suspended and dissolved matter at the interface between the ocean and the atmosphere, and at the boundaries between the epipelagic zone and the mesopelagic zone (~200 m), and the mesopelagic zone and the bathypelagic zone (~1000 m).

The fluxes and composition of the living and nonliving substances in the upper 1000-meter layer of the ocean are governed by the followings:

—the dynamical factors, first of all the horizontal advection, turbulence, and vertical mixing;

—the biogeochemical factors, such as the migration, primary production, and breath of organisms.

Their influence is nonstationary and the timedependence of these factors varies with the depth.

To understand the process of the tens of years long adaptation of the marine environment to the climate trends and the response to the large-scale phenomena, such as El Niño and the North Atlantic Oscillation, measurements are needed within the sampling range from several hours to several days. Frequent measurements are necessary for studying the driving mechanisms that are directly responsible for changes in the marine environment.

Marine ecosystems are constantly influenced by the dynamical processes with periods close to daily, inertial, and semidiurnal time scales, whose amplitude of fluctuations is large (see, for example, [1]). The influences of irregular events, such as upwellings and cascadings, on ecosystems can be very substantial too, and they should be monitored. This is a difficult problem because such events occur only several times a year. Only continuous measurements are fit to estimate the impact of short-period, sometimes chaotic, dynamic processes upon the marine biota.

High intermittence in time is characteristic of biotic processes, too. A typical example is the daily migrations of the mesozooplankton. For instance, in the oxic layer of the Black Sea, the migrating species of mesozooplankton are descending and ascending for 2 and 3 hours during the dawn and sunset, respectively [9, 10, 13]. It is natural that periodicity of the events of descend and ascend varies with the seasons. To investigate such significant but short-term processes, it is necessary to carry out frequent soundings during at least one season (or better one year) to account for the seasonality of the background conditions.

Vertical profiling, unlike measurements at fixed depth levels, should be adequate to the fine-structure anomalies of the marine environment. To obtain vertical profiles of the thermohaline lenses and intrusions, the accumulations of plankton, and the sound scattering layers the spatial resolution should be at least 1 m. Thin horizontally extended accumulations of organisms are characteristic of the layered organization of marine ecosystems (see review [12]). Thin sound scattering layers often turn out to be a manifestation of accumulations of mesozooplankton and micronekton near the vertical gradients of the properties of the marine environment and the interfaces of the water masses [6, 8]. For example, according to the measurements of the vertical profiles of the acoustic backscattering at the 2 MHz frequency in the northeast part of the Black Sea, a layer of a diapause of copepods of *Calanus euxinus* (up to several millimeters in length) is about 1 m thick and varies in depth coherently with the depth of the isopycnal surface of 15.8 g/m^3 in the lower part of the redox zone at the depths from 130 to 160 m [11]. Internal waves, intrusions, mixing, horizontal advection, and other physical processes lead to the redistribution of organisms, which results in changes in the thin layers for only a few hours.

Thus, for studying the marine ecosystems and their reaction to external forcings, including the climate anomalies, it is necessary to measure the vertical profiles of the ocean physical, chemical, and biological characteristics at resolution better than 1 m and to perform profilings at intervals of about one hour.

2.2. Ecological monitoring of sea waters. The conceptual project of the environmental monitoring system for sea water with the Aqualog profiler in a core of the system (fig. 1) was developed under umbrella of the Russian federal targeted program Development of Civil Marine Technology in 2009–2016 by request of the Ministry of Emergency Situations of the Russian Federation at the P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences (SIO RAS) in 2011.

Besides the Aqualog profiler itself, the project's marine techniqueinvolved a communication system equipment for the transmission of data and control commands. The communication system consists of two parts as follows-

—a subsystem of underwater communication by means of the inductive modems in a mooring cable for ice-free water areas or a subsystem of hydroacoustic modems;

—a subsystem of communication to a coastal or shipborne center of the data acquisition and processing (a surface telemetric buoy with modems for satellite, VHF, and mobile phone communication in icefree waters or a bottom fiber-optical cable for the icecovered waters).

The coastal part of the system involve a module for the data acquisition and processing and the monitoring management.

It should be noted that the technology of the automated profiling at moored buoy stations surpasses the current requirements of the Rules of Quality Control of Seawaters valid in the Russian Federation (GOST 17.1.3.08-82 Nature protection. Hydrosphere.) concerning the measurements at fixed depth levels, because this technology supports the measurements of the vertical profiles of the parameters of the marine environment at 1 m resolution in the water's column from near-surface 5–10 m depth to the bottom layer. The vertical soundings by means of the profiler have to be performed at least twice daily, i.e., more frequently than twice monthly according to the GOST 17.1.3.08-82 regulations.

The advantages of the proposed approach are as follows:

—the minimization of the risk of the loss of the equipment due to the application of an anchored buoy-mounted system equipped with a vertically moving carrier with sensors instead of a freely drifting probe;

—the automatic monitoring is carried out continuously in the specified region so that long term data series of the vertical distributions are accumulated, which is necessary for monitoring the characteristics of the marine environment according to GOST 17.1.3.08-82;

—the system operates in the on-line mode: the measurement data and control commands are transmitted in real time;

—the system is adaptable to specific objectives thanks to the modularity of the carrier design, which facilitates the use of the modern oceanographic sensors.

3. FEATURES OF THE AQUALOG PROFILER

Profilers as a part of buoy-mounted systems, where the mooring line serves as a running cable, allow one to essentially optimize the process of the measurements at oceanological stations. The present day profilers of this type include the SeaTramp PP2 (www.oceanorigo.com; http://www.oceanorigo.com), the McLane Moored Profiler (MMP) [7], and the Aqualog [4, 11]. Instead of several sets of sensors at the fixed depths, these systems use a single array of sensors substantially reducing the cost of the measurements. During one deployment, a profiler is able to carry out continuous measurements at a fixed site during a season or longer, including under-ice observations in the winter.

The Aqualog probe profiler (Fig. 2) represents a carrier completed with oceanological measuring sensors and a system of real-time communication and control [4]. The carrier travels automatically at about 0.2 m/s speed lengthwise the vertically tense cable at a submerged buoy-mounted station.

The microprocessor control system of the Aqualog (Fig. 3) supports the following main functions:

—the downloading of the profiling schedule from the MS Windows PC;

—the downloading of the commands and the uploading of the telemetric information into the PC;

—the control of the operation mode;

—turning on and off the electric motordrive at the specified depths at the specified instants of time; and

—collecting and accumulating the hydrophysical, biooptical, and hydrochemical measurement data in flash memory.

When designing and manufacturing the profiler, special attention was paid to corrosion resistance and other damaging influences of the marine environment.

Therefore, the most modern plastic and composite materials are used when manufacturing the profiler. The instrument housing is made of polyacetal, the frame is made of a high-molecular polyethylene with polyamide fixtures, the cowling is manufactured of - gelcoated composite material, and glass spheres are used as the buoyancy modules. Since 2012, the electric motordrive with a magnetic coupling is contained in the titanium pressurecas to allow a profiling down to the maximum depth of 1000 m e, and.

The Aqualog profiler is intended for autonomous long-term operation to acquire long-term data series. For example, under conditions of moderate currents (up to 0.3 m/s) at a site at 500 m isobath, where the pathway of one cycle is 1 km long, the power supply from a block of 72 lithium D-type power cells should suffice for a one year period of operation at a rate of one profiling cycle per day. For shorter deployment periods, alkaline D-type cells are applied. The specifications of the Aqualog are given in the table.

The vertical resolution and accuracy of the measurements depend on the sensors used. For example, when the profiler moves at 0.2 m/cm, the vertical resolution makes up 0.05–0.15 dbar for the pressure, 0.6–1.8 m for the current velocity, and 0.8–2.4 m for the dissolved oxygen. The CTD probe TRDI Citadel ES and more reliable probes SBE 49 CTD and SBE 52ÌÐ CTD are specially designed for measurements from mobile platforms. They are compact, easier to integrate at a carrier, and consume minimum energy. However, they have no additional data I/O channels, except for the channel of the sensor of the dissolved oxygen on the SBE 52ÌÐ CTD probe. The RBR XR-620 probe and the more bulky CTD SBE 19 plus CTD and Idronaut 316 CTD probes have 3–4 channels for the installation of additional sensors, such as a fluorometer or turbidimeter. The integration of such instruments at the Aqualog carrier solves the problem of the extension of the applications without increasing the number of measurement channels. The sensors are being turning on and off by the microprocessor unit of the Aqualog carrier. The data of the acoustic current meters are stored in their own memory and transferred into a PC after finishing the observations.

In order to monitor the state of marine ecosystem, the Aqualog carrier can be equipped with specialized devices, for example, the Franatech METS CH_4 sensor and the Satlantic SUNA nitrate sensor, as well as the SubChem APNA sensor suit for dissolved inorganic nitrates, phosphates, silicates, and iron (II) . Valuable experience was gained thanks to using of the four-channel AQUATEC AQUAScat 1000 Acoustic Backscatter System at the profiler that for observations of the concentration and vertical structure of the in-water suspended matter. The big potential for incorporating different instruments makes the Aqualog system particularly flexible and tunable for solving different problems.

As for the transmission of the data and the telemetric information, the Aqualog profiler can accommodate an underwater inductive SBE IMM modem, a

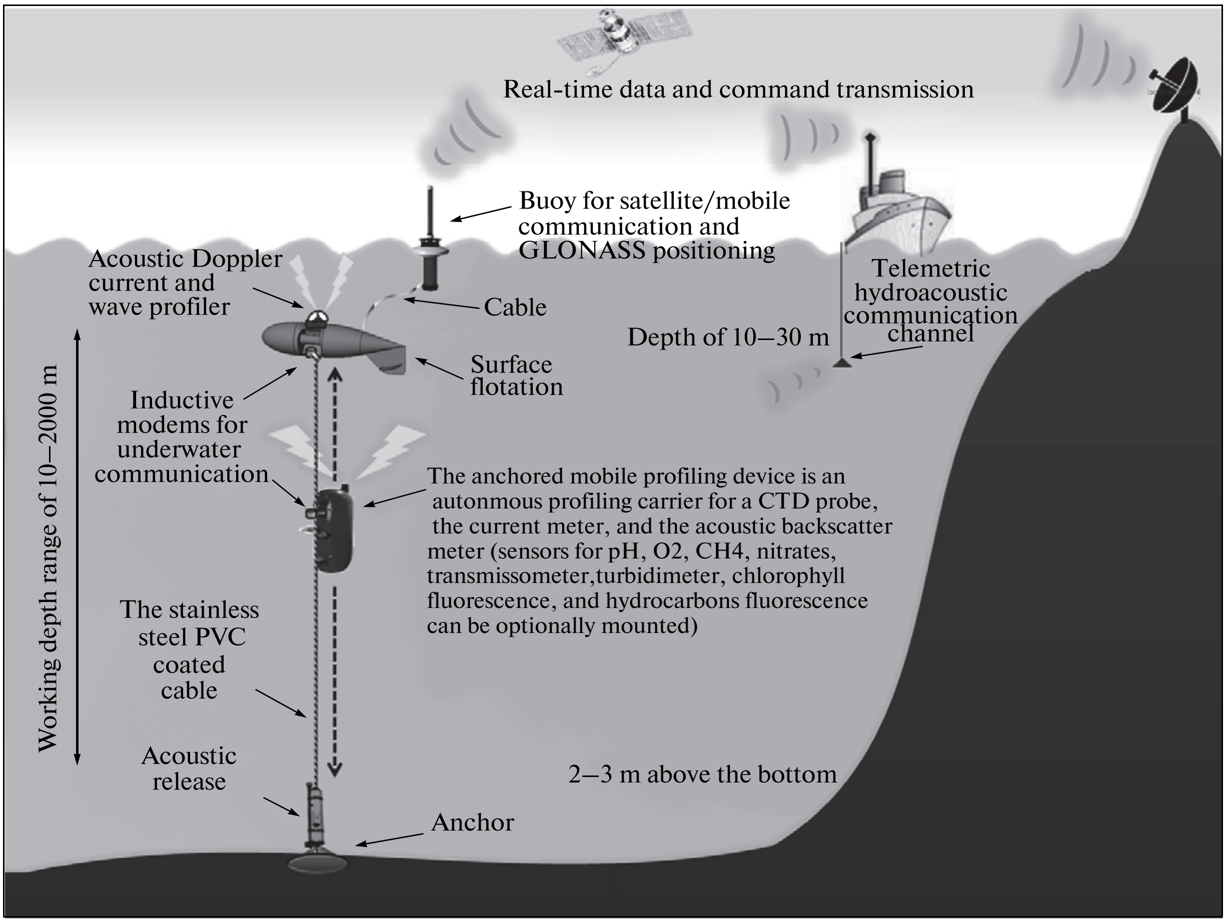

Fig. 1. The Aqualog profiler as a part of the ocean monitoring system for ice-free waters.

digital hydroacoustic Benthos ATM 885 modem, or an Evologics hydroacoustic modern S2CR 7/17 modem [4] . The Aqualog profiler can be optionally delivered with a buoy complete with the inductive or the hydroacoustic modems and with the firmware for mobile communication via GSM/GPRS, the ARGOS or IRIDIUM satellite communication, and the VHG radio communication. The Aqualog profiler is, in essence, an oceanological observatory for real-time monitoring of the environment.

4. EXPERIENCE IN APPLICATION OF THE AQUALOG PROFILER

In 2010–2012, the Aqualog profiler was used for scientific research in the Baltic, Kara, Red, Dead, Mediterranean, and Black Seas and in the Sea of Japan [5, 11]. Research was carried out in various climatic conditions, for example, in February 2010 in the waters of the northern Japan Sea partially covered with ice where the water temperature fell below 1°C. The pilot experiment in the Dead Sea in October 2012, which featured the major survivability test of the device, demonstrated the excellence of its corrosion resistance and reliability in the waters of salinity as high as 300–400 psu.

The submerged buoy-mounted stations equipped with the profilers were oftendeployed in the Black Sea from small-size ships, for example, from a boat only 12 m in length and 22 t in displacement. In spite of the fact that strong gales occasionally occurred in the deployment areas, we aspired to deploy the profiler mooring so that the submerged flotations were as close as possible to the sea surface. For example, even under autumnal conditions in the Black Sea at storms about 6 points on the Beaufort scale strong, the submerged flotations were deployed at a depth level of 15–20 m, which allowed us to obtain data on the response of the sea upon atmospheric forcings.

4.1. Functioning of the Aqualog profiler according to the Black Sea field experiment in 2011. The Aqualog profiler mounted on a submerged mooring operated from June 26 to August 22, 2011 at the site 44°29.44′ N, 37°58.38′ E at where the sea depth is 265 m at the upper part of the continental slope off the Bay of Gelendzhik in the northeastern Black Sea. The profiler automatically carried out the profiling cycles at the depths from 15 to 200 m every day at 00:00, 03:00,

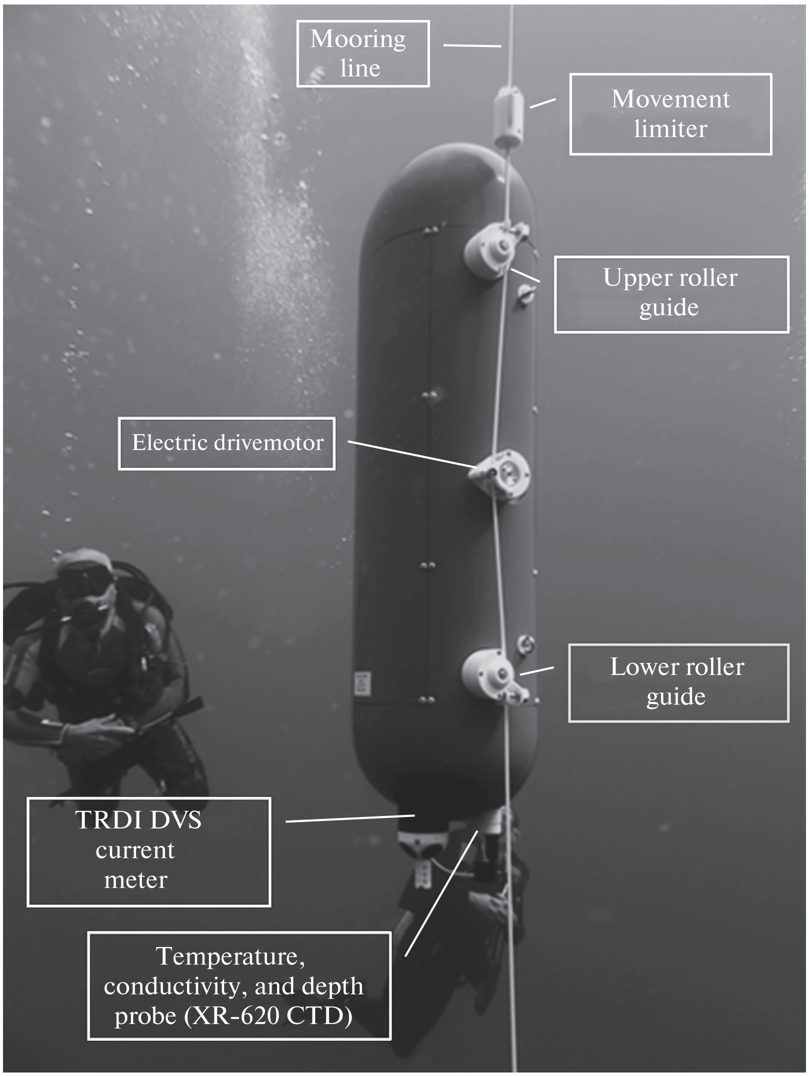

Fig. 2. The Aqualog after crawling up along the mooring line stopped below the upper Movement limiter.

06:00, 08:00, 10:00, 15:00, 18:00, and 21:00 hours. Each time, the profiler descended from the parking depth level of 100 dbar into the anoxic zone at 200 dbar, remained there for 3 min, ascended up to the 15 m depth, remained there for 15 min, and descended down to the 100th dbar depth. The entire profiling cycle took about 52 min. For the whole mooring survey, the profiler completed 458 profiling cycles travelling for about 170 km.

Until 2011 inclusive, the Aqualog profiler motordrive mechanical parts (except for the bearings) were made of stainless steel.

The profiler was equipped with the Idronaut 316 CTD probe complete with sensors for dissolved oxygen, ORP, and pH, as well as with the Nortek Aquadopp acoustic Doppler current meter with a two-axial inclinometer and a compass. Thanks to the regular descents into the hydrogen sulfide zone, the profiler avoided biofouling and the sensors of the temperature and electric conductivity remained in excellent working condition during whole mooring survey.

Before the deployment, the device was balanced so that its weight in the water was equal to the weight of the water the profiler dispalaces at the depth of 200 m. Provided that the density difference between the surface water and the water at the 200 m depth changes from 2.6 g/l in June to 6 g/l in mid-August and that the total volume of the profiler and sensors made up about 80 l, it is easy to estimate that in the upper mixed layer the profiler was overloaded by about 0.2 kg at the beginning of the survey to about 0.5 kg by the end of the survey.

The Aqualog profiler reliably operated even at the mooring line inclinations as high as 15°–16°. Such inclinations were due to the strong currents . The maximum speed of the sea current, at which the profiler continued to steadily scan the water column, was about 0.75 m/s.

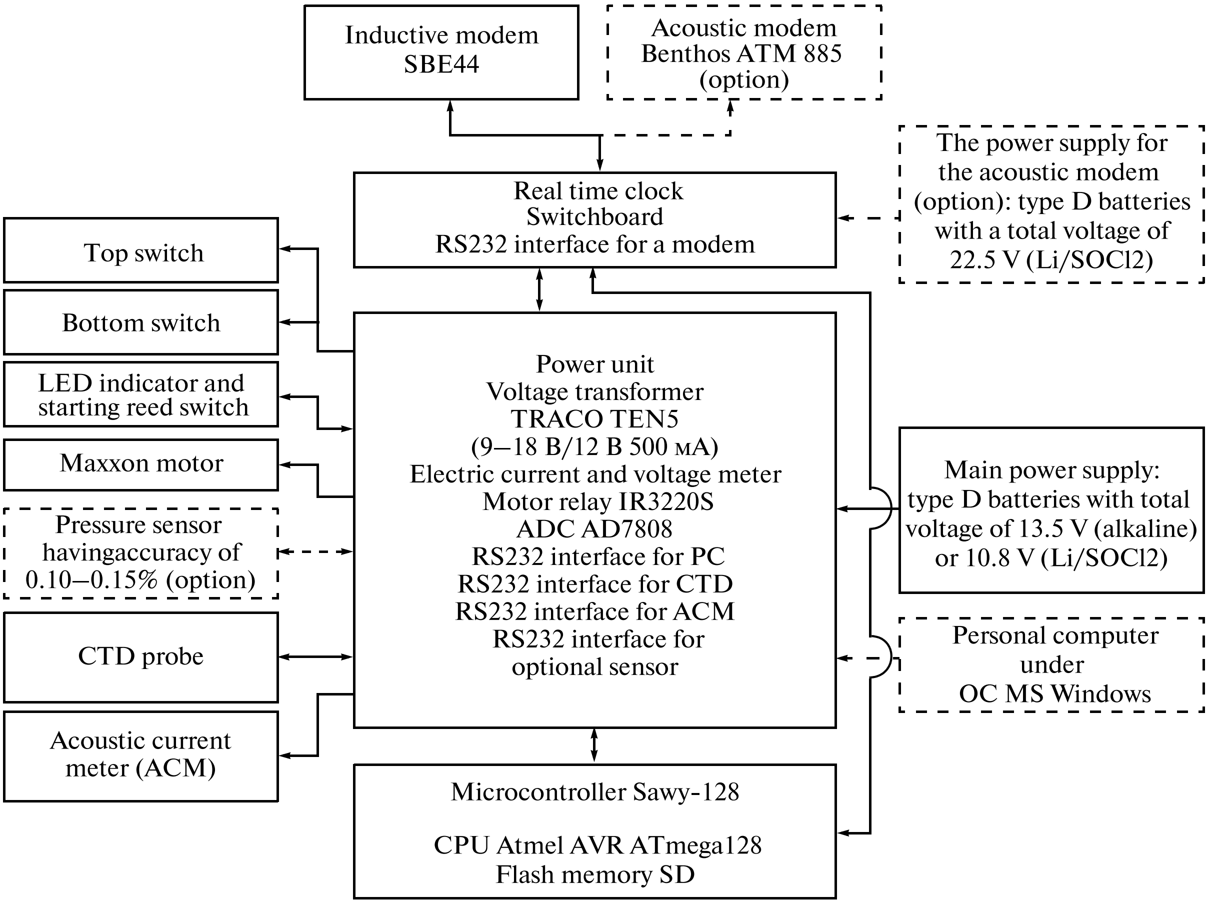

Fig. 3. Functional diagram of the microprocessor unit of the Aqualog profiler.

In the profiling mode, the profiler's energy consumption was rather low. Notice that, in the two month long survey, the mechanical parts of the profiler wore in: according to the measurements in the layer of 180–200 m, where the currents were rather low, the energy consumption decreased by 0.06 W both when surfacing and diving. Fig. 4 displays the data on the energy consumption by the motordrive during the profiler descend (W) depending on the depth and the current velocity.

It is evident from Fig. 4 that the energy consumption of the diving profiler at low current velocities of up to 0.03 m/s, as a rule, did not exceed 1.5 W with 1.1 W on the average. According to the measurements in the upper layer of the sea between isopycnals of σ_T= 13.5–14 (the depth of this layer fluctuated from 15–30 m to 40–60 m), when the horizontal advection accelerated up to 0.7 m/s, the dependence of the energy consumption W on the current speed $|U|$ is approximated by a polynomial: $W = k_1U^2 - k_2|U| + k_3$, where k_1 = 3.6 W s^2/m^2, k_2 = 0.045 W s/m, and k_3 = 1.1 W.

The mooring line bends under the current drag, and the upward buoyant force, which is proportional to the inclination of the device, starts to affect the profiler. The movement becomes slower owing to loss in the virtual buoyancy of the profiler plus the water entrained beneath the cowling for some time after the beginning of the motion. As is known, the resistance to the flow around an object is proportional to the squared speed of the flow, and this leads to an increase in the friction at the profiler's roller.

According to the experimental data obtained in the summer of 2011, the diving motion of the profiler was essentially complicated at strong currents because of the combined action of the drag force and the slightly reduced weight of the device due to the weight of the entrained volume of water (rather light water remained beneath of the cowling). When the current speed increased to 0.7 m/s, the power concumption for the downward movement of the profiles became as high as 3 W. The power drain peaks over 3 W were mainly recorded when the profiler turned its motordrive on.

The consumption of energy W was not associated with the current speed when moving up in the layer of σ_T = 13.5–14 (Fig. 4). In other words, the action of the pushing-upward force due to the current was counterbalanced by the increase in the weight because of the effect of the entrained mass of the water.

The main specifications of the Aqualog profiler

Specification	Value
Speed of moving	0.15–0.3 m/s
Working depth range	7–1000 m
Total profiling distance (without oceanographic sensors) in still water	800 km
Power consumption:	
Rated input voltage	10.5–13.5 V
Maximum power consumption during profiling (without oceanographic sensors)	2–6 W
Power consumption in the sleep mode	0.006 W
Interface	RS 232
Weight and dimensions:	
Dimensions	1.45 × 0.35 × 0.65 m
Weight in air (without oceanographic sensors)	68 kg
Weight in water	±3 N
Oceanographic sensors:	
– temperature, conductivity, and pressure sensors	SBE 52 MP CTD, SBE 49 CTD, SBE 19plus CTD , RBR XR-620 CTD, Idronaut 316 CTD, TRDI Citadel CTD ES
– dissolved oxygen sensors, pH sensors, ORP sensors	AANDERAA 4330F, SBE 43 DO, Idronaut DO, Idronaut Redox, Idronaut pH, SBE 27 pH
– fluorometers, turbidimeters, transmissometers	Sea Point, WET Labs ECO FLBBCD Triplet, Wet Lab Transmissometer
– hydrochemical sensors for nitrates, phosphates, silicates, iron (II), and methane	Satlantic SUNA, SubChem APNA, Franatech METS
– acoustic Doppler velocity meters and acoustic backscatter meters	Nortek Aquadopp, TRDI Doppler Volume Sampler, AQUATEC AQUAScat 1000

According to Fig. 4, in the absence of currents, the average power consumption per one measurement cycle (down and up motion) made up 1.30 W. At that, the power consumption for the downward traveling can be reduced by 15% thanks to the buoyancy deficit being as low as 2 N, which roughly equals 0.25% of the 80 l of the profiler's volume. Estimates show that a buoyancy deficit of 5 N would not be sufficient to counterbalance the pushing-upward force induced by currents when lowering the profiler. It is important that the downward movement of the device was interrupted at the 100 m depth level at least for one hour when the water entrained earlier beneath the cowling was completely replaced.

3.2. Scientific results of the experiment in the Black Sea in 2011. For the first time, the Aqualog profiler allowed us to obtain long-term time series of the multiparameter fine-structure vertical profiles of the key characteristics of the marine environment at fixed sites: the current's velocity, the thermohaline characteristics, the dissolved oxygen, the pH of the water, and the acoustic scattering from the plankton and suspended matter.

The fine-structure measurements of the current velocity and sound-scattering layers are especially interesting. The vertical profiles of the current velocity between the surface and bottom layers (1020 m) at 1 m resolution were obtained for the first time in the Black Sea in 2011 by means of the Aqualog profiler and the attached Aquadopp acoustic Doppler current meter. The measurements were carried out on June 17–19 off the Bay of Gelendzhik at the foot of the continental slope at 44°28.28′ N, 37°56.24′ E.

Fig. 5 demonstrates the results of these measurements acquired during 14 descent–ascent cycles of the Aqualog profiler. The upper 100 meters of the sea were dominated by the northwestward water transport at a speed up to 0.27 m/s, which indicates the Rim Current. In the layer of 100–150 m, there was the northwestward flow sharply slowed down. The current was absent from the 200 to 400 m depths, but there was a southeastward counter current at greater depths,

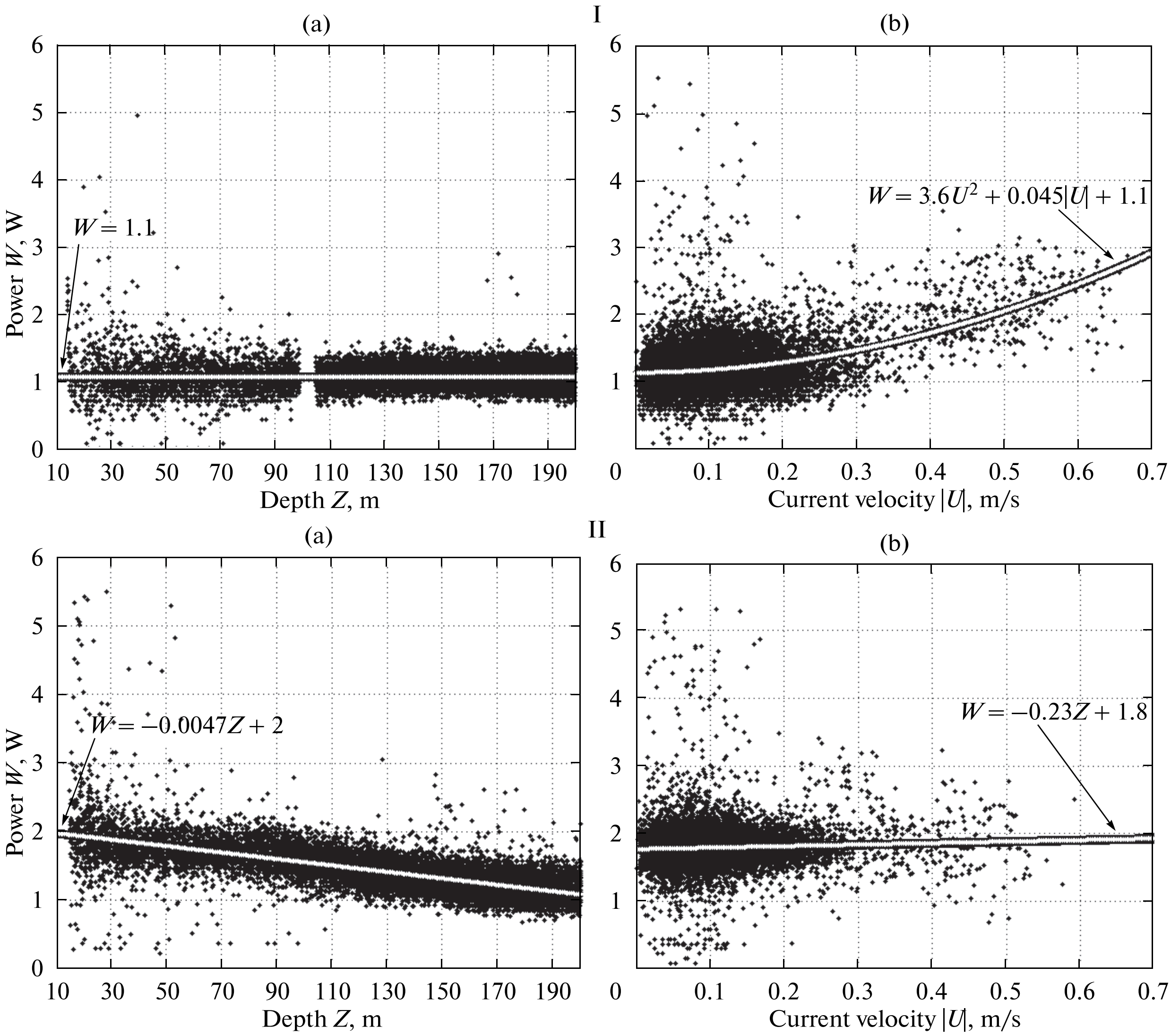

Fig. 4. Energy consumption due to the profiler traveling: I, downwards; II, upwards. (a) at low current speed up to 0.03 m/s; (b) dependence on the current's speed in the layer between the isopycnals $T = 13.5–14$ with the polynomial approximation shown as a double line.

whose core featured a speed of 0.03 m/s and occupied a layer from the 700 to 850 m depth.

5. CONCLUSION

Thus, we refined the technology [4] for the automatic sensing of the water column by means of the profiling carrier with a payload of oceanolographic sensors moving along the vertically taut mooring line between a submerged buoy and an anchor.

The practical application of this technology concerns primarily the monitoring of the in-water pollution and the potentially harmful natural and anthropogenous processes in the seas of the Russian Federation. The technology is also intended for ensuring the all-year-round monitoring below the sea ice in the Arctic.

We manufactured a small series of the Aqualog profilers. The operation modes of the profiler were tested at water temperature as low as −1°C, salinity of the water as high as 300 PSU, and at mooring sites as deep as 1000 m. The tests showed that the profiler can carry out cycles of descent–ascent under conditions of fairly strong sea currents having the speeds up to 0.7–0.8 m/s when the mooring line's inclination achived 10°–15°.

The systematic measurements by means of the Aqualog profilers of the vertical fine-structure of the key parameters of the marine environment were established in the Baltic and Black Seas. . Unlike traditional buoy-mounted moorings with the instrumentation fixed at a number of depth levels, the new approach allows us to carry out continuous measurements of the vertical profiles of the marine environment's charac-

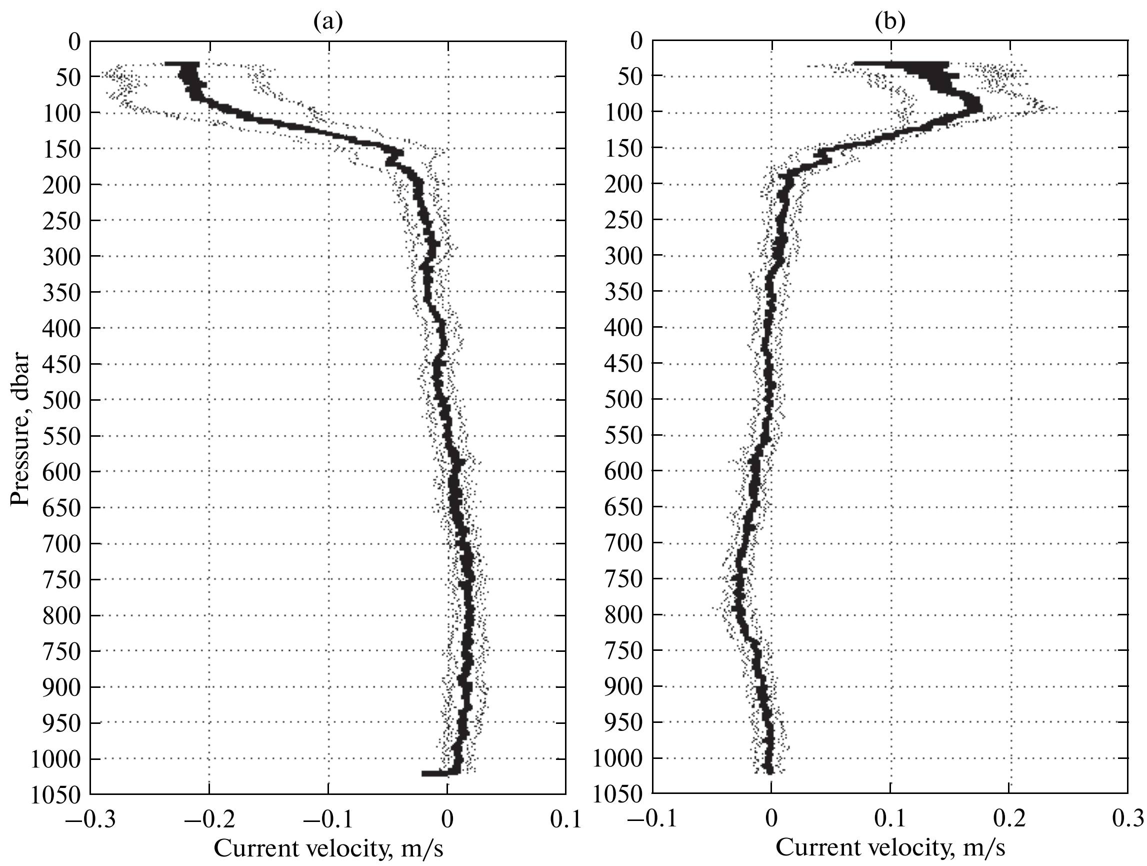

Fig. 5. Vertical fine-structure profile of the meridional component of the current speed obtained by the Aqualog profiler on June 17–19, 2011, in the northeastern Black Sea. The continuous and dashed lines indicate the profiles of the average values and the standard deviations, respectively.

teristics with fine-structure vertical resolution. In the summer of 2011, we discovered a counter current within the 400 m thick water layer underlying the Rim Current in the abyssal area of the Russian sector of the Black Sea.

ACKNOWLEDGMENTS

The authors are grateful to S.S. Nizov (SIO RAS), V.V. Kremenetsky (SIO RAS), and D.M. Solovyev (MHI NASU) for their help during the field works in the Black Sea in 2011 and to Academician of the Russian Academy of Sciences G.V. Smirnov, who supported the project and gave many useful recommendations.

This work was supported by the Russian Foundation for Basic Research (project nos. 11-05-90302-Abh and 10-05-01091a) and by the targeted program The Development of Unique Instruments and Equipment for Russian Academy of Sciences Institutions. Aqualog Ltd., EDBOE RAS, and the Southern Branch of the SIO RAS (Gelendzhik) helpfully supported the field experiments.

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SPELL: 1. Nauka, 2. Liberatore, 3. Holliday, 4. Greenlaw