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Algorithmic and Software Data Registration of Hydrological Meters Based on the Distributed Thermoprofilemeters

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Abstract

The paper describes developed and software-implemented algorithms for primary regulation and processing of measurement data of hydrological meters built on the basis of distributed temperature sensors – thermoprofilemeters. Thermoprofilemeters are spatial temperature sensors made of heat-sensitive continuous conductors (in particular, copper), which are laid in a busbar of a given length in a protective shell-tube. The spatial resolution of the meter is determined by the placement and length of each sensor section. Algorithmic-software data processing of conductor resistances makes it possible to recover temperature values averaged on sections of continuous profile using matrix of calibration coefficients. Interpolation and approximation of the resulting discrete series provides a calculation of the instantaneous spline profile of temperature, which is then used to sequentially plot a dynamic picture of the variability of the temperature field in the form of a colour gradient and isolines. In the online telemetry measurement mode, this method allows to clearly visualize the picture of spatial temperature distribution both during static installation of the sensor and during depth sensing, as well as algorithmically detect and control other hydrological parameters and processes in the aqueous medium: interfaces, surface and internal waves, upwelling, surge phenomena, vertical rates of transfer of water masses, etc. The spatial resolution and length of thermoprofilemeters can vary from several centimeters to tens of meters depending on the problems being solved. The use of sensors in hydrological measuring systems can be carried out in static and probing modes. At the same time, the application software for each type of sensor and measurement method allows using specialized data processing and display functions.

Keywords: program algorithm, distributed temperature sensor, thermoprofilemeter, isotherm, vertical profile, heat storage, thermocline, internal waves, temperature field, heat exchange, termistor chain

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Алгоритмически-программное обеспечение регистрации данных гидрологических измерителей на базе распределенных термопрофилемеров

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Аннотация

Описаны разработанные и реализованные программно алгоритмы первичной регистрации и обработки измерительных данных гидрологических измерителей, построенных на базе распределенных датчиков температуры – термопрофилемеров. Термопрофилемеры – пространственные датчики температуры, изготовленные из термочувствительных (в частности, медных) непрерывных проводников, ортогонально уложенных в шину заданной длины в защитной оболочке-трубке. Пространственное разрешение измерителя определяется укладкой и длиной каждого участка датчика. Алгоритмически-программная обработка данных сопротивлений проводников позволяет восстанавливать с помощью матриц градуировочных коэффициентов осредненные на участках непрерывного профиля значения температур. Интерполяция и аппроксимация полученного дискретного ряда обеспечивает расчет мгновенного сплайн-профиля температуры, который далее используется для последовательного построения динамической картины изменчивости поля температуры в виде цветового градиента и изолиний. В оперативном телеметрическом режиме измерений такой метод позволяет наглядно визуализировать картину пространственного распределения температуры как при статической установке датчика, так и при зондировании по глубине, а также алгоритмически обнаруживать и контролировать другие гидрологические параметры и процессы в водной среде: границы раздела, поверхностные и внутренние волны, апвеллинг, сгонно-нагонные явления, вертикальные скорости переноса водных масс и др. Пространственное разрешение и длина термопрофилемеров при изготовлении в зависимости от решаемых задач могут варьироваться от нескольких сантиметров до десятков метров. В гидрологических измерительных системах датчики могут применяться в статическом и зондирующем режимах. При этом прикладное программное обеспечение для каждого типа датчика и метода проведения измерений позволяет использовать специализированные функции обработки и отображения данных.

Ключевые слова: программный алгоритм, распределенный датчик температуры, термопрофилемер, изотерма, вертикальный профиль, теплозапас, термоклин, внутренние волны, поле температуры, теплообмен, термокоса

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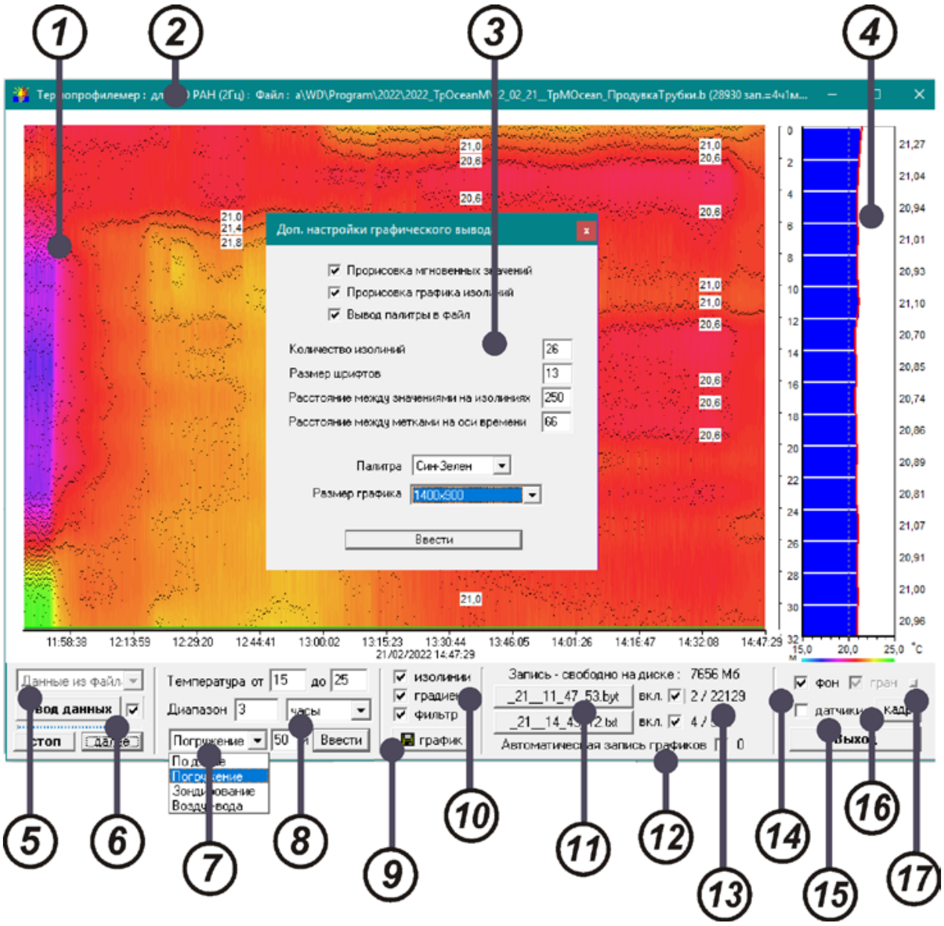
Introduction

Measurement of instantaneous spatial temperature profiles in the aquatic environment using distributed sensors or multipoint temperature transmitters from discrete sensors has been carried out for many years. The data obtained in this way are necessary for solving a number of hydrological problems, including monitoring and studying heat transfer and heat storage processes, detecting and studying the processes of water mass transfer through currents, surge phenomena and internal waves, monitoring boundaries of media separation and density distribution by heat transfer coefficients [1–10]. The electronic equipment of the measuring part of the sensors is being improved with the development of technical means and microelectronics, and new tasks of processing, comparison and analysis are set before the methodological and algorithmic-software parts. Along with the widespread relatively simple in technical implementation multipoint temperature transmitters [5–8], consisting of spatially discrete digital sensors, there are distributed temperature sensors – thermoprofilemeters (TP), built on the principle of orthogonally stacked thermally sensitive conductors [3, 10, 11]. Despite the relatively greater complexity in manufacturing and the need for individual calibration, TP have, in comparison with digital multipoint temperature transmitters, a number of advantages: greater measurement accuracy (error less than 0.1 °C), spatial continuity (the temperature in the area is constructively determined by averaging over the entire length, not at a point) and in some cases higher reliability due to the additional possibilities of a protective design and the absence of microelectronics in a controlled environment.

Equipment and data

The development and improvement of application software for working with the author's experimental and prototype TP samples [3, 10] has been carried out since 1996. During this time, distributed sensors for research in the Black Sea, in the Arctic and Antarctic regions, as well as for use on rivers and in systems for measuring the level and boundaries of media separation in coastal waters have been created. Since a number of created systems contain, in addition to TP, other measuring modules and sensors, let us focus on the algorithmic software for processing temperature profile data with spatial and temporal reference with a standard connection of the device to the computer interface via serial hardware (RS232/485) or virtual (USB modules, Bluetooth, etc.) COM port of the computer.

When creating the main specialized dialog software, Borland Pascal and C (MS DOS), C++ and Delphi (MS Windows) programming languages and environments were chronologically used. During the measurements, data were recorded and processed in autonomous and telemetric modes. In the post-processing mode, the primary tasks were the prompt preparation of reports and the transfer of visual numerical and graphical results to the data bank. Since the created hydrological TP had different lengths (from 20 cm to 50 m), spatial resolution (section length



Доп. настройки графического вывод

☑ Прорисовка мгновенных значений
☑ Прорисовка графика изолиний
☑ Вывод палитры в файл

Количество изолиний 26
Размер шрифтов 13
Расстояние между значениями на изолиниях 250
Расстояние между метками на оси времени 66

Палитра Син-Зелен
Размер графика 1400x900

Ввести

Температура от 15 до 25
Диапазон 3 часы
Погружение 50
Ввести

☑ изолинии
☑ градиен
☑ фильтр
график

Запись - свободно на диске : 7656 Мб
_21__11_47_53.byt вкл. ☑ 2 / 22129
вкл. ☑
Автоматическая запись графиков

☑ фон ☑ гран
☐ датчики
Кадр

F i g . 1 . View of the main window of the program interface for initial recording and processing of measuring data of thermoprofilemeters: *1* – gradient and temperature profile isolines over time area; *2* – information line; *3* – advanced graphics window settings and temperature isolines output; *4* – moment averaged temperature values in sections and calculated spline-interpolated profile; *5* – control and indication of data input (from file (post-processing) / from COM port (telemetry mode)); *6* – flow control and input indication of primary data; *7* – selection of graphical mode of measurement data display with reference to depth or space; *8* – settings of time ranges and temperature scale of graphic output; *9* – option of saving graphs to files (bmp/jpg); *10* – setting options for isolines output, color gradient, median filtering and data averaging; *11* – options for recording primary data and measurement results into files (code (byt) and text (dat/txt)); *12* – option for settings of automatic frame-by-frame saving of graphs to graphic files; *13* – indication for recording code files and text files of measurement processing results; *14* – adjustment of the background of graphs (black/white); *15* – option for displaying the window of numerical and graphical output of secondary sensor data (pressure sensors, etc.); *16* – option of displaying the window of numerical output of statistical and code values as well as settings for post-processing of data; *17* – selection of the calibration coefficient file from 2 cm to 2 m), and also different applications (stationary, towed and sounding), universal software algorithms for processing primary information and graphical output were developed, which allow, under various experimental conditions, to quickly observe the dynamics of the temperature field with direct reference to space and time (Fig. 1). Unlike the output of a standard set of graphs, which is most often used for discrete sensors of multipoint temperature transmitters on separately specified horizons [1, 4, 6–9], this type of measurement information display is preferable. However, it can only be ensured by obtaining highly accurate and methodically complete primary data.

Results

The complete package of algorithmic software for TP includes a number of separate programs:

– program for modeling distributed sensors in terms of length, spatial resolution, matrices of orthogonal functions and materials for the manufacture of temperature-sensitive elements for specified application conditions (real dynamics and spatial variability of temperature profiles);

– program for metrological verification of the sensor and automatic calculation of matrices of calibration coefficients for TP sections;

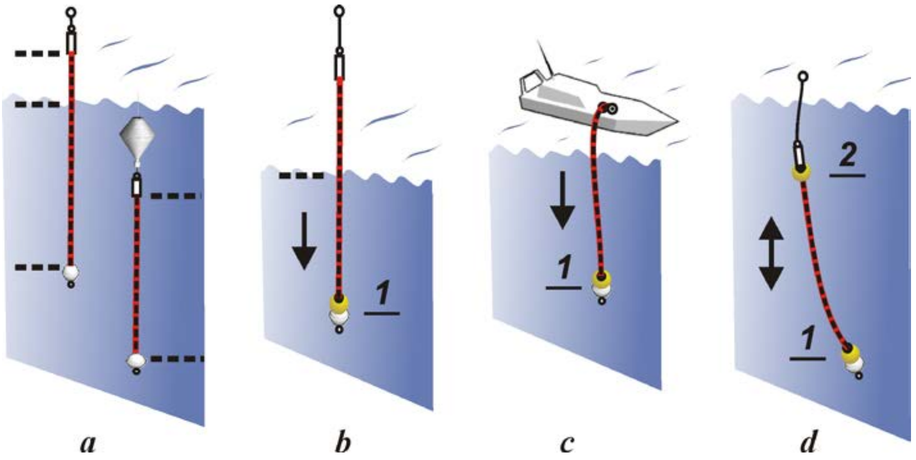
– program for numerical and graphical display and registration of TP measurement data [1)];

– complex data processing program.

In the user mode, a dialog program for primary registration and processing of measurement data is used (Fig. 1).

The use of hydrological TP when using up to two built-in pressure sensors (depth control) is carried out in four main modes (Fig. 2). Binding of the measuring temperature profile to the depth or boundaries of media separation (air and water) in stationary (platform, pier, moored buoy) or dynamic (bleeding, sounding, towing, submerged or surface drifting buoy) modes is provided depending on the tasks and equipment with pressure sensors. Accordingly, the user sets (Fig. 1 (designation *7*)) the selected type of measurement information display. The simplest option in this case is a stationary setting of a TP with a rigid spatial reference of the sensor to a given profile and primary boundaries of media separation without using pressure sensors (Fig. 2, *a*).

[1)] Gaisky, P.V., 2022. [*Program for Registration and Processing of Thermoprofilemeter Measurement Data “THERMOPROF”*]. Sevastopol: MHI. State Registration no. 2022611315.

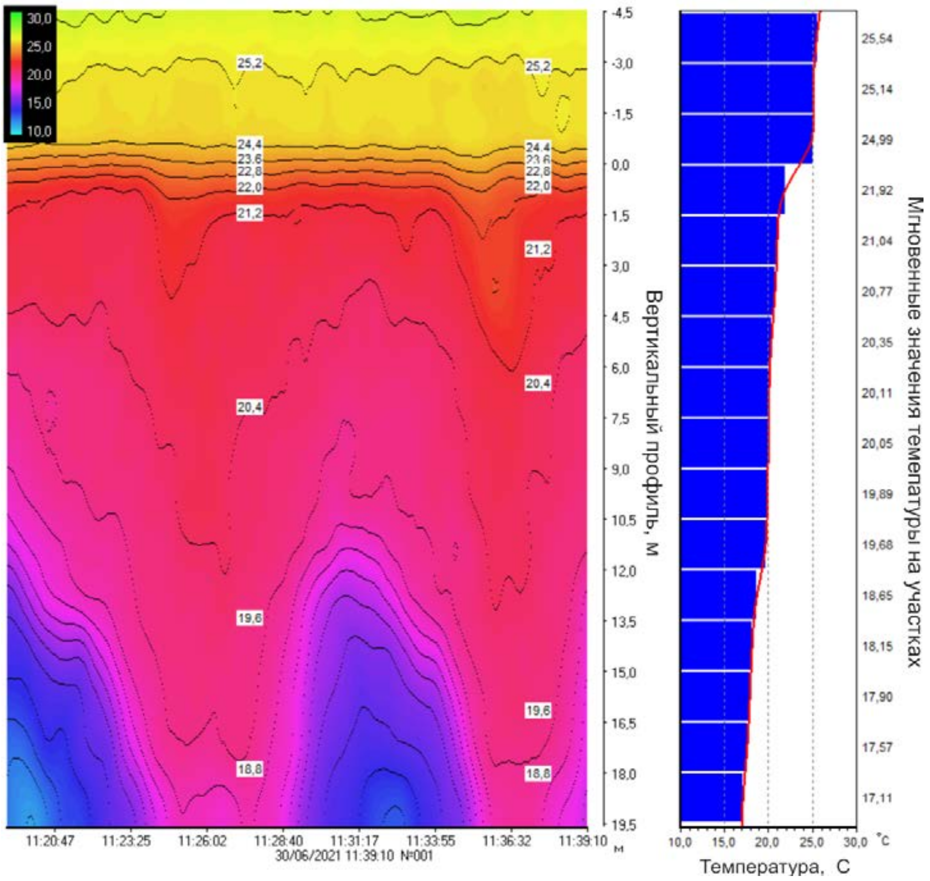


F i g . 2 . Methods of setting and using hydrological distributed sensors: stationary (rigid binding to spatial coordinates and boundaries of media separation) (*a*), vertical installation or sounding with one pressure sensor in the lower part (*b*), bleeding or towing from the side of the floating craft with one pressure sensor in the lower part (*c*), towing or sounding with two pressure sensors at the upper and lower ends of the thermoprofilemeter (*d*) (*1*, *2* – pressure sensor position)

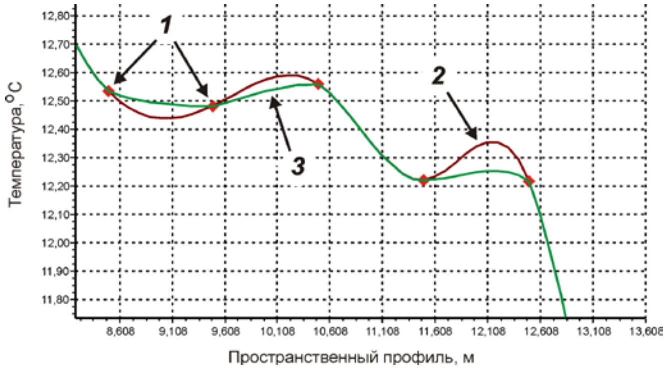
The construction of measurement graphs is carried out in the telemetric mode, including in the data post-processing mode. The right side displays instantaneous temperature values in the form of columnar (conditionally discrete) diagrams calculated for all distributed sections of the TP profile (Fig. 3). This data is used to reconstruct a continuous approximated profile using spline interpolation. In this case, the spline coefficients are calculated and are quantitatively equal to a number of graph points for the current vertical graphic resolution of the user's display.

Despite the achievement of almost zero deviation from the uniformly discrete initial data of the primary measurement series, the spline in some cases exhibits intermediate outliers (Fig. 4), when the spline bend goes beyond the values of neighboring boundary points. Statistical analysis of these calculated outliers with the initially correct correspondence of the design resolution of the TP to the spatial variability of temperature in a controlled environment (which can be determined, if necessary, by preliminary modeling using real data) showed their error in 99 % of the cases. Correction of these outliers upon detection is carried out automatically (Fig. 4) using logarithmic or power-law interpolation on a given segment, depending on the nature of the deviation

$$T = a + b \times \log_{10} X \quad \text{and} \quad T = \pm a \times X^{b},$$



F i g . 3 . Example of graphical display of measurements on oceanographic platform of thermoprofilemeter fixed vertically at air-water interface up to a depth of 19.5 m



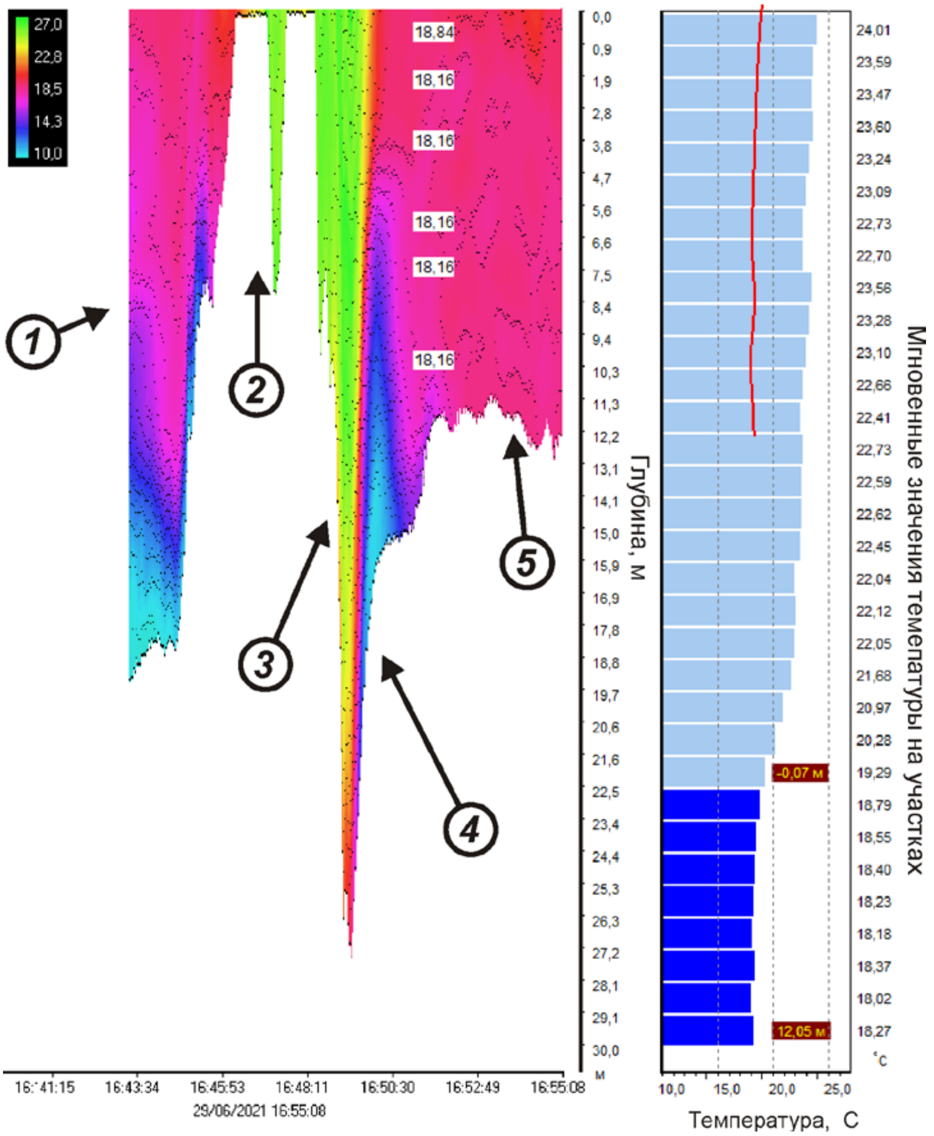
F i g . 4 . Example of additional correction of the spline section of temperature measurement: initial measurement data on thermoprofilemeter sections (*1*), calculated profile after spline interpolation (*2*), resulting continuous profile after correction (*3*) where X is spatial coordinate of a point; T is calculated temperature at the point; a and b are interpolation coefficients.

The resulting graphical pixel-continuous temperature profile series is compared with a user-specified color gradient over the range and displayed on the window of graphs (isolines) along the time base. The drawing of the isoline point on the resulting gradient strip is ensured by hitting the specified value of the isoline in the interval of value of neighboring pixels. Thus, in a given time range, regardless of previous measurements, a picture of the temperature field is formed sequentially with shifts in dynamics and with reference to a spatial profile. This method makes it possible to display the gradient and isolines promptly without two-dimensional interpolation, which requires long-term data accumulation and much more computational resources. However, the guarantee of the visual quality of this processing, expressed in the smoothness of the gradient and continuity of the isolines, is reliability (in terms of errors, inertia and spatial resolution) of the obtained primary measurement information.

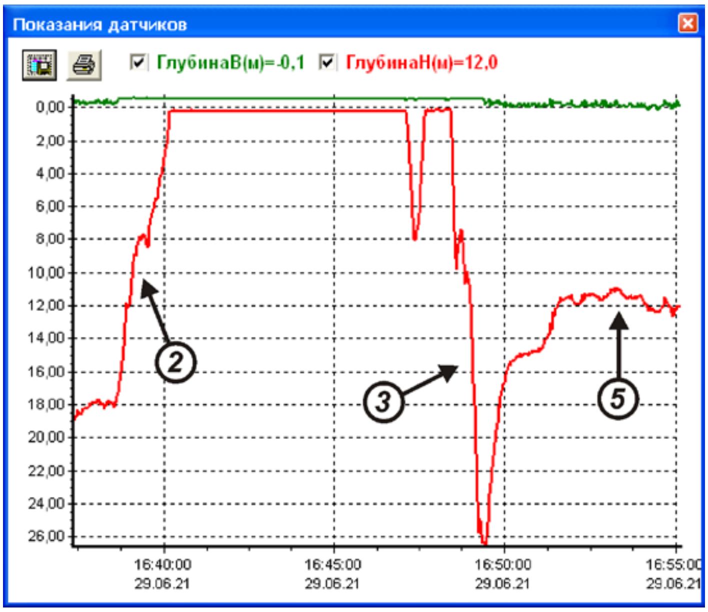
Graphical display of TP data in dynamic operating modes (when changing position in space) is based on data from hydrostatic pressure sensors and user settings of the program. In particular, the "Immersion" program mode optimally displays the measurements obtained by bleeding the lower part of the TP from the vessel into the water (Fig. 5). The depth of the sensor is fixed according to the readings of the lower pressure sensor (Fig. 6), while the upper part is on the deck. In this case, interpolation and output to the isoline graph is carried out only for the submerged part. Provided that the underwater part of the TP is located vertically, the spatial reference of measurements will be correct, otherwise the depth can be corrected only if there are visual marks on the sensor or there is a pronounced temperature difference between water and air. To obtain a reliable vertical profile, it is also necessary to take into account the inertia of the sensor (Fig. 5) and the ship's motions during towing (Fig. 6).

An example of operation of "Sounding" program mode when using two pressure sensors is shown in Fig. 7. The TP position is assumed to be conditionally linear in depth.

One of the most important tasks in the application of hydrological TP is detection of internal waves and control of their parameters. Since the internal wave manifestation is well tracked in the thermocline region, where, with the proposed graphical display, the highest concentration of continuous temperature isolines is observed, it is proposed to use data on spatio-temporal characteristics of the isoline



F i g . 5 . Example of recording measurements during immersing and towing of the buried part of the TP: the end of towing (*1*), lifting on board (*2*), partial immersing overboard and inertial cooling (3), the beginning of towing and inertial heating (*4*), drift and surface swell (*5*)



☑ ГлубинаВ(м)=-0,1 ☑ ГлубинаН(м)=12,0

Fig. 6. Readings of device pressure sensors (upper and lower) to record measurements in Fig. 5: lifting onboard (*2*), partial immersing overboard (*3*), drift and surface swell (*5*)

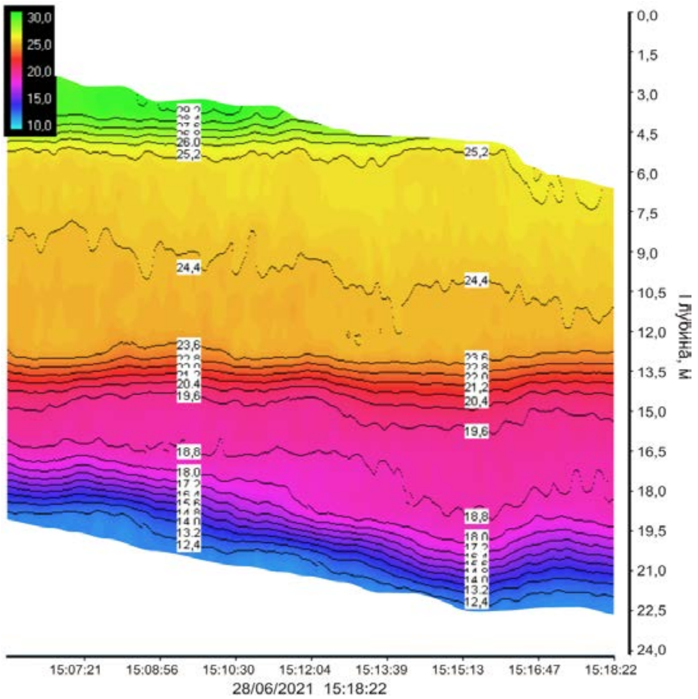
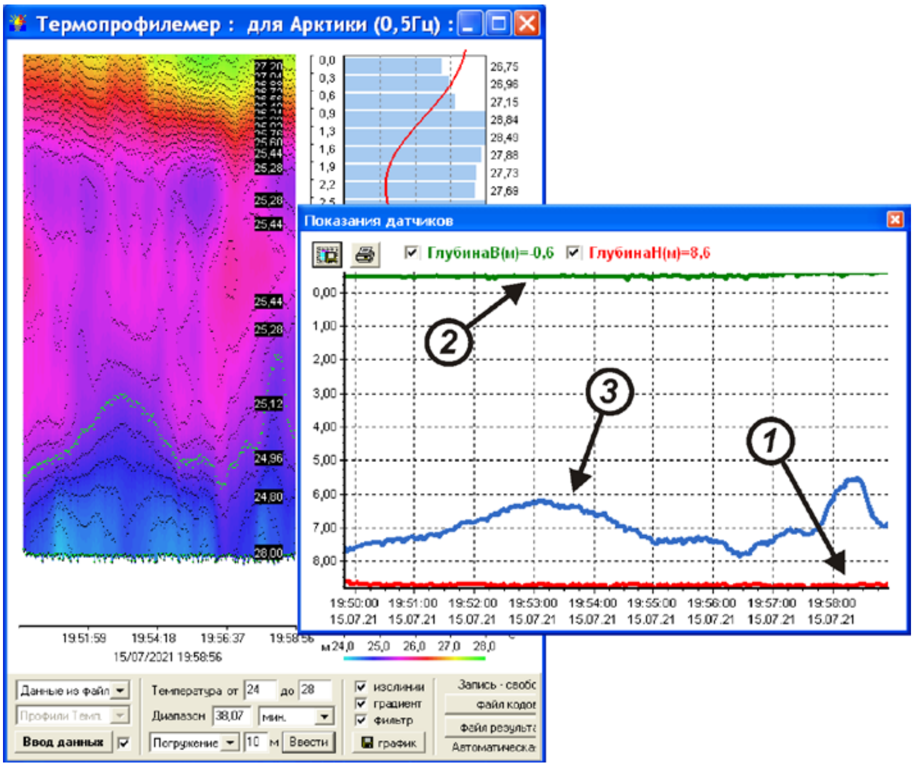


Fig. 7. Example of plotting isolines in "Sounding" mode



☑ ГлубинаВ(м)=-0,6 ☑ ГлубинаН(м)=8,6

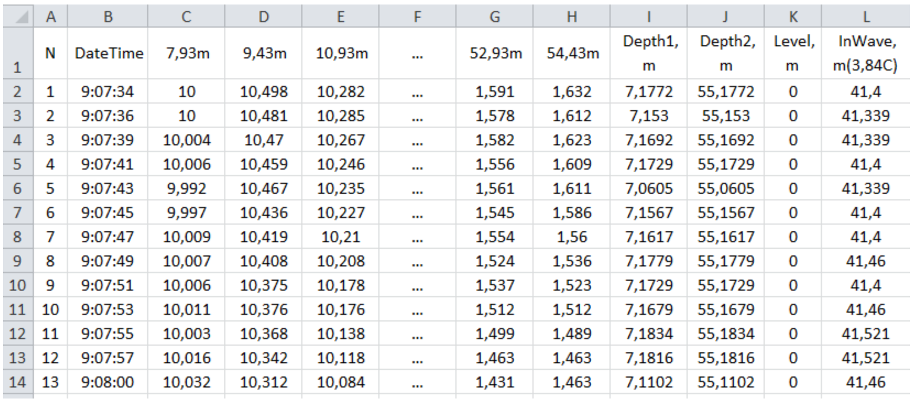
Температура от 24 до 28

Диапазон 38,07 мин.

Погружение 10 м

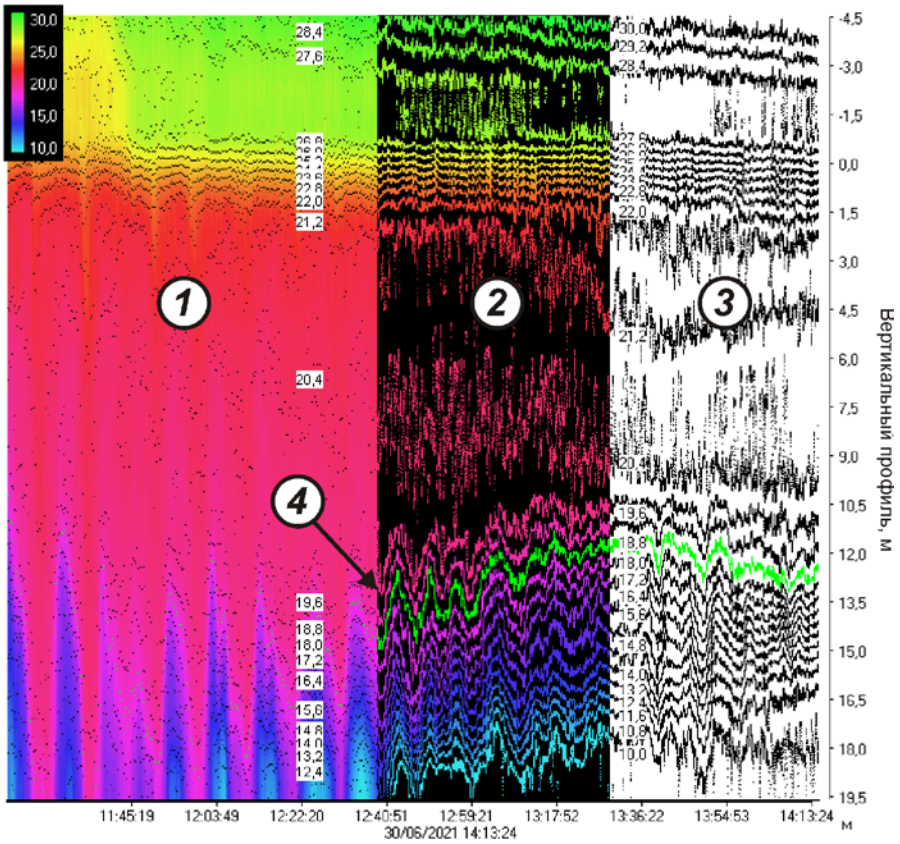
☑ изолинии
☑ градиент
☑ фильтр

Fig. 8. Tracking and output graph of user selected isotherm: lower pressure sensor plot (*1*), upper pressure sensor plot (*2*), plot of monitored (from depth bottom) isotherm 25.12 °C (*3*)



	A	B	C	D	E	F	G	H	I	J	K	L
1	N	DateTime	7,93m	9,43m	10,93m	...	52,93m	54,43m	Depth1, m	Depth2, m	Level, m	InWave, m(3,84C)
2	1	9:07:34	10	10,498	10,282	...	1,591	1,632	7,1772	55,1772	0	41,4
3	2	9:07:36	10	10,481	10,285	...	1,578	1,612	7,153	55,153	0	41,339
4	3	9:07:39	10,004	10,47	10,267	...	1,582	1,623	7,1692	55,1692	0	41,339
5	4	9:07:41	10,006	10,459	10,246	...	1,556	1,609	7,1729	55,1729	0	41,4
6	5	9:07:43	9,992	10,467	10,235	...	1,561	1,611	7,0605	55,0605	0	41,339
7	6	9:07:45	9,997	10,436	10,227	...	1,545	1,586	7,1567	55,1567	0	41,4
8	7	9:07:47	10,009	10,419	10,21	...	1,554	1,56	7,1617	55,1617	0	41,4
9	8	9:07:49	10,007	10,408	10,208	...	1,524	1,536	7,1779	55,1779	0	41,46
10	9	9:07:51	10,006	10,375	10,178	...	1,537	1,523	7,1729	55,1729	0	41,4
11	10	9:07:53	10,011	10,376	10,176	...	1,512	1,512	7,1679	55,1679	0	41,46
12	11	9:07:55	10,003	10,368	10,138	...	1,499	1,489	7,1834	55,1834	0	41,521
13	12	9:07:57	10,016	10,342	10,118	...	1,463	1,463	7,1816	55,1816	0	41,521
14	13	9:08:00	10,032	10,312	10,084	...	1,431	1,463	7,1102	55,1102	0	41,46

Fig. 9. Example of writing a 48-meter TP sensor measurement results to a text file



F i g . 10. Demonstration of the output of the gradient-isolines graph at various settings: colour gradient and isolines (*1*), colour isolines without gradient (*2*), black-and-white output of isolines (*3*), indication of the selected internal wave isoline (*4*)

selected by the user for spectral-wave analysis. In this case, the selected isoline, when processing measurements, is marked with a separate color and displayed on the graph (Fig. 8), and its spatial displacements in depth and time are recorded in the general text file of the results (Fig. 9).

Various modes of information output on isoline graphs are shown in Fig. 10. The time ranges for the output of isolines are set by the width of the time interval with an automatic shift of the graph to the left when a new data packet is received on the right. For the post-processing mode, one can set a specific time interval with a start and an end. The daily display mode uses a 24-hour scale. For processing large data arrays or for telemetric operation of the device in an offline mode, automatic frame-by-frame (daily, etc.) saving of graph windows and text files of measurement results in standard formats is provided.

Conclusion

As practical experience has shown, the developed algorithmic software for the primary registration, processing and numerical and graphical output of measurement data from hydrological distributed temperature sensors TP is a reliable tool for obtaining operational and visual information about the processes of heat transfer and transfer of thermally bound masses in water environment. The possibility of adaptive display of data in various modes of using the TP provides high-quality telemetric binding of measurements to spatio-temporal coordinates and, therefore, accelerates further interpretation of the results and planning of experiments. A necessary factor in obtaining reliable graphic information is qualitative metrological characteristics of the meter and a verified method of its use in specific conditions of environmental variability.

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