

Original article

String Wave Gauge with a Shielded Wire for Wave Measurements

E. M. Zuikova, Yu. A. Titchenko , D. A. Kovaldov, V. Yu. Karaev,
V. I. Titov

A. V. Gaponov-Grekhov Institute of Applied Physics, Russian Academy of Sciences,
Nizhny Novgorod, Russian Federation

 yuriy@ipfran.ru

Abstract

Purpose. This study aims to describe a prototype of a string wave gauge designed for dynamic recording of wave elevations in both salt and fresh water across a wide range of wavelengths, including capillary waves. The prototype is engineered to be insensitive to salt deposition on the conducting wire and resistant to short circuits caused by conductive debris. It is intended for use in unattended wave gauge “grids” to record two-dimensional wave spectra and to support sea wave studies with remote sensing methods for data interpretation and validation.

Methods and Results. A capacitive string wave gauge featuring a shielded wire configured as a closed two-wire loop is presented for measuring water surface elevations in both salt and fresh water. Compared to a conductive wire, the shielded wire prevents sensitivity loss due to salt deposition and eliminates short circuits caused by small conductive debris. The wave gauge exhibits a wide linear dynamic range, capable of recording waves from millimeters to several meters in height in both salt and fresh water. During operation, the wire requires no cleaning, and the gauge can remain submerged for extended periods without loss of sensitivity or temperature-induced signal “drifts”.

Conclusions. The operational principles and design features of the wave gauge are described, along with the results of testing in river and sea conditions. The influence of the distance between the “strings” on the device’s effectiveness in salt and fresh water was investigated under laboratory conditions. For a multi-string design, a method to eliminate mutual interference among the wave gauge “strings” was developed. The proposed measurement setup involves mounting the control unit of the string wave gauge at a height of several dozens of meters above the “strings”, facilitating convenient installation above water for measurements from a bridge or a sea platform.

Keywords: surface waves, wave height, gravity-capillary waves, water level, string wave gauge, *in-situ* measurements

Acknowledgements: The authors are grateful to the employee of IAP RAS E. V. Lebedev for high-quality development of the printed circuit board. The study was carried out under a state assignment of IAP RAS (FFUF-2024-0033).

For citation: Zuikova, E.M., Titchenko, Yu.A., Kovaldov, D.A., Karaev, V.Yu. and Titov, V.I., 2025. String Wave Gauge with a Shielded Wire for Wave Measurements. *Physical Oceanography*, 32(5), pp. 613-623.

© 2025, E. M. Zuikova, Yu. A. Titchenko, D. A. Kovaldov, V. Yu. Karaev, V. I. Titov

© 2025, Physical Oceanography



Introduction

Various types of wave gauges ^{1, 2, 3} [1–3] have been developed for measuring wave heights in rivers and seas [1–3], with string ⁴ [4] and laser [5] gauges being among the most accurate. The string wave gauge is notably the simplest to manufacture and the most reliable for *in-situ* measurements. A well-known example in Russia is the string wave gauge installed on the oceanographic platform of the Marine Hydrophysical Institute in Katsiveli, which has operated for many years and is actively used for wave monitoring and complimentary measurements [6–8].

Standard string wave gauges, which use a single conducting wire as the “string”, face significant limitations due to contamination from salt deposits, fouling by floating algae, and small conductive debris. In Canada (www.akamina.com), a loop of shielded wire configured as a closed two-wire line was proposed for recording changes in liquid level. This design has proven effective in lakes, rivers and various laboratory setups [9, 10]. Compared to a single wire, the closed two-wire loop doubles the capacitance, which is critical for measuring short waves with heights on the order of millimeters. The use of a shielded wire eliminates oxide formation that could alter the string’s capacitance prevents short circuits caused by small conductive debris. This approach was adopted at the Institute of Applied Physics of the Russian Academy of Sciences to develop a prototype capacitive string wave gauge (hereinafter referred to as wave gauge), which is described in this study. The wave gauge was tested for three months on the Oka River in Nizhny Novgorod [11], confirming its performance. Some results from its field use in the Black Sea are also presented here.

This study aims to describe the prototype capacitive string wave gauge with a shielded wire, highlight the advantages of using a closed two-wire line and discuss the results of its field testing.

Wave gauge design

Photographs of the wave gauge deployed in field conditions during measurements on the Oka River, including images of the strings, are shown in Fig. 1.

For measuring waves with wavelengths shorter than half a meter, a loop of wire with a diameter of 0.3 mm, forming a 5–10 mm wide and 0.3–2 m long loop, was used. The loop was stretched over rubber bushings and secured with pins to a metal rod with a diameter of 5 or 15 mm, depending on the loop length. The two wires of the loop are soldered to the central core of a shielded RF-type RK-75 cable, with the cable’s shield connected to the metal rod. The signal is transmitted to the processing unit via an SR-50 connector (radio frequency connector). As the cable’s capacitance adds to the string’s capacitance, its length is limited, making it preferable to position the processing unit close to the string.

¹ Korovin, V.P., 2007. *Oceanological Observations in the Coastal Zone of the Sea. A Manual*. Saint Petersburg: Russian State Hydrometeorological University, 434 p. (in Russian).

² MARINET, 2012. *D2.1 Wave Instrumentation Database. Work Package 2: Standards and Best Practice*, 55 p.

³ Rosenberg, A.D., 1980. [*Study of the Sea Surface by Radio and Acoustic Methods*]. Thesis of Doctor of Phys.-Math. Sci. Moscow, 237 p. (in Russian).

⁴ Antonov, V.S. and Sadovsky, I.N., 2007. *Sea Surface Wave Gauge IVMP-1: Design Description and CAPMOS’05 Field Experiment Data*. Preprint. Moscow, 36 p. (in Russian).

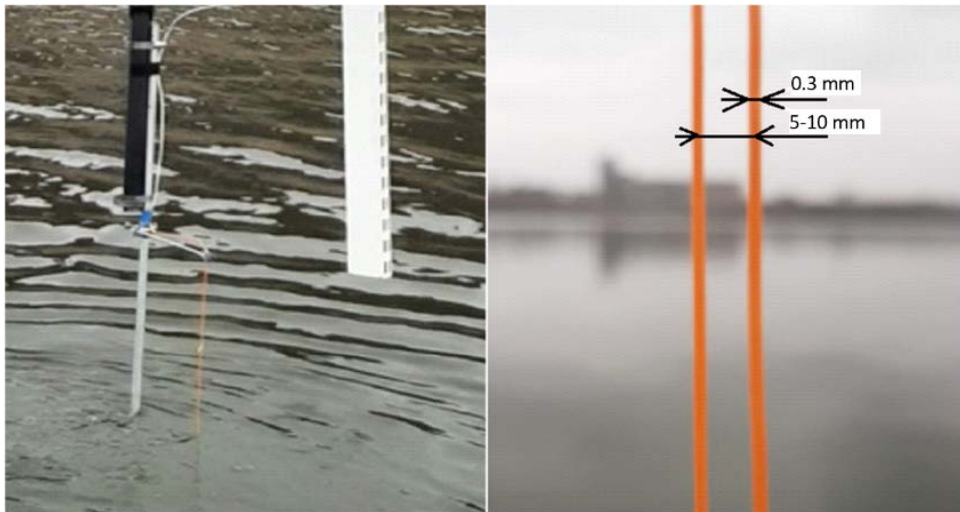


Fig. 1. Wave gauge in the measuring setup (*left*), and “strings” (*right*)

The capacitance of the loop varies with the immersion level in water due to the difference between the dielectric constant of air (equal to one) and that of fresh water (equal to 80) or seawater (equal to 78). The loops utilize MS 16-33 (special mounting) wire with a cross-section of 0.03 mm^2 (or 0.05 or 0.08 mm^2) and insulation made of solid monolithic fluoroplastic. This insulation enables the measurement of liquid levels in aggressive media.

For measuring waves several meters high, a single shielded wire with the immersed end insulated from water, or a wire folded in half, can be used. The folded configuration facilitates attachment to a plumb line for tensioning the wire and eliminates the need to insulate the submerged end from seawater. Doubling the string’s capacitance is an additional benefit, particularly for short strings up to 20 cm long. The central core of the RK cable is connected to the wire or loop, while the shield is connected to a separate conducting wire submerged in the water or to a metal structure in contact with the water. To simplify the design and enhance durability, attaching the wire to a shielded cable while using it as a ground was explored. However, this approach was unsuccessful due to slow water runoff (up to tens of seconds) after the immersed cable portion emerges from the water. For increased strength, the wire can be attached to a 1 mm fishing line, which exhibits negligible water runoff, though an additional wire for water contact is required.

Changes in the wave gauge’s capacitance, corresponding to variations in wave height (the length of the submerged string), are detected using a capacitive bridge, which provides high sensitivity. Initially, a variable capacitor was used to adjust the bridge, but a variable resistor was later adopted to simplify the design.

String wave gauge circuit

The circuit diagram of the wave gauge is shown in Fig. 2. A signal from a generator, operating at a frequency of tens of kilohertz in the first version and several kilohertz in the second version, is applied to the bridge DA1.1. An additional amplification circuit, assembled on DA1.2., optimizes the signal level. Amplifiers

DA2.1 and DA2.2 amplify the signals from the string and the reference capacitance C9, respectively, to expand the linear dynamic range. The capacitance C9 is set to approximately half the string's capacitance and consists of two components: a primary capacitance integrated as a chip on the printed circuit board and an adjustable capacitance of type KM47 mounted on pins on the component side for fine-tuning. The difference between the signals from the wave gauge capacitance and the reference capacitance C9 is extracted by DA3. DA4 serves as a synchronous detector, processing the signal from DA3 alongside the reference signal from DA1.2. Synchronous detection minimizes input interference. A low-pass filter with a cutoff frequency of 10 or 30 Hz, implemented on DA5, processes the output, which is then recorded on a laptop. The wave gauge circuit is housed in a duralumin case measuring 20 × 70 × 80 mm. With this signal processing circuit for the string wave gauge using a shielded wire, a dynamic range relative to noise of ~ 80 dB was achieved, with a maximum output of 10 V and noise levels below 1 mV.

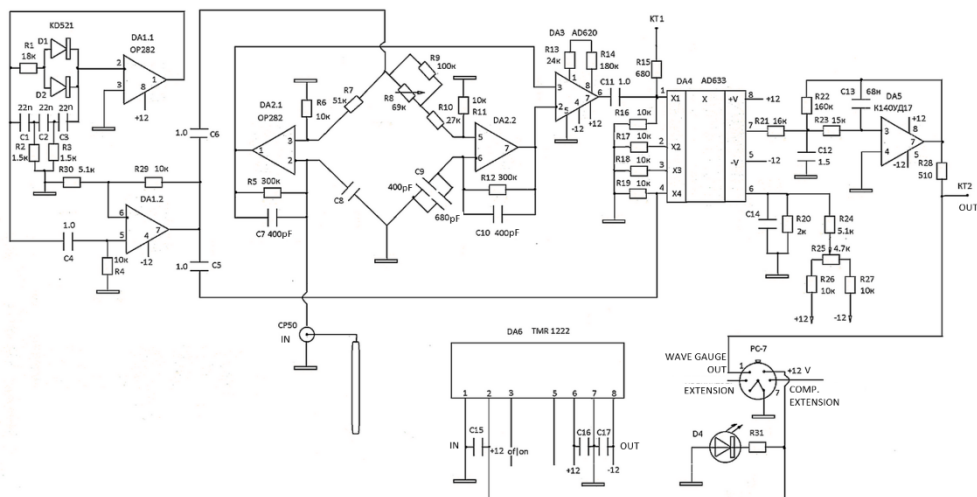


Fig. 2. Wave gauge circuit

Temperature-related “drifts” in the output signals of the processing unit were measured under laboratory conditions with air temperatures ranging from – 10 to + 50 °C and were found to be within a few percent.

Study of the influence of distance between strings on measurements

This section analyzes a scheme for eliminating mutual interference between strings, applicable to wave gauge grids designed for measuring two-dimensional wave spectra. In laboratory conditions, the influence of the distance between strings on interference levels in salt water was investigated using two 40 cm strings and two 7 m strings. For the 40 cm strings (one equipped with a 5 kHz generator and the other with a 2.8 kHz generator, both approximately half-immersed in salt water), the interference from the 2.8 kHz generator on the 5 kHz string was measured at various distances. The interference was measured relative to the signal obtained when the immersion level in water changed by 10 cm. At a distance of less than

5 mm, the interference was -16 dB; at 50 mm, it was -28 dB; and at 120 mm, it was -35 dB. Comparisons with interference levels for strings removed from water revealed that the interference magnitude in salt water matched that of the string portions in air, indicating that the primary source of interference is the string segment exposed to air.

For two 7 m strings placed adjacent to each other in salt water, no interference was observed, indicating an absence of mutual influence between the strings.

In fresh water, however, the mutual influence between strings decreases more slowly with distance compared to air. For 7 m strings at a distance of 3–5 mm, the interference from the 2.8 kHz string on the 5 kHz string was -13 dB; at 16 cm, it was -16 dB; at 33 cm, it was -19 dB, relative to the signal change for an 10 cm variation in immersion level. In air, for strings 3–5 mm, the interference was -4 dB, and at 3 cm, it was -20 dB.

In cases where strings are sufficiently spaced, the mutual influence of adjacent strings can often be neglected. However, when interference is significant, it needs to be mitigated. The wave gauge circuit (Fig. 2) facilitates the elimination of mutual interference through synchronous detection. This is achieved by using distinct frequencies for each string and performing synchronous detection with the reference signal corresponding to each string's frequency. The number of processing circuits may match the number of strings, or a single processing circuit with sequential frequency switching is sufficient. At low signal levels, interference from neighboring strings operating at different frequencies does not distort the signal. For example, with a signal of 0.4 V and interference 8 dB above the signal, the output signal remains unaffected. At higher signal and interference levels, the maximum operating level must be reduced to prevent signal distortion, consequently reducing the dynamic range.

Measurement methodology

Before initiating measurements, half of the string is submerged in water. The reference capacitance is pre-set to match the capacitance of the half-submerged string in water. For example, in fresh water, an MS wire with a cross-section of 0.08 mm^2 and a length of 3.5 m, folded in half, has a capacitance of 1200 pF, corresponding to ~ 3.4 pF/cm. The capacitance of the RK cable is ~ 70 pF, while the loop's capacitance in air is ~ 30 pF. For a loop made of MS wire with a cross-section of 0.05 mm^2 , the capacitance is 2.2 pF/cm, and for two loops, it is 4.4 pF/cm. The AC signal from the control output on the front panel of the processing unit is connected to an oscilloscope or laptop. By adjusting the resistance of potentiometer R8 on the front panel, the signal at the control output KT1 is minimized, balancing the bridge capacitances according to the formula: string capacitance $C = C_9 \cdot R_8 / R_7$. Subsequently, the DC offset at the KT2 output is minimized using potentiometer R24 on the front panel.

For wave elevation measurements in real-world conditions, the wave gauge is calibrated prior to experiments by changing its immersion depth by a predetermined amount using verified instruments to measure the wave gauge signals. Fig. 3 illustrates the signal dependence of a 7 m loop string made of MS wire with a cross-section of 0.08 mm^2 , with capacitances $C_7 = C_{10} = 400$ pF, at varying wave gauge sensitivities (corresponding to different values of resistance R5; Fig. 3, *left*) and

immersion depths in fresh and salt water with a salinity of 20 g/L (Fig. 3, right). The data points represent water level values during calibration, which are approximated by a straight line. Thus, the relationship between voltage and string immersion depth is considered linear over a substantial range.

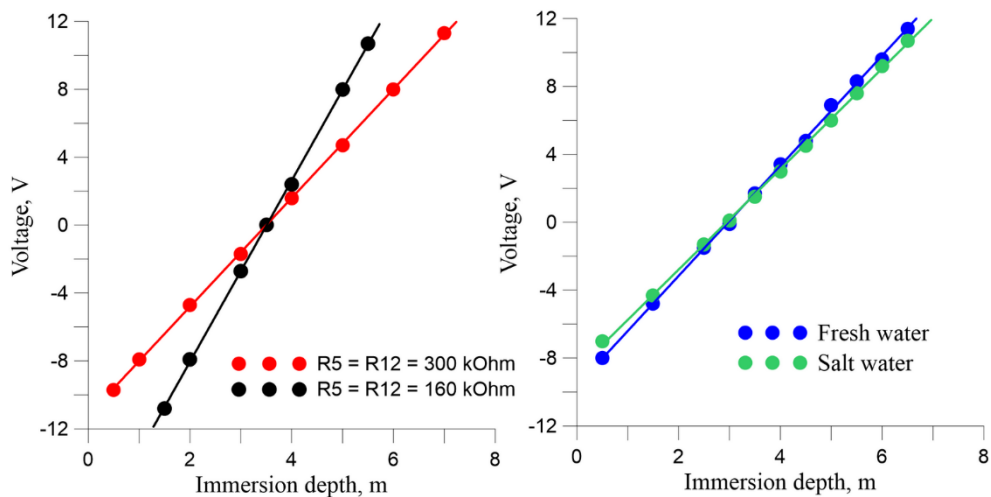


Fig. 3. Dependence of output signal upon the string immersion depth at different sensitivity (*left*), and for fresh and salt water (*right*)

For a string longer than two meters, a fishing line is employed to enhance structural strength. The control unit of the string wave gauge can be mounted at a height of several tens of meters above the water surface (on a bridge or oil platform). At the bottom, the loop is fitted onto a rubber bushing and attached to the fishing line, which is tensioned by a plumb line (weight of 2–3 kg). At the top, the loop is secured to a rubber bushing, connected to the fishing line via a rubber band, and tied to a Kevlar cable extending upward. The processing unit is mounted nearby, with power wires (12 V) and the wave gauge output signal (“WAVE GAUGE OUT”) from the PC-7 connector routed along the cable. The fishing line bears the primary tension in this configuration.

To simplify setup and enable measurements with the string positioned at a significant distance from the processing unit and recording device, a method was developed to ensure the wave gauge’s operability. The inclusion of a bridge in the processing circuit facilitates this solution. An extension cable is connected to the string, and an identical extension cable is connected to the compensating capacitance C9, effectively mitigating temperature-induced “drifts” and other minor factors. The string is linked to the input of the processing circuit via a short RK cable and an SR-50 connector, while the PC-7 connector (Fig. 2) supplies power (12 V) to the processing circuit and transmits the wave gauge signal from the output (“WAVE GAUGE OUT”). When using extensions, the PC-7 connector also facilitates signal transmission from the string via the “EXTENSION” input and connects the compensating second identical extension to capacitance C9 via the PC-7 “COMP. EXTENSION” input. The simplest extension cable is an unshielded Internet cable with two twisted pairs and a separate grounding wire. In recent

versions of the river wave gauge, for loop wires up to 2 m fixed on metal rods, ~ 3 m extensions with two twisted pairs are employed for convenience. The dynamic range relative to noise remained unchanged. In a laboratory simulation of operation from an oil platform, a 7 m string configured as a loop was connected to the processing and recording unit using 30 m extensions of an Internet cable with two twisted pairs. The capacitance of this string, immersed 3.5 m in salt water, was ~ 1200 pF, while the capacitance of the 30 m cable was 2400 pF.

The experiment confirmed that the dependence of the signal on immersion depth in salt water remained consistent after the MS wire string was submerged for 6 days. The influence of the loop width (the distance between the wires in the loop) on the received signal was also investigated. In fresh water, the signal showed no dependence on loop width. In salt water, when the loop width was reduced to 2 mm, the signal remained unchanged; however, at smaller widths, a delay of several seconds was observed when lifting the string, attributed to inertia caused by slow water runoff. No such inertia was observed during string immersion.

This delay is a limitation of the loop string configuration with wires positioned close together. In contrast, a single-string wave gauge exhibited no inertia but had lower sensitivity. Inertia in the loop can be eliminated by maintaining a sufficient gap between the wires, for example, by securing them to the outer or inner side of thermal rings placed every 50–30 cm along the string. However, the minimum measurable wave length must be at least 4 times the loop width.

Results of *in-situ* wave measurements using the wave gauge

Wave height measurements of less than 0.5 m were conducted on a river across several seasons. The string's sensitivity remained unchanged during prolonged immersion in water [11].

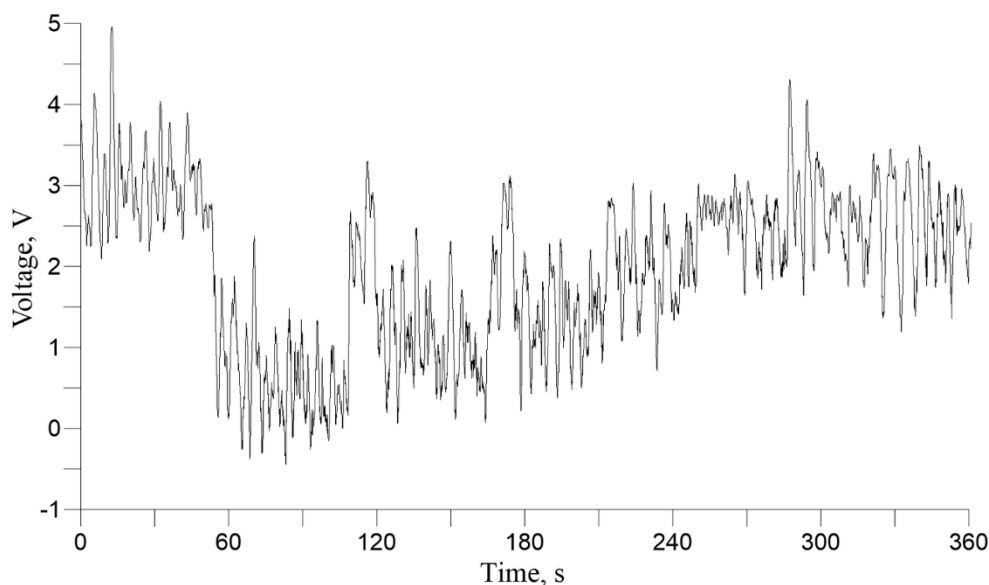


Fig. 4. Calibration of the wave gauge

At sea (Gelendzhik), a 2.5 m loop string made of MS wire with a cross-section of 0.08 mm², reinforced with a fishing line, was used to measure waves. Fig. 4 presents the wave gauge calibration record at sea. The wave gauge initially recorded waves at the 0 cm horizon, followed by measurements at heights of 40 cm, 30 cm, 20 cm and 10 cm above the zero horizon.

A calibration line was derived (Fig. 5), with data points representing the average voltage values for different immersion levels. The calibration line is described by the equation $h = 14.916U - 5.66$. This equation is used to convert measured voltage into wave height. The root-mean-square deviation of the calibration line from the experimental data points is 3.6 cm.

Fig. 6 represents a 20-minute (1200 s) realization of the calibrated wave gauge signal recorded on June 16, 2024, at the Gelendzhik test site.

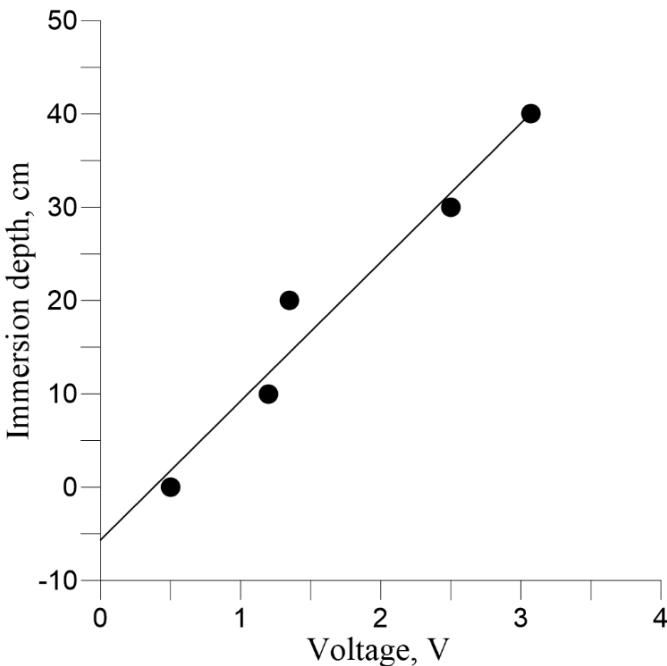


Fig. 5. Calibration line of the wave gauge

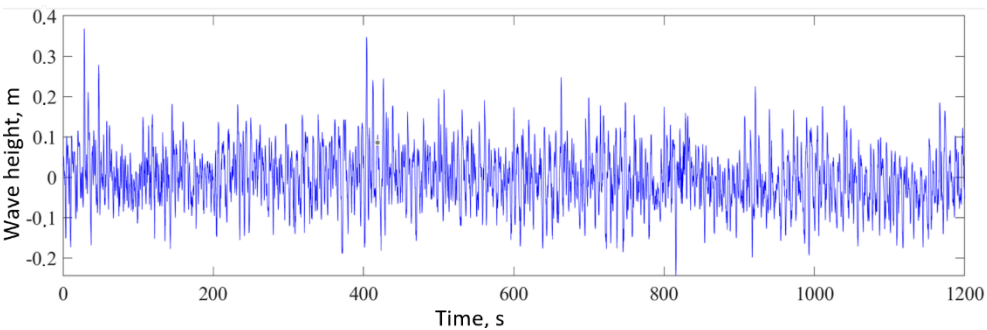


Fig. 6. Implementation of the calibrated signal of wave gauge

Fig. 7 illustrates the spectrum of the wave elevation realization (based on Fig. 6), obtained by averaging uncorrelated spectra from non-overlapping 60 s segments. The spectrum represents the power spectral density, defined as the squared modulus of the Fourier transform of wave elevations. A narrow peak at zero frequency, attributed to the mean component of the wave gauge signal, is removed by subtracting the average (Fig. 6).

The spectrum in Fig. 7 is narrowband, with a peak at 0.13 Hz and a broadening at the base toward higher frequencies, corresponding to shorter waves relative to the wavelength at the spectral peak. Using the dispersion relation $\omega^2 = gk$, the wavelength at the spectral peak is estimated to be ~ 87 m.

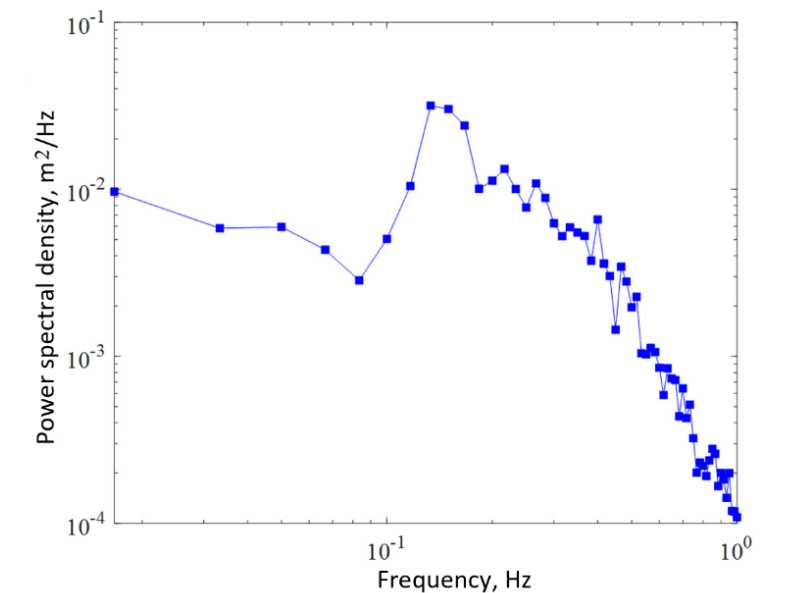


Fig. 7. Wave elevation spectrum obtained by averaging the uncorrelated spectra

Conclusions

The developed prototype of a string wave gauge with a shielded wire, designed for measuring waves in both fresh and salt water, exhibits a wide linear dynamic range, capable of measuring wavelengths from millimeters to several meters. The linearity of the dynamic range was verified for strings up to 7 m in length.

The main advantage of the shielded wire string wave gauge is its resistance to salt deposition and short circuits caused by small conductive debris, ensuring consistent sensitivity during prolonged immersion in water.

The incorporation of a capacitive bridge in the processing unit enables the string to be positioned remotely from the signal processing and recording unit, for example, using a 30 m Internet cable, with an identical cable employed as a compensating capacitance in the other arm of the bridge. This configuration allows the processing and recording units to be placed far from the water, such as on an oil platform.

A method to eliminate mutual interference between strings using synchronous detection is proposed, facilitating the development of autonomous grids for recording two-dimensional wave spectra. The use of MS wire with solid fluoroplastic insulation enables liquid level measurements in aggressive media.

REFERENCES

1. Zuykova, E.M., Luchinin, A.G. and Titov, V.I., 1985. [Determination of the Characteristics of Spatio-Temporal Wave Spectra from Optical Images of the Sea Surface]. *Proceedings of the USSR Academy of Sciences. Atmospheric and Oceanic Physics*, 21(10), pp. 1095-1102 (in Russian).
2. Molkov, A.A. and Dolin, L.S., 2012. Determination of Wind Roughness Characteristics Based on an Underwater Image of the Sea Surface. *Izvestiya, Atmospheric and Oceanic Physics*, 48(5), pp. 552-564. <https://doi.org/10.1134/S0001433812050088>
3. Salin, B.M. and Salin, M.B., 2015. Combined Method for Measuring 3D Wave Spectra. I. Algorithms to Transform the Optical-Brightness Field into the Wave-Height Distribution. *Radiophysics and Quantum Electronics*, 58(2), pp. 114-123. <https://doi.org/10.1007/s11141-015-9586-1>
4. Smolov, V.E. and Rozvadovskiy, A.F., 2020. Application of the Arduino Platform for Recording Wind Waves. *Physical Oceanography*, 27(4), pp. 430-441. <https://doi.org/10.22449/1573-160X-2020-4-430-441>
5. Sterlyadkin, V.V., Kulikovskii, K.V. and Badulin, S.I., 2024. Field Measurements of Sea Surface Shape and One-Dimensional Spatial Wave Spectrum. *Sovremennye Problemy Distantionnogo Zondirovaniya Zemli iz Kosmosa*, 21(1), pp. 270-285. <https://doi.org/10.21046/2070-7401-2024-21-1-270-285> (in Russian).
6. Panfilova, M., Ryabkova, M., Karaev, V. and Skiba, E., 2020. Retrieval of the Statistical Characteristics of Wind Waves from the Width and Shift of the Doppler Spectrum of the Backscattered Microwave Signal at Low Incidence Angles. *IEEE Transactions on Geoscience and Remote Sensing*, 58(3), pp. 2225-2231. <https://doi.org/10.1109/TGRS.2019.2955546>
7. Dulov, V.A., Yurovskaya, M.V., Fomin, V.V., Shokurov, M.V., Yurovsky, Yu.Yu., Barabanov, V.S. and Garmashov, A.V., 2024. Extreme Black Sea Storm in November, 2023. *Physical Oceanography*, 31(2), pp. 295-316.
8. Titov, V.I. and Antonov, A.A., 2024. Reconstruction of Sea Surface Relief and Sea Wave Spectra Using a Sea Surface Image. *Cosmic Research*, 62(S1), pp. S150-S156. <https://doi.org/10.1134/S0010952524601270>
9. Sarmiento, J., Iturrioz, A., Ayllón, V., Guanche, R. and Losada, I.J., 2019. Experimental Modelling of a Multi-Use Floating Platform for Wave and Wind Energy Harvesting. *Ocean Engineering*, 173, pp. 761-773. <https://doi.org/10.1016/j.oceaneng.2018.12.046>
10. Kim, H., Jeon, C., Kim, K. and Seo, J., 2023. Uncertainty Assessment of Wave Elevation Field Measurement Using a Depth Camera. *Journal of Marine Science and Engineering*, 11(3), 657. <https://doi.org/10.3390/jmse11030657>
11. Ryabkova, M.S., Karaev, V.Yu., Titchenko, Yu.A., Meshkov, E.M., Zuikova, E.M., Kovaldov, D.A., Ponur, K.A. and Baydakov, G.A., 2022. [Measurements of the Wave Spectrum on a River Using a String Wave Graph and an Acoustic Wave Graph]. In: IKI RAS, 2022. *Proceedings of the 20th International Conference "Current Problems of Remote Sensing of the Earth from Space"*. Moscow: IKI RAS, p. 209. <https://doi.org/10.21046/20DZZconf-2022a> (in Russian).

Submitted 28.03.2025; approved after review 10.04.2025;
accepted for publication 11.07.2025.

About the authors:

Emma M. Zuikova, Leading Electronics Engineer, Department of Radiophysical Methods in Hydrophysics, A.V. Gaponov-Grekhov Institute of Applied Physics, Russian Academy of Sciences (46 Ul'yanova Str., Nizhny Novgorod, 603950, Russian Federation), **ORCID ID: 0000-0003-0343-8879**, zuikova@ipfran.ru

Yuri A. Titchenko, Deputy Head of Department of Radiophysical Methods in Hydrophysics, A.V. Gaponov-Grekhov Institute of Applied Physics, Russian Academy of Sciences (46 Ul'yanova Str., Nizhny Novgorod, 603950, Russian Federation), CSc. (Phys.-Math.), **ORCID ID: 0000-0001-7762-7731**, yuriy@ipfran.ru

Dmitry A. Kovaldov, Research Intern, Laboratory for Modeling of Plasma Geophysical and Astrophysical Phenomena, Department of Geophysical Electrodynamics, A. V. Gaponov-Grekhov Institute of Applied Physics, Russian Academy of Sciences (46 Ul'yanova Str., Nizhny Novgorod, 603950, Russian Federation), **ORCID ID: 0000-0002-9535-4949**, d.kovaldov@ipfran.ru

Vladimir Yu. Karaev, Head of Laboratory for Analysis and Modeling of Satellite Data, Department of Radiophysical Methods in Hydrophysics, A.V. Gaponov-Grekhov Institute of Applied Physics, Russian Academy of Sciences (46 Ul'yanova Str., Nizhny Novgorod, 603950, Russian Federation), CSc. (Phys.-Math.), **ORCID ID: 0000-0002-4054-4905**, volody@ipfran.ru

Viktor I. Titov, Senior Research Associate, Department of Radiophysical Methods in Hydrophysics, A.V. Gaponov-Grekhov Institute of Applied Physics, Russian Academy of Sciences (46 Ul'yanova Str., Nizhny Novgorod, 603950, Russian Federation), CSc (Phys.-Math.), **ORCID ID: 0000-0001-9483-8231**, titov@ipfran.ru

Contribution of the co-authors:

Emma M. Zuikova – prototype concept development; circuit design; final assembly and testing of prototype characteristics

Yuri A. Titchenko – participation in field experiments; preparation of illustrative materials; critical analysis and revision of the text

Dmitry A. Kovaldov – conducting field experiments; participation in results analysis; preparation of illustrative materials

Vladimir Yu. Karaev – participation in prototype concept development; analysis of laboratory tests and field measurements

Viktor I. Titov – development of article concept and structure; selection of illustrative materials; analysis and synthesis of results

The authors have read and approved the final manuscript.

The authors declare that they have no conflict of interest.