

Original paper

Wave Buoy Logger for Coastal Studies

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Abstract

The paper presents prototype wave buoy loggers designed to collect raw data from a built-in inertial motion unit without transmitting the data to the user. These buoys require maintenance but have a significantly simpler design and much lower cost compared to unattended analogs, making them particularly useful for various coastal studies. The study aims to demonstrate that measuring wave parameters in field conditions with acceptable accuracy is achievable without loss of data quality. The buoys were tested in a field experiment at the Black Sea Hydrophysical Sub-Satellite Polygon of Marine Hydrophysical Institute, Russian Academy of Sciences. Reference measurements were obtained using wire wave gauges installed on the Stationary Oceanographic Platform (44.393047°N, 33.984596°E). Three identical buoys were deployed near the platform using different mooring configurations: a heavy anchor with an elastic insert (rubber cord), a heavy anchor without an elastic insert, and a buoy suspended directly from the platform without an anchor. Continuous measurements were conducted over seven days, during which significant wave height varied from 0.2 to 1 m, and wind speeds ranged from 0 to 15 m/s, coming from east-erly, westerly, and northerly directions. Under these conditions, the root-mean-square error in estimating significant wave height was no more than 5–6 cm (both with and without the rubber cord), with the linear regression coefficient deviating from 1 by less than 5%. The root-mean-square errors for the spectral peak wave period and direction were 0.37–0.62 s and 50–65°, respectively. These errors are comparable to the resolution of the applied methods and the natural statistical variability of wave parameter estimates.

Keywords: buoy, wave gauge, inertial measurements, wind waves, wave parameters, oceanographic platform, field experiment

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Волноизмерительный буй-логгер для прибрежных исследований

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Аннотация

Представлены прототипы волноизмерительных буй-логгеров, предназначенных для сбора исходных данных со встроенных в них инерциальных датчиков, без передачи их на берег. Буи такого типа нуждаются в обслуживании, но имеют существенно более простую конструкцию и низкую стоимость по сравнению с необслуживаемыми аналогами, что может быть востребовано в различных прибрежных исследованиях. Цель работы – продемонстрировать в натурных условиях, что предлагаемый тип буйев может эффективно использоваться для измерения характеристик волнения без потери качества данных. Испытания буйев проведены в натурном эксперименте на Черноморском гидрофизическом подспутниковом полигоне Морского гидрофизического института РАН. В качестве референтной информации о волнах использованы данные измерений струнными волнографами, установленными на стационарной океанографической платформе (44.393047° с. ш., 33.984596° в. д.). Три одинаковых буя были установлены вблизи платформы с использованием разных вариантов удерживающего устройства: на массивном якоре с эластичной вставкой (амортизатором) и без нее, а также без якоря на подвесе с платформы. Непрерывные измерения велись в течение 7 сут, в течение которых высота значительных волн менялась от 0.2 до 1 м, скорость ветра от 0 до 15 м/с при его восточном, западном, северном направлениях. В этих условиях среднеквадратичная ошибка оценки высоты значительных волн составила не более 5–6 см (с амортизатором и без него) при отклонении коэффициента линейной регрессии от единицы не более чем на 5 %. Среднеквадратичные ошибки периода и направления волн спектрального пика составили 0.37–0.62 с и 50–65° соответственно при измерении буйем с амортизатором и без него. Такие ошибки измерений сопоставимы с разрешающей способностью используемых методов и естественным статистическим разбросом средних оценок параметров волн.

Ключевые слова: буй, волнограф, инерциальные измерения, ветровые волны, параметры волн, океанографическая платформа, натурный эксперимент

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Introduction

In marine research, episodic short-term observations of surface waves are often required for targeted experiments. This is particularly true in coastal research, such as when studying wave nonlinearity in the coastal zone [1, 2], wave interaction with currents [3], the formation of bottom sediments [4–6], beach and coastline dynamics [7, 8], and other phenomena [9–12]. In such conditions, traditional wave buoys,

designed for continuous monitoring of waves at any point in the ocean, are not always feasible due to their relatively high cost. For short-term coastal studies, many of their features are redundant, including autonomous power supplies, large memory capacity, multi-channel communication systems, and massive high-strength hulls. Additionally, specialized experiments often require up to several dozen such buoys to enable simultaneous measurements across a section or grid.

In this context, it is practical to develop a simple wave measuring device that records only the measurements from a sensor sensitive to wave motion, such as a buoy logger. The increasing use of small, low-cost microelectromechanical inertial motion units (IMUs) in wave-measuring devices also supports this solution [11, 13–16].

The paper presents the results of field trials of a prototype device developed at Marine Hydrophysical Institute (MHI). The experiment involved three identical buoy samples configured differently. It is known that the retaining device can influence wave measurements by buoy sensors^{1), 2)} [2]. Thus, to extend the service life of the system and mitigate jolts when the hull interacts with steep waves, an elastic element, typically a section of rubber cord several meters long with maximum elasticity, is included in the anchoring device [17]. To demonstrate the effect of the retaining line clearly, three mooring options were tested: a standard anchor cable without an elastic insert, a cable with a highly elastic insert (within limits ensuring retention during the experiment), and a methodological option – a bifilar suspension without an anchor from the oceanographic platform.

The aim of this study is to demonstrate in real-life conditions that buoy loggers built using readily available components can perform short-term measurements of wave characteristics with acceptable quality.

Materials and methods

Equipment

The buoy is based on the MPU9250 inertial motion unit (IMU), which integrates a microelectromechanical accelerometer, gyroscope, and magnetometer. As previously demonstrated [14, 18], such IMUs, despite their relatively low cost, are suitable for measuring sea wave characteristics. The buoy records initial measurements of three-axis acceleration, angular velocities, magnetic field, and IMU temperature at a sampling frequency of 25 Hz. These data are stored on a memory card with a capacity of up to 32 GB using an Atmega328p microcontroller synchronized with universal time via a DS3231-based real-time clock.

¹⁾ Earle, M.D., 1996. *Nondirectional and Directional Wave Data Analysis Procedures*. NDBC technical document 96-01. Stennis Space Center, 43 p.

²⁾ Gryazin, D.G., 2000. [*Calculation and Design of Buoys for Measuring Sea Waves*]. Saint Petersburg: SpbGITMO (TU), 134 p. (in Russian).

The circuit is housed in a sealed plastic cylindrical hull, mounted on a printed circuit board rigidly fixed in the hull's axial plane. The IMU is positioned within 1.5 mm of the hull's axis (the board's thickness) and is vertically offset to align its center as closely as possible with the point of the hull's resonant oscillations. The hull is equipped with a lenticular float, a 40 cm diameter disc with chamfers, made of 100 mm thick expanded polystyrene. A stainless-steel eyelet is attached to the hull's base, connecting to a ballast (for adjusting the hull's draft) and a retaining cable via a swivel.

Power is supplied by six 18650 lithium-ion batteries with a total capacity of approximately 48 W·h, positioned at the base of the hull on both sides of the board.

For additional verification of measurement quality, a second IMU (a BNO055) was mounted on the back of the board. The axes of both motion units were aligned as closely as possible (within 180° rotation accuracy), and the distance between their centers was no more than 4 mm.

Experiment

The experiment was conducted in October 2024 at the Black Sea Hydrophysical Sub-Satellite Polygon near the Stationary Oceanographic Platform (Fig. 1). Bathymetry data were sourced from <https://www.ncei.noaa.gov/products/etopo-global-relief-model>.

Buoy 1 was deployed approximately 200 m from the platform at a location with a sea depth of about 27 m. A massive stone weight with a dry mass of approximately 70 kg served as an anchor. The buoy was connected to the weight using an eight-strand nylon cord with a core diameter of 8 mm.

Buoy 2 was deployed at the same depth, but approximately 50 m closer to the platform. Unlike the first buoy, it was connected to the anchor cable via a 7 m long, 6 mm diameter nylon-braided rubber cord (hereinafter referred to as the rubber cord). The parameters of this rubber cord were chosen to prevent breakage during the experiment while ensuring maximum elasticity of the connection.

Buoy 3 was positioned between two platform supports on a bifilar suspension made of nylon cord, approximately 8 m from the pile foundation. This setup was designed to evaluate the feasibility of conducting methodological work from the platform without the need for more costly anchor-based deployments.

Buoys 1 and 2 were deployed for approximately 7 days, while Buoy 3 was deployed only on the final day of measurements.

Parallel measurements of wave parameters were conducted from the platform using wire-resistive wave gauges, which recorded sea surface levels with an accuracy of ± 1 cm at frequencies up to 5 Hz [19, 20]. These measurement data serve as reference data in this study. Additionally, auxiliary meteorological observations were conducted using standard hydrometeorological instruments. Specifically, wind speed and direction at a height of 21 m were measured using a cup anemometer and wind vane.

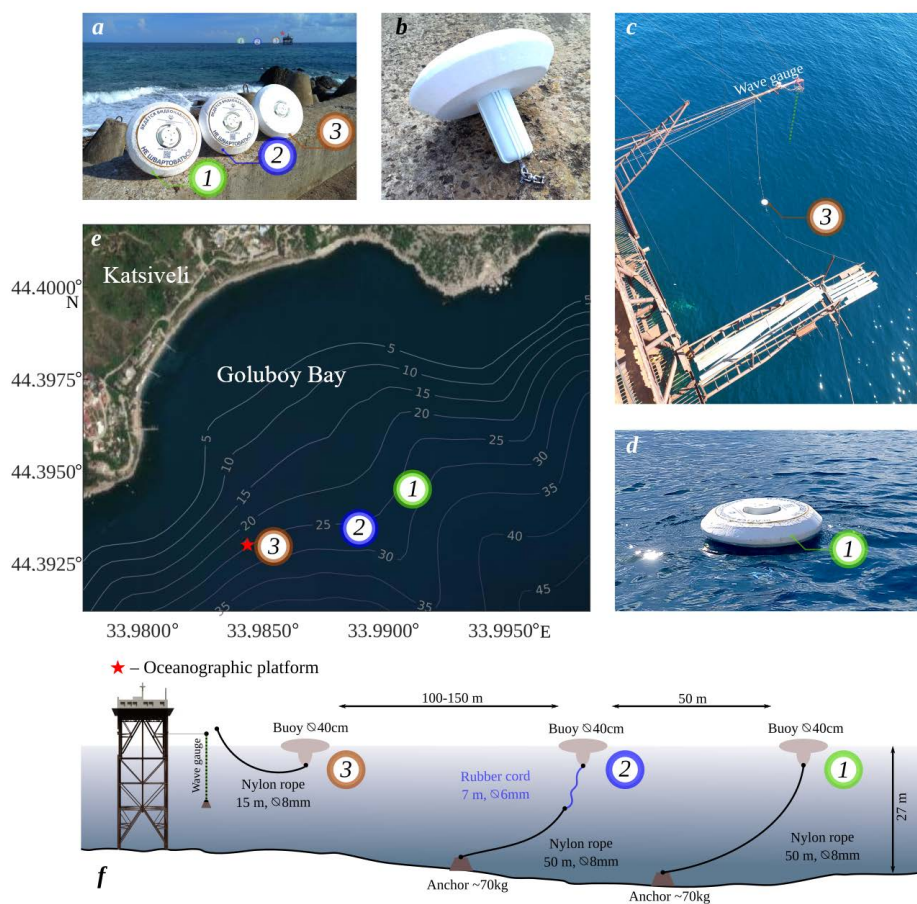


Fig. 1. Field experiment setup: *a, b* – buoy exterior design; *c* – deployment of Buoy 3 from the platform; *d* – deployment of Buoy 1 with anchor; *e* – satellite image of the study site with bathymetry overlay (URL: <https://www.arcgis.com/apps/View/index.html?appid=504e3ff67457481e839bb941a709350f>); *f* – schematic depth profile illustrating buoy deployment configurations

Data processing methodology

In this study, the raw data from the buoys consist of time series of three-axis acceleration, angular velocity, and magnetic field, while wire-resistive wave gauges provide synchronous measurements of sea surface elevations at six points (the center and vertices of a pentagon with a 25 cm radius). To estimate wave characteristics, we applied a well-established method described in [21], which derives the frequency-angle spectrum as a truncated Fourier series based on measurements of vertical displacements and inclinations in two orthogonal planes:

$$S(f, \theta) = a_0 + \sum a_n \cos(n\theta) + b_n \sin(n\theta), \quad (1)$$

where f is the frequency and θ is the wave direction (defined as the direction from which the waves propagate relative to the north).

For measurements with wire-resistive wave gauges, instantaneous slopes ζ and elevations z were estimated by fitting a plane (using the least squares method) based on six elevation measurements at points with known horizontal coordinates. The coefficients for formula (1) in this case are as follows:

$$\begin{aligned} a_0 &= C_{11}/\pi, \quad a_1 = Q_{12}/k\pi, \quad b_1 = Q_{13}/k\pi, \\ a_2 &= (C_{11} - C_{22})/k^2\pi, \quad b_2 = 2C_{23}/k^2\pi, \end{aligned} \quad (2)$$

where C_{mn} and Q_{mn} are the real and imaginary parts of the spectrum estimate $S_{mn} = C_{mn} + iQ_{mn}$. The subscripts denote the parameters for which the spectrum is calculated: 1 for elevations; 2 for slopes ζ_x in the east-west direction; 3 for slopes ζ_y in the north-south direction. The wave number is calculated using the dispersion relation $k = (2\pi f)^2/g$, where g is the acceleration due to gravity.

For buoy measurements, vertical accelerations were used in place of elevations, assuming the buoy closely follows the wave slopes. In this case, equations (2) take the form:

$$\begin{aligned} a_0 &= C_{11}/\pi (2\pi f)^4, \quad a_1 = Q_{12}/k\pi (2\pi f)^2, \quad b_1 = Q_{13}/k\pi (2\pi f)^2, \\ a_2 &= (C_{22} - C_{33})/k^2\pi, \quad b_2 = 2C_{23}/k^2\pi, \end{aligned}$$

where subscript 1 denotes vertical acceleration. The slopes were calculated similarly to [14] from the measured angular velocities η taking into account the current orientation of the buoy relative to true north:

$$\eta_x = -(\eta_{0x}\sin(\phi) + \eta_{0y}\cos(\phi)), \quad \eta_y = -(\eta_{0x}\cos(\phi) - \eta_{0y}\sin(\phi)),$$

where η_{0x}, η_{0y} are the angular velocities measured by the gyroscope, and the azimuth angle ϕ , corrected for the local magnetic declination (7.3°) at the experiment site, was determined from the horizontal components of the measured magnetic field: $\phi = \text{Arg}(m_x + im_y)$. Unknown offsets in the magnetic field measurements, arising from the magnetization of buoy components, were determined using the condition that the absolute value of the geomagnetic field intensity vector M is constant:

$$(m_{ix} - m_{0x})^2 + (m_{iy} - m_{0y})^2 + (m_{iz} - m_{0z})^2 = M^2,$$

where m_{ix}, m_{iy}, m_{iz} are the magnetometer measurements at time i .

Based on the calculated one-dimensional elevation spectrum $S(f) = \pi a_0$, the significant wave height was estimated as:

$$H_s = 4\sqrt{\int S(f)df},$$

where the lower integration limit f_1 was determined by the first local minimum in the elevation spectrum to avoid low-frequency noise inherent in measurements

with buoy IMUs [22] (this issue does not apply to measurements with wire-resistive wave gauges).

The spectral peak frequency f_p and its corresponding period T_p were determined based on the maximum of the elevation spectrum, provided that $f > f_1$.

The mean wave direction θ_p at the spectral peak, according to [21], is given by: $\theta_p = \text{Arg}(a_1 + i b_1)$.

The recordings were divided into one-minute sequential fragments, from which the squared Fourier transforms were calculated and then averaged over 30-minute intervals to obtain the spectrum estimate (equation (1)).

Results

The frequency spectra of elevations, derived from wave gauge and Buoy 1 and Buoy 2 measurements, are shown in Fig. 2 as a function of time for the entire measurement period (results for Buoy 3, deployed for a significantly shorter period, are omitted for brevity). Wind speed during this period (Fig. 2, *a*) varied from 0 to 15 m/s, with directions from the east, west, and north. Thus, during the week-long experiment, measurements were conducted under the most typical conditions for this water area.

As shown in Fig. 2, *b*, which presents the reference spectra, various conditions were observed: fading waves and swells (October 3), developing wind waves (October 7 and 9), and several spectral peaks (October 4, 8, and 9). These features are also evident in the spectra derived from Buoy 1 and Buoy 2 measurements. However, these spectra differ from the reference spectra, with an underestimated high-frequency component $f > 1.5$ Hz and an overestimated low-frequency component $f < f_p$. The first effect arises due to the weak response of the hull to waves shorter than its characteristic size [23]. This effect has minimal impact on significant wave height estimates because the elevation spectrum decays rapidly with frequency f^{-4} . The second effect can introduce significant errors in wave height estimates, as demonstrated in [22]. To address this, the estimate H_s in this study is calculated starting from the frequency f_1 , defined as the first local minimum in the elevation spectrum. This approach is equivalent to high-frequency filtering, commonly applied to raw measurement data from buoys¹⁾. However, for measurements with wire-resistive wave gauges, such filtering is unnecessary, as the spectral density at low frequencies (below the peak) is several orders of magnitude lower than in the spectral maximum region.

The time series of significant wave heights calculated using this method are shown in Fig. 3, *b*. Notably, despite the absence of additional calibration, the results demonstrate strong agreement between the wave gauge measurements and all three buoy configurations across all setup types.

The differences between the measurement data from the BNO055 motion unit and MPU9250 in this figure are within the thickness of the graph line and are therefore not shown. Thus, the consistency of results across six samples of two different motion unit models indicates that the factory calibration of these IMUs provides the specified accuracy (typically within a few percent).

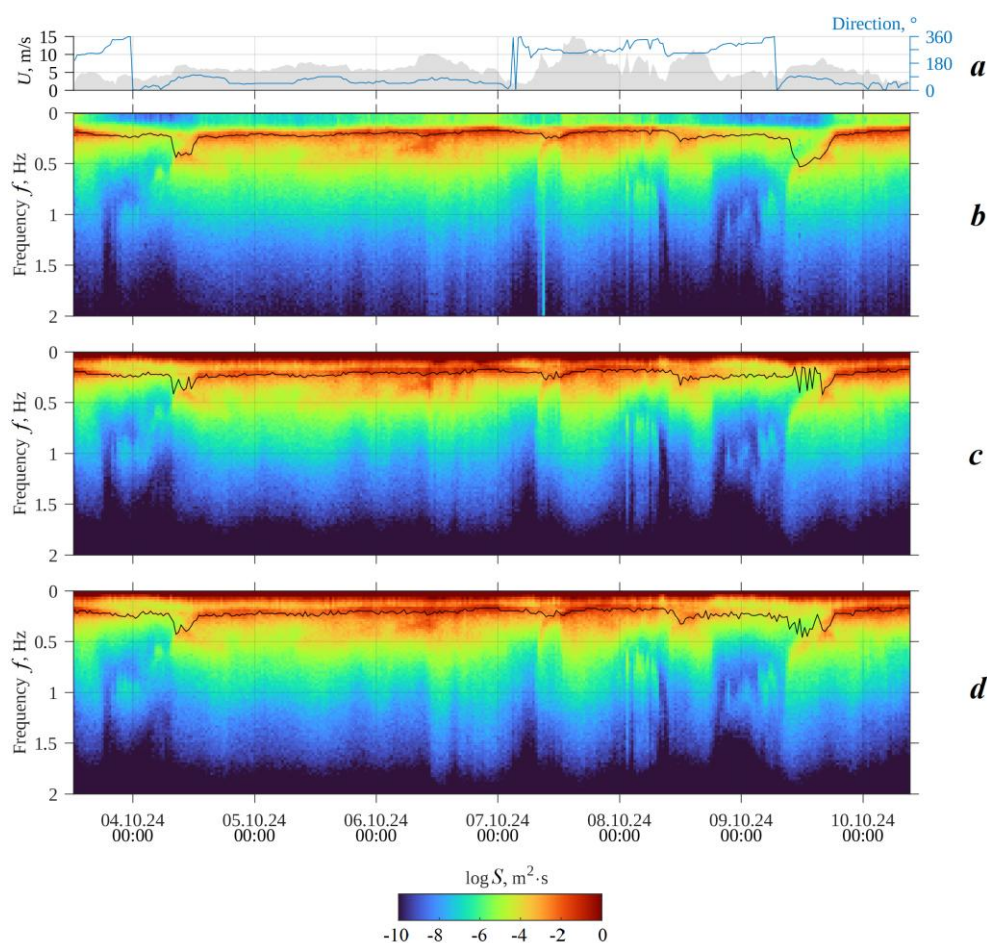


Fig. 2. Wind speed and direction (*a*) during the experiment, frequency spectrum evolution from measurements of (*b*) wave gauge, (*c*) Buoy 1 without rubber cord, (*d*) Buoy 2 with rubber cord

Notably, more significant differences arise from the presence of an elastic rubber cord in the retaining device, as evident for October 6 and 7. The differences between the measured and reference wave heights in these two cases have opposite signs. This is likely due to the complex current patterns observed during the experiment, with strong currents often opposing the wind and waves. However, the influence of currents requires separate study and is beyond the scope of this work.

Analysis of the calculated spectral peak wave periods (Fig. 3, *c*) shows strong agreement between observations and reference values. However, in cases of young waves superimposed on swell (October 4 and 9), discrepancies were observed when spectral peaks of similar amplitude at different frequencies produced an effect resembling chattering. Notably, when a rubber cord was used (Buoy 2, orange line), this effect was significantly reduced.



Fig. 3. Wind speed and direction (*a*) during the experiment, time series of wave parameters estimated from measurements of wave gauge (black) and Buoys 1 (blue), 2 (orange), 3 (green): *b* – significant wave height; *c* – spectral peak wave period; *d* – spectral peak wave direction

The greatest discrepancies with reference measurements are observed in the estimates of spectral peak wave directions (Fig. 3, *d*). Although mean values are determined with high accuracy, short-term spikes occur, primarily during weak winds (between October 3 and 4, and after October 8). Notably, similar features, though less pronounced, are also present in reference measurements from wire wave gauges, due to the specifics of the directional spectrum calculation algorithm, which is restricted to the first five terms of the Fourier series (equation (1)). The use of a rubber cord improves the accuracy of direction estimates (e.g., see Fig. 3, *d*, blue curve after October 8). The non-standard bifilar suspension from the platform exhibited unexpectedly small deviations from the reference values.

Scatterplots for the three wave parameters discussed, H_s , T_p and θ_p , are shown in Fig. 4, along with statistical metrics. For Buoys 1 and 2, which provide the most

data, high correlation coefficients for significant wave heights are observed, exceeding 0.93, with a linear regression coefficient deviation from unity of no more than 5%. The root-mean-square error of measurements was ~ 6 cm for setups with a rubber cord and 5 cm for those without. Notably, measurements were taken at spatially separated points, so a significant portion of this error is attributed to the statistical variability of H_s , which is typically 10–15%¹⁾.

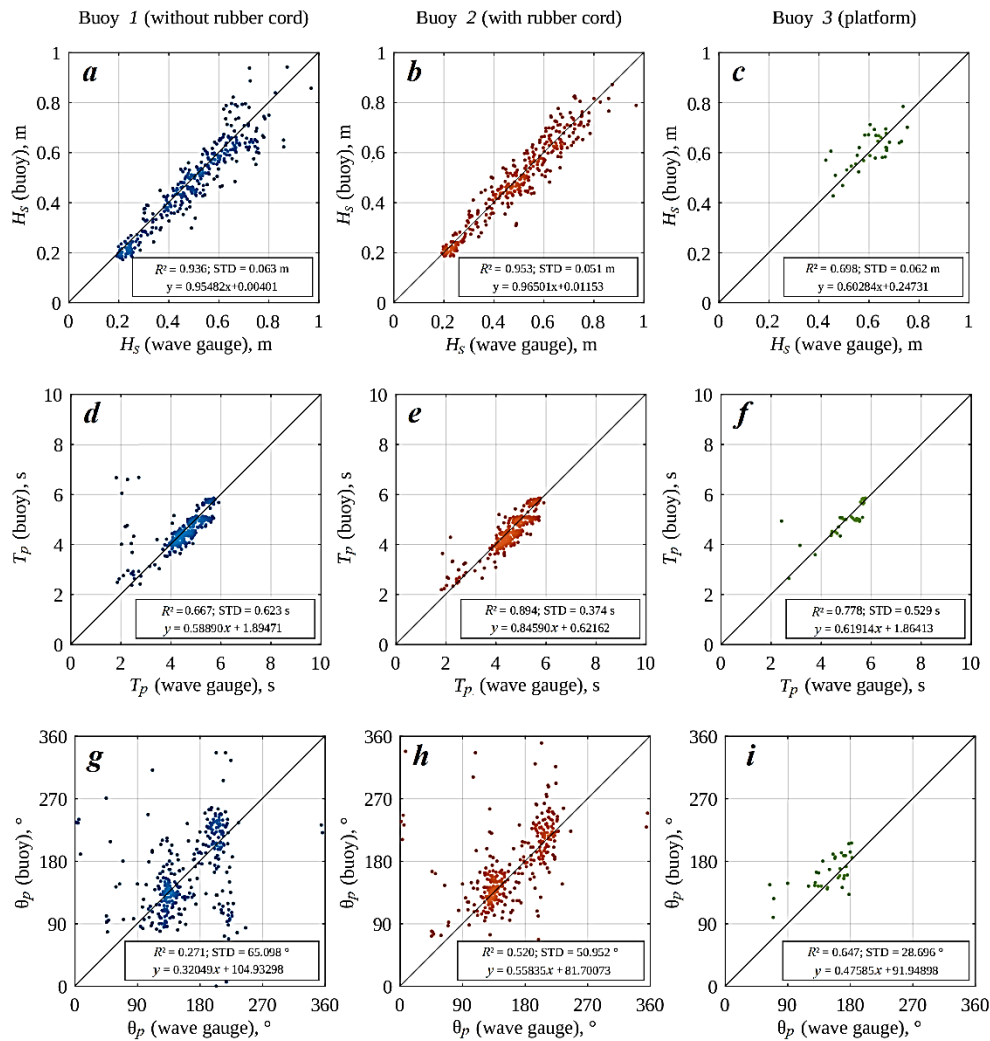


Fig. 4. Wave parameters: significant wave height (a, b, c), spectral peak wave period (d, e, f), spectral peak wave direction (g, h, i) obtained by Buoy 1 (without rubber cord) (a, d, g), Buoy 2 (with rubber cord) (b, e, h), Buoy 3 (platform deployment) (c, f, i) compared with reference wave gauge measurements

The consistency between the estimated and reference values of the spectral peak wave period T_p is lower, as discussed previously, due to the chattering effect described above. Meanwhile, when obvious outliers are excluded, the correlation coefficient reaches values comparable to those for significant wave height estimates.

The largest discrepancies with reference measurements are observed for wave directions of 50–65° (Fig. 4, *g, h, i*), consistent with the analysis of the time series (Fig. 3, *d*). However, this deviation is comparable to the resolution of the method used (approximately 90°)¹⁾ [21].

The use of an elastic rubber cord improves the accuracy of estimates in all cases compared to reference values, though the improvement is modest, despite deliberately selecting the most elastic (but least reliable) rubber cord.

Conclusion

This study presents the results of field tests of wave-measuring buoy loggers developed at Marine Hydrophysical Institute, designed with maximal simplicity to record initial measurement data on a memory card.

The experiment was conducted near the MHI Stationary Oceanographic Platform. Three buoys with identical IMUs were tested in three different configurations: without an elastic rubber cord, with an elastic rubber cord, and with a bifilar suspension from the platform. Comparison with reference measurements from wire-resistive wave gauges showed strong agreement across all estimates for the three setups. For example, in the observed range of significant wave heights (0.2–1 m), the root-mean-square error of height measurements was no more than 5 cm for the setup with an elastic rubber cord and no more than 6 cm without it. Corresponding values for spectral peak wave periods were 0.37 s and 0.62 s, and for spectral peak wave directions were 50° and 65°. Therefore, when there is a high risk of buoy loss, the elastic rubber cord can be omitted from the retaining device at the cost of a slight reduction in data accuracy.

A key limitation of the measuring devices presented in this study is the need for maintenance, including data retrieval and battery replacement. However, this measurement approach may be suitable for various coastal tasks or specialized experiments that do not require long-term deployments.

The advantages of this approach include its extremely low cost, which is 2 to 3 orders of magnitude lower than that of traditional unattended models. This enables extensive field studies of waves across sections or grids, where multiple identical devices are needed. Additionally, a significant advantage, in our view, is that researchers have access to raw data directly from the IMU without preprocessing. This enhances the transparency and flexibility of further analysis and allows the processing algorithm to be adapted based on specific research objectives.

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Oleg B. Kudinov – development and production of the measuring devices, conducting field trials

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