Original article

Prospects for Radar Monitoring of Wind Speed, Wind Wave Spectra and Velocity of Currents from an Oceanographic Platform

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Abstract
The article aims to present the prospects of radar monitoring of the marine environment from an oceanographic platform located near the village of Katsiveli on the South coast of Crimea at the Black Sea hydrophysical sub-satellite test site of the Marine Hydrophysical Institute of the Russian Academy of Sciences. Operation of the radar station from the platform in Katsiveli would allow continuous round-view mode recording of the wind speed fields, wind wave spectra, and a current velocity vector in the water area of a 1 km radius with a resolution of up to 100 meters. The paper describes approaches and problems in estimating wind speed fields, wind wave spectra, and current velocity vectors using a navigation radar. It is shown that the already known methods developed in satellite and ship radar are suitable for the reconstruction of the mentioned fields from the radar signal if we use the results of wind wave-breaking studies carried out from the Katsiveli platform. The approaches were tested in autumn 2022 from the Katsiveli platform using radar stations MRS-1011 (X-band, electromagnetic wavelength 3 cm) and MRS-3000 (Ka-band, electromagnetic wavelength 8 mm). Both stations have power and Doppler channels, horizontal polarizations of emission and reception, and perform all-around scanning of the water area at grazing angles to the sea surface not exceeding 10°. The specialized experiment included the radar operation simultaneously with the standard equipment of the platform, and data processing was based on the described recovery algorithms. As a result of the experiment, it is shown that the recovered frequency spectra of wind waves agree with the spectra measured with a conventional string wave recorder, the recovered spatial fields of wind and currents meet the traditional concepts, and the field of currents agrees qualitatively with the Doppler channel data. The data obtained with radar stations demonstrate the possibility of recovery of wind speed fields, vectors of the velocity of currents, and wave frequency spectra in a water area with a radius of about 1 km with a spatial resolution of tens of meters. Radar monitoring from the Katsiveli platform provides a technical base for studies of air-sea interactions and wave-current interactions and for the development and validation of satellite technologies and regional models of the marine environment.

Keywords: radar, sea surface, normalized radar cross-section, Doppler spectrum, scatterometry, wave spectra, current velocity, in situ measurements, monitoring, oceanographic platform

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Перспективы радиолокационного мониторинга скорости ветра, спектров ветровых волн и скорости течения с океанографической платформы

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Аннотация
Цель статьи – представить перспективы радиолокационного мониторинга морской среды с океанографической платформы, расположенной вблизи поселка Кацивели на Южном берегу Крыма на Черноморском гидрофизическом подспутниковом полигоне Морского гидрофизического института РАН. Работа радиолокационной станции с платформы в Кацивели позволила бы регистрировать в непрерывном режиме кругового обзора поля скорости ветра, спектров ветровых волн и вектора скорости течения в акватории радиуса 1 км с разрешением до 100 м. Описаны подходы и проблемы при оценке полей скорости ветра, спектров ветровых волн и вектора скорости течения с помощью навигационного радара. Показано, что для восстановления перечисленных полей по сигналу радара пригодны уже известные методы, развитые в спутниковой и корабельной радиолокации, если воспользоваться результатами исследований обрушений ветровых волн, проведенных с платформы в Кацивели. Апробация подходов выполнена осенью 2022 г. с платформы в Кацивели на основе радиолокационных станций *MRS*-1011 (*X*-диапазон, длина электромагнитной волны 3 см) и *MRS*-3000 (*Ka*-диапазон, длина электромагнитной волны 8 мм). Обе станции имеют мощностные и доплеровские каналы, горизонтальные поляризации излучения и приема и осуществляют круговой обзор акватории под скользящими углами к морской поверхности, не превышающими 10°. Специализированный эксперимент включал работу радара одновременно со штатным оборудованием платформы, а обработка данных основывалась на описанных алгоритмах восстановления. В результате эксперимента показано, что восстановленные частотные спектры ветровых волн согласуются со спектрами, измеренными традиционным струнным волнографом, восстановленные пространственные поля ветра и течений отвечают традиционным представлениям, причем поле течений согласуется на качественном уровне с данными доплеровского канала. Данные, полученные с помощью радиолокационных станций, демонстрируют возможности восстановления полей скорости ветра, векторов скорости течения и частотных спектров волнения в акватории

радиусом около километра с пространственным разрешением в десятки метров. Радиолокационный мониторинг с платформы в Кацивели предоставляет техническую базу для исследований взаимодействия океана и атмосферы, взаимодействия ветровых волн и течений, для отработки и валидации спутниковых технологий и региональных моделей морской среды.

Ключевые слова: радиолокатор, морская поверхность, удельная эффективная площадь рассеяния, доплеровский спектр, скаттерометрия, спектры волн, скорость течения, натурные измерения, мониторинг, океанографическая платформа

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1. Introduction

From the stationary oceanographic platform near the village of Katsiveli (hereinafter referred to as "the Katsiveli platform"), both specialized marine experiments and continuous monitoring of the coastal zone (see, for example, the collection [1)] and the papers [1–5]), are traditionally carried out [6]. The platform and its surrounding water area form an experimental test site (the Black Sea hydrophysical sub-satellite test site (BHSTS) of Marine Hydrophysical Institute of the Russian Academy of Sciences), where standard measuring equipment operates [6], and some measurement data are displayed in real time on publicly accessible websites (see, for example, current information about the state of the sea on a constantly working website http://dvs.net.ru/mhiplatform/index.shtml). Over decades of research, extensive archival data on the characteristics of the marine environment at the test site and their variability have been accumulated [1, 6]. Thus, there are ample opportunities both for optimal planning of experimental work at the test site and for expanded control of external conditions during experiments. Therefore, the conditions for carrying out work at the test site are similar to those in the laboratory. Today, this kind of "*in situ* laboratories" is necessary primarily for the developing and tuning the regional models of the marine environment and validation of satellite technologies for ocean monitoring.

A natural step to strengthen the measuring capabilities of the "*in situ* laboratory" in Katsiveli would be to carry out continuous radar monitoring of the water area surrounding the platform with a radius of about 1 km (Fig. 1). Such monitoring could provide fields of surface currents, surface wind speed and wind wave spectra with a spatial resolution of up to tens of meters. A suitable device for such purposes is a coherent navigation radar, capable of, in addition

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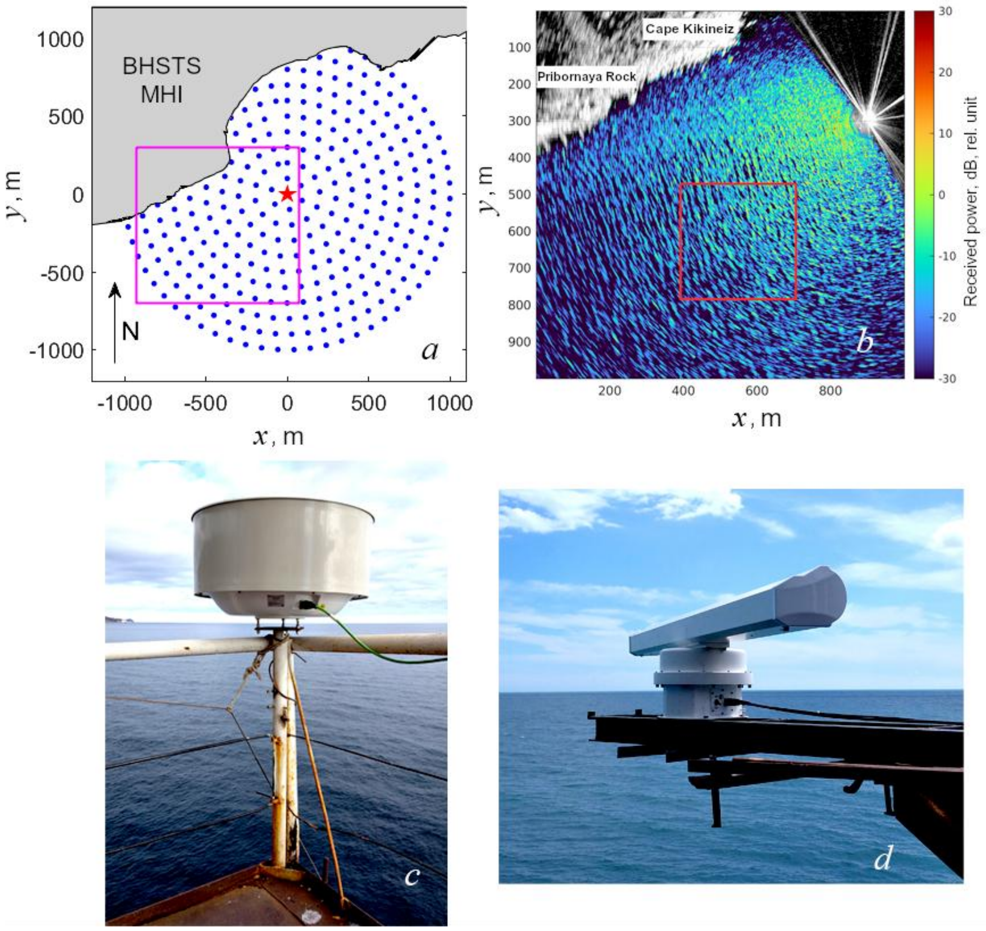
[1)] Ivanov, V.A., ed., 2010. *Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources. To 30th Years Anniversary of the Oceanographic Platform in Kaciveli – Results and Perspectives*. Sevastopol: MHI. Iss. 21, 265 p. (in Russian).

to the standard reflection power, recording the signal phase (Doppler frequency shift), and therefore the speed of the irradiated surface.

Fig. 1, *a* shows a schematic monitoring area; Fig. 1, *b* shows a real radar image of its fragment; Fig. 1, *c*, *d* shows domestic radar stations (radars), purchased by MHI to perform such work. The image (Fig. 1, *b*) shows the signal power, in the field of which wind waves are clearly distinguishable. Each pixel in the image can be considered as a “virtual station” where a time series of signal characteristics is recorded. A set of “virtual stations”, shown schematically in Fig. 1, *a*, provides detailed spatiotemporal fields of the studied characteristics of the marine environment.



F i g . 1 . Radar monitoring from the Katsiveli platform: *a* – monitoring area (the star denotes the platform location, the dots are virtual stations); *b* – radar image of the rectangular area selected in Fig. 1, *a*; *c* – MRS-3000 radar; *d* – MRS-1011 radar

Radar monitoring from the Katsiveli platform would provide an experimental basis for carrying out relevant studies of the ocean-atmosphere interaction, wind waves and currents interaction, conducting satellite experiments, developing and validating of the regional marine environment models. At the same time, the methods developed in recent decades for reconstructing wind speed, wind wave spectra, and current speed from satellite measurements provide a theoretical basis for the implementation of the project.

Radar measurements of the sea surface at small grazing angles not exceeding 10°, characteristic of coastal or marine radars, have backscattering features which are determined not by the resonant Bragg scattering, but by reflection from the breaking crests of wind waves (see, e.g. [7] and the references therein).

To solve applied problems, in particular, to restore wind speed, the geophysical model functions (GMFs) constructed from radar data are used. In the paper [8], it was proposed to use a third-order GMF to estimate wind speed from marine radars. At wind speeds of ~ 4 and 22 m/s, the speed reconstruction errors were ~ 0.8 and ~ 0.1 m/s, respectively. An empirical GMF, taking into account the grazing angle and the observation azimuth, is given in [5], where it is shown that the dependence of the normalized radar cross-section on wind speed is described by a power function with an exponent of 2.8.

Marine navigation radars are also widely used to determine marine environment characteristics [9, 10]. To estimate the surface current velocity and sea depth from the deformation of the dispersion curve, a technique was proposed for analyzing sequences of images of a radar plan-position indicator [11], subsequently improved to a commercial product [12]. In the same vein, other methods for restoring sea surface monitoring are being developed. An example is the WaMos system [13], which combines subsystems for observing waves, ice conditions, oil spills, as well as its Russian analogue also known as SeaVision [14]. A new source of information, but one that has not yet fully revealed its potential, is the Doppler velocity of scatterers, the measurement of which has become relatively simple with the introduction of solid-state coherent radars [15].

The purpose of this article is to discuss the use of marine radars for monitoring surface wind speed fields, wind wave spectra and surface currents from the Katsiveli platform. Below, the radar equipment installed on the platform is described, the ideology of obtaining estimates of the listed fields is presented, and preliminary results of the *in situ* proof-of-concept experiments in the autumn 2022 are presented.

2. Data and methods

2.1. Equipment and general description of work

In the autumn of 2022, MRS-1011 and MRS-3000 radars were installed on the Katsiveli platform (Fig. 1). Both stations operate on horizontal transmit/receive polarization providing a 360-degree view of the water area at grazing angles. The MRS-1011 station operates in the *X*-band (electromagnetic wavelength 3 cm), generally accepted for marine radars. The MRS-3000 station operates in the Ka-band (electromagnetic wavelength 8 mm), which is currently considered promising for improving the spatial resolution of satellite radars [16]. Data collection is carried out on media located on the platform, and work management and control of its correctness are carried out remotely via the Internet.

During the experiment , signals from an array of string wave gauges were continuously registered from the platform. A detailed description of the equipment used and the signal processing is given in sections 2.3 and 3.4 of the monograph [6]. Wind speed and direction, air temperature and humidity, water temperature in the upper 1-m layer were continuously recorded by a DavisVantagePro weather station installed on the platform.

2.2. The ideology of wind speed recovery

The speed and direction of the surface wind for almost the entire World Ocean are reconstructed using the data from satellite scatterometers using geophysical model functions, which are estimated experimentally from sub-satellite oceanographic buoy data. Analogs of the GMF for a radar operating from a platform can be obtained using the same method, accumulating an array of simultaneous measurements of the radar signal and wind speed using standard equipment installed on the platform. However, unlike satellite scatterometers, a navigation radar operates at grazing angles to the sea surface. This determines the GMF specificity, since the observed radar scattering is formed only by the highest wave crests visible from the radar location [17]. At wind speeds above 5 m/s, when the radar signal from the sea surface is strong enough to operate the radar, such crests typically correspond to breaking waves. The results of the studies of wave breaking statistics obtained in recent years [18, 19], including the Katsiveli platform [1, 4, 6], make it possible to predetermine the GMF shape for a radar operating at grazing angles.

The wave breaking contribution to the normalized radar cross-section (NRCS) of the sea surface is presented in the following form

$$\sigma_{wb} \propto \int \sigma_{0wb} dq, \qquad (1)$$

where σ_{0wb} is NRCS of the breaking zones; dq is the sea surface portion covered by breaking. According to O. Phillips [20] and numerous studies based on his approach (see, for example, [4, 18, 19]), $dq \propto k^{-1}\,\Lambda(k)\,dk$, where $\Lambda(k)\,dk$ is the length of the breaking crests per unit surface area in the range of wave numbers $(k,\ k + dk)$. Following [21], we will describe the length of the crests of breaking waves as

$$\Lambda(k,\varphi) = \frac{1}{2k}\left(\frac{B(k,\varphi)}{\alpha}\right)^{n+1}, \qquad (2)$$

where $B(k,\ \varphi) = k^{-4}\ S(k,\ \varphi)$ is the wind wave saturation spectrum associated with the elevation spectrum $S(k,\ \varphi)$; α and n are dimensionless parameters; φ is the direction of wave propagation. From expression (1) taking into account $B(k,\ \varphi) \propto (U^2/c^2)^{1/n}$ and formula (2), we obtain the relation for NRCS at grazing angles

$$\sigma_{wb} \propto \int \sigma_{0wb}\left(\frac{U^2}{c^2}\right)^{\frac{n+1}{n}} dk\,d\varphi, \qquad (3)$$

where c is the phase wave speed; U is the wind speed. The power of the radar signal received is described by the well-known radar equation

$$P = C\sigma_{wb}R^{-3}, \qquad (4)$$

where C is the radar parameter; R is the distance to the scatterer. From here, taking into account (3), a general expression for (4) follows, which is a proxy for GMF:

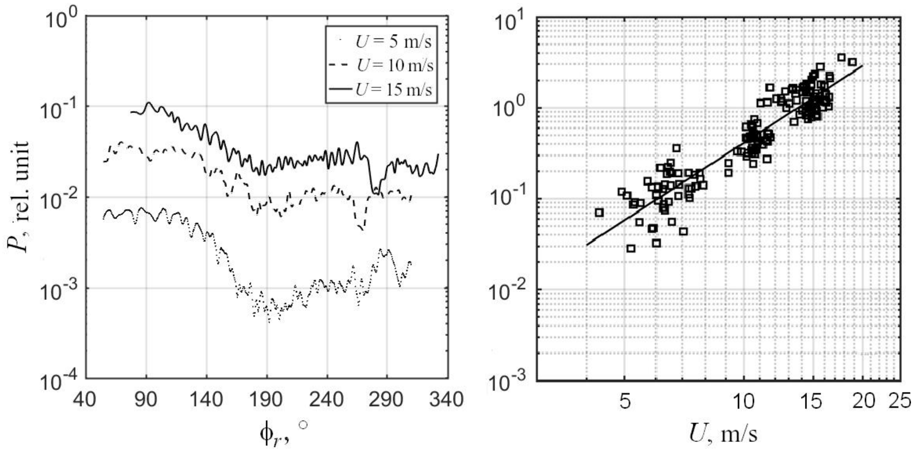
$$P = C(\varphi_r)U^m, \qquad (5)$$

where φ_r is the azimuth of radar observations, measured from the wind direction.

The constant m and the function $C(\varphi_r)$ in (5) are determined experimentally from arrays of simultaneous measurements of wind speed and radar signal. Such an array was accumulated during measurements from the Katsiveli platform with a radar with characteristics similar to the MRS-1011 station, as part of the work supported by the state assignment of MHI RAS No. 0827-2014-0010 presented in the paper [5]. A summary of these data for a range of 200 m, chosen as an example, is shown in Fig. 2. Functions $C(\varphi_r)$ for various wind speeds have maximum values when measured against the wind, $\varphi = 90°$ (Fig. 2, *a*). Dependence of signal power on wind speed at $\varphi = 90°$is shown in Fig. 2, *b*, where a solid line shows the power-law dependence of PU^m at $m = 2.8$. Using expression (5) and the obtained dependences of the signal power on the observation azimuth, we estimate wind speed using the following formula:

$$U = \left(P/C(\varphi_{up})\right)^{1/m}, \qquad (6)$$

where φ_{up} is the radar-to-wind direction.



F i g . 2 . Radar signal power depending on the observation azimuth (*a*) and wind speed (*b*)

As follows from formula (6), the values of U are satisfactorily described by a power function $U = (13.2 \pm 0.4)\cdot P^{\,0.30 \pm 0.02}$. The error in determining wind speed obtained from the data presented in Fig. 2, *b*, is $U = \pm 0.1U$. Thus, for example, at $U = 15$ m/s, the accuracy of wind speed reconstruction is ±1.5 m/s.

2.3. The ideology of recovering the spectra of wind waves and surface current velocities

The ideology of estimating the spectra of wind waves and the velocity of near-surface currents from radar images of the ocean surface has been known for a relatively long time [22]. The characteristics of wind waves can be restored by Fourier transform of the radar image fragments, as follows from Fig. 1, *b*, where the waves are clearly visible. The resulting radar spectrum $S_R(k_x, k_y)$, where k_x, k_y are the wave vector components, is related to the spectrum of sea surface elevations $S(k_x, k_y)$, as

$$S_R(k_x,k_y) = \mathrm{M}(U,k,\phi)S(k_x,k_y), \tag{7}$$

where $\mathrm{M}(U, k, \phi)$ is the modulation transfer function (MTF); k is the wave vector magnitude, and ϕ is its direction, measured from the wind direction [23]. This approach is similar to the reconstruction of wave spectra from ocean images obtained by optical scanners [1, 24]. The three-dimensional function $\mathrm{M}(U, k, \phi)$ for the case of radar at grazing angles was discussed in [14, 17, 23]. In principle, its form can be obtained experimentally by performing simultaneous assessments of wave spectra using a radar and an array of string wave recorders at known wind speeds. With a known MTFM(U, k, ϕ), the two-dimensional spectrum $S(k_x, k_y)$ can be simply restored using formula (7).

However, this approach requires extremely long expeditionary work. A simplified approach is to replace the MTF with a constant M_0 for the region of the spectral peak of wind waves. Then the frequency spectrum of elevations $S(f)$, where f is the wave frequency, measured in Hz, can be found from as

$$S_R(f) = M_0 S(f),$$

where $S_R(f) = \oint S_R(k \cdot \cos(\phi), k \cdot \sin(\phi)) k (dk / df) d\phi$, and dk/df is determined from the dispersion relation for surface waves

$$2\pi f = \sqrt{gk \tanh(kH)} + k_x V_x + k_y V_y, \tag{8}$$

where g is the acceleration of gravity; H is the sea depth at observation point; V_x and V_y are the current velocity components. Within the framework of a simplified approach for estimating wave spectra during measurements from a stationary platform, the current speed can be set to zero. For the case of measurements from the Katsiveli platform, when the wind wavelengths do not exceed the double depth, the deep-water approximation can be used. Then the dispersion relation (8) is reduced to $2\pi f = \sqrt{gk}$ and in this form is used to recalculate $S_R(f, k_x, k_y)$. A simplified approach has recently been validated using both measurements from a wave buoy and calculations using the WaveWatch-3 wave model [14].

The ideology of reconstructing the velocity of the near-surface current from a sequence of radar images [22] is similar to the ideology of reconstructing currents from optical images from satellites (see, for example, [25]) and video recordings from an unmanned aerial vehicle [26]. Since a radar enables one to observe variability of the wave field in space and time, by the three-dimensional Fourier transform of a sequence of radar images it is possible to estimate the radar spatiotemporal spectra $S_R(f, k_x, k_y)$. Since wind waves obey the dispersion relation (8), the parameters f, k_x, k_y of the spectrum $S_R(f, k_x, k_y)$ also satisfy equation (8). Having a large set of points (f, k_x, k_y), we find the current velocity components from the overdetermined system of equations (8). This approach, using video recordings instead of radar image sequences, has recently been thoroughly validated in a laboratory setup [27]. For radar monitoring from the Katsiveli platform, this approach provides a radar estimate of the current velocity vector, regardless of the mechanism of wave manifestation in the radar signal.

Measuring the radar signal phase makes it possible to estimate the Doppler spectra of the sea surface $S_D(f)$ formed by moving scatterers [2, 3]. The gravity center of the Doppler spectrum, "Doppler centroid",

$$f_D = \int f S_D(f) df \Big/ \left(\int S_D(f) df \right), \tag{9}$$

contains information about the average value of the velocity component of scatterers along the radar beam V_D: $f_D = k_R V_D / \pi$, where k_R is the wave number of an electromagnetic wave [28]. The f_D field measured from satellites gives a qualitatively correct picture of the main ocean currents [28], which initiated special projects SKIM (European Space Agency) and WaCM/DopplerScatt (NASA) to develop satellite missions for Doppler current measurements [16]. However, in addition to currents, a significant contribution to V_D is made by the slopes and orbital velocities of energy-containing wind waves and wave breaking. Moreover, during a strong storm, the raindrop fraction in the air distorts the Doppler signal [3, 16, 28, 29]. The studies of Doppler shifts within the framework of radar monitoring from the Katsiveli platform will make it possible, on the one hand, to solve fundamental issues of the current reconstructing from space, on the other hand, they will provide alternative estimates of current velocity in addition to the estimates obtained by the dispersion relation analysis method.

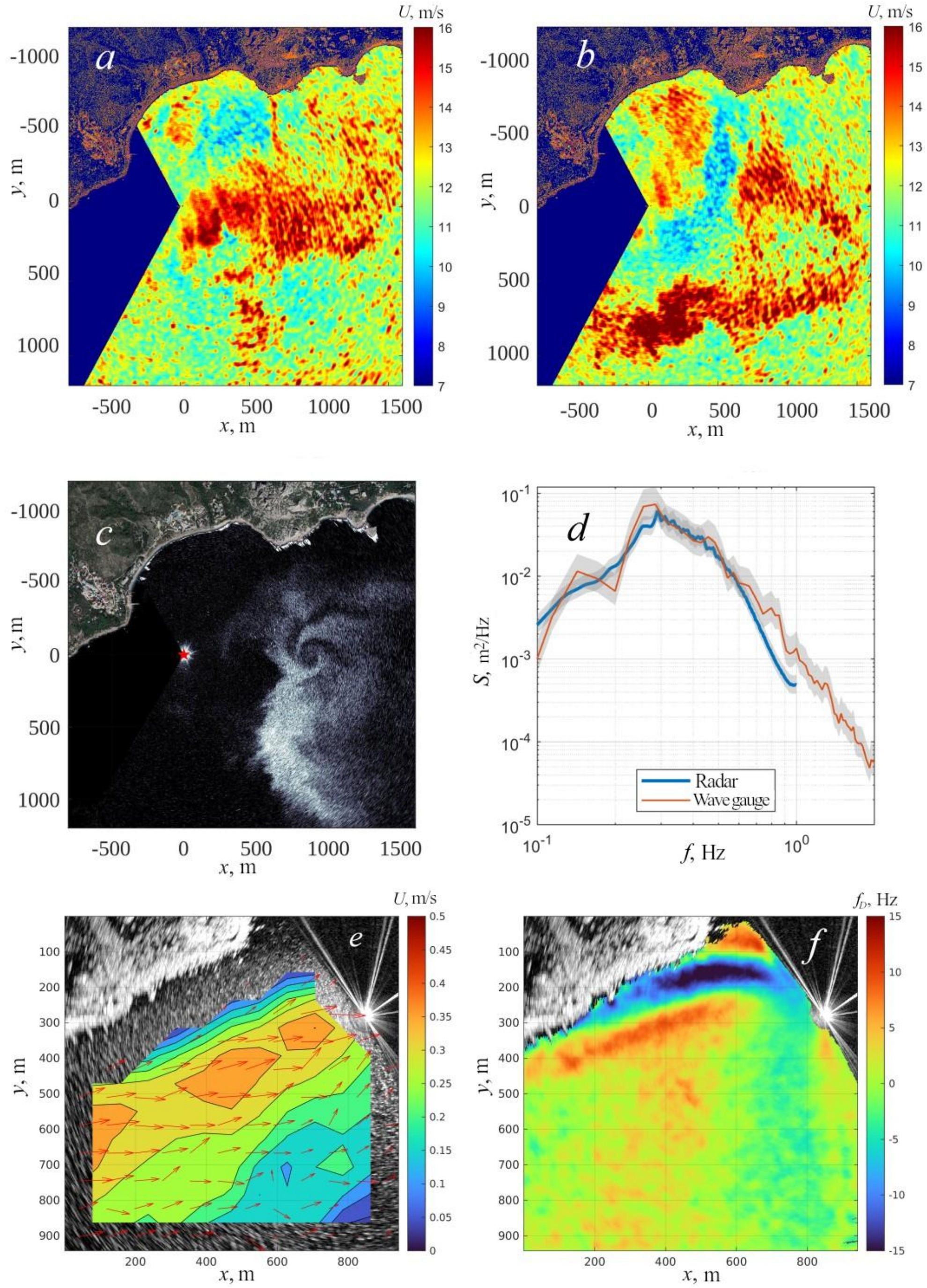
Results

Fig. 3 demonstrates the radar monitoring capabilities confirmed during radar testing. Fig. 3, *a*, *b* shows the spatiotemporal variability of the reconstructed wind speed fields. In this case, a katabatic wind ("coastline") was observed with an average speed of 12 m/s. The areas of increased wind speed over a kilometer in length, oriented approximately parallel to the coastline, were transported with the wind speed towards the open sea. The figures show the same structure with a time shift of about a minute.

Fig. 3, *c* corresponds to the situation of rain in light wind conditions. The radar signal is determined by volumetric scattering on raindrops, and the reduced field shows horizontal distribution of the raindrop fraction in a layer of driving air with a thickness of about the height of the radar installation (~ 10 m) [3]. This distribution clearly shows a vortex structure. Radars make it possible to observe frontal and vortex structures with scales from hundreds of meters to a kilometer, evolving in the near-water layer of the atmosphere. Observations of such structures using a line of optical sensors are described in [30].

Fig. 3, *d* shows an example of the reconstructed wave frequency spectrum. The spectrum was estimated for the image fragment highlighted in Fig. 1, *b* with a pink rectangle. Although the simplified method described above was used for the calculation, comparison with the spectrum estimated from the wave gauge record shows good agreement in the region of energy-carrying waves (Fig. 3, *d*).

Fig. 3, *e* shows an example of the reconstructed field of current velocity vectors. An alongshore jet with a current velocity of 30–35 cm/s and a direction coinciding with the direction of the wind and waves is deteced. The current weakens in the wind shadow zone near the shore and on the seaward side. Fig. 3, *f* shows the simultaneously recorded Doppler centroid field f_D (9). Despite the f_D artifacts in the northern part, associated with the signal registration peculiarities, both fields have a similar spatial structure. This can be considered as a confirmation at a qualitative level of the assessment of the current field, performed on the basis of fundamentally different data – using dispersion analysis of the radar signal power.



F i g . 3 . Radar-derived recovered fields of wind speed (*a*, *b*), raindrop fraction field (qualitatively) (*c*), wave frequency spectrum estimated from radar signal and wave gauge measurements (*d*), recovered field of current velocity vectors (*e*), Doppler frequency shift (*f*) corresponding to the field of currents (*e*)

4. Conclusion

This paper presents a project to equip the oceanographic platform in Katsiveli with a radar station based on a marine radar in order to significantly expand research capabilities of the "*in situ* laboratory" at the Black Sea hydrophysical sub-satellite test site. Operation of the station will make it possible to monitor wind speed fields, wind wave spectra and current velocity vector in a water area with a radius of 1 km with a resolution of up to 100 m. The study of these fields is obviously of independent interest. However, when conducting experimental work on the interaction of the ocean and the atmosphere, wind waves and currents, as well as when developing and validating satellite technologies and regional models of the marine environment, detailed information about the current fields of wind speed and current velocity vector, as well as spectra of wind waves will greatly enhance reliability and validity of experimental conclusions.

The article shows that recovery of the listed fields from a radar signal is based on the already known methods developed for satellite and marine radar processing, as well as on the results of studies of wind wave breaking conducted from the Katsiveli platform. In order to test field restoration in the autumn of 2022, a special experiment was carried out from the Katsiveli platform using two new MRS-1011 and MRS-3000 marine radars, operating at electromagnetic wavelengths of 3 cm and 8 mm. The approaches to estimating wind speed fields, wind wave spectra, and current velocity vectors described in the article were applied to the reconstruction of the listed fields.

A preliminary data analysis showed:

– The wind speed field contains propagating frontal and vortex structures with scales from hundreds of meters to a kilometer, evolving in the surface layer of the atmosphere, which were previously observed by other methods.

– The reconstructed frequency spectra of wind waves are consistent with the spectra measured by a traditional string wave gauge.

– The current field contains an alongshore jet with maximum velocity values reaching 35 cm/s; its direction coincides with the direction of wind and waves. This current picture is qualitatively confirmed by the Doppler signal field obtained from the radar.

The results of the work carried out demonstrate the prospects for continuous radar monitoring at the Black Sea hydrophysical sub-satellite test site and the associated new capabilities of the "*in situ* laboratory" in Katsiveli.

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