ISSN 0027-1349, Moscow University Physics Bulletin, 2017, Vol. 72, No. 4, pp. 410–414. © Allerton Press, Inc., 2017.
Original Russian Text © K.V. Pokazeev, A.S. Zapevalov, K.E. Lebedev, 2017, published in Vestnik Moskovskogo Universiteta, Seriya 3: Fizika, Astronomiya, 2017, No. 4, pp. 68–72.

PHYSICS OF EARTH, ATMOSPHERE, AND HYDROSPHERE

Measurements of Sea Surface Slopes by Laser Sensing from a Space Vehicle

K. V. Pokazeev[a]*, A. S. Zapevalov[b], and K. E. Lebedev[b]*****

[a] *Faculty of Physics, Moscow State University, Moscow, 119991 Russia*
[b] *Marine Hydrophysical Institute, Russian Academy of Sciences, Sevastopol, 299001 Russia*
**e-mail: sea@phvs.msu.ru*
***e-mail: sevzepter@mail.ru*
****e-mail: nick_leb@mail.ru*
Received June 23, 2016

Abstract—The measurement errors of dispersions of sea surface slopes using spacecraft lidar were analyzed. The errors caused by deviations of the actual wave field from the Gaussian isotropic surface were considered. It is revealed that the unaccounted deviations of slope distributions from the Gaussian distribution lead to a systematic underestimation of the calculated slope dispersion by approximately 11–14%. In addition, it is revealed that the anisotropy of slopes during their dispersion calculation using the data of vertical laser sensing from space vehicle can be neglected.

Keywords: remote sensing, sea surface slopes, optical measurements, lidar.
DOI: 10.3103/S0027134917040117

INTRODUCTION

The water-to-air boundary roughness determines any process in which acoustic or electromagnetic waves interact with the sea surface; it affects the intensity of the atmosphere-ocean exchange processes. The sea surface slopes relate to the main parameters that characterize the roughness.

One of the most promising methods for studying the characteristics of the sea surface is the method of laser sensing. One can distinguish two trends in this method. The first trend (detecting spots of light) is used when the sensing is carried out from a small height (of approximately 10 m) and the diameter of a laser spot on the surface is several millimeters [1, 2]. The surface areas whose slope satisfies the condition of reflection of the laser beam into a photodetector aperture periodically enter into the illuminated region [3]. The photodetector output signal is a pulse sequence of varying durations and amplitudes, by which the sea surface characteristics are calculated [4].

During sensing from a great height (from a space vehicle) the diameter of the spot on the sea surface is a few dozen meters [5]. The area under laser illumination contains a large number of elements that satisfy the specular reflection condition. In this case, the calculations of the sea surface characteristics are carried out based on the models built for the analysis of signals of space-based optical scanners [6–8].

A general disadvantage of the calculations of statistical estimations of sea surface slopes by the laser sensing data is that they make it possible to obtain the statistical estimations of the slopes only within a priori built models [9]. Generally, it is assumed that the slope distribution is Gaussian and isotropic [10, 11]. The goal of this work was an analysis of the errors due to these assumptions into the calculation of the dispersion of sea surface slopes during laser sensing from a spacecraft.

1. SPECULAR LIGHT REFLECTION FROM THE SEA SURFACE

The signal recorded at the spacecraft as a result of the reflection of sunlight from the sea surface is related with the statistical distribution of its slopes. The specular reflection of sunlight from the sea surface is described by a bidirectional reflection direction function, which defines the ratio of the brightness of the radiation that is reflected secularly by the surface $I_r(\theta_r, \varphi)$ to the solar radiation flux density $H_s(\theta_s, \varphi = 0)$ [7].

$$R = \frac{\pi I_r(\theta_r, \varphi)}{H_s(\theta_s, \varphi = 0)\cos\theta_s} = \frac{\pi F_w(\beta)}{4\cos\theta_s\cos\theta_v\cos\theta^4\beta} P(\xi_x, \xi_y), \tag{1}$$

where θ_s and θ_r are the zenith angles of incident sunbeams and the beams reflected in the direction of the

Estimates of coefficients C_{22}, C_{04} and C_{40}.

	Ref. 15	Ref. 7	Ref. 20
C_{22}	0.12 ± 0.06	0.12 ± 0.03	0.17 ± 0.27
C_{04}	0.23 ± 0.41	0.4 ± 0.1	0.43 ± 0.46
C_{40}	0.40 ± 0.23	0.3 ± 0.05	0.33 ± 0.43

spacecraft; $F_w(\beta)$ is the Fresnel reflection coefficient for seawater; $P(\xi_x, \xi_y)$ is the two-dimensional probability distribution function of orthogonal components of sea surface slopes ξ_x and ξ_y; and β is the slope angle of the sea surface defined by the condition $\tan\beta = \sqrt{\xi_x^2 + \xi_y^2}$. Here, the angle $\beta = \frac{1}{2}\arccos(\cos\theta_s \cos\theta_v + \sin\theta_s \sin\theta_v \sin\varphi)$.

The specular reflection condition is of the form $\theta_s = \theta_v$, $\varphi = \pi$. With the fulfillment of these conditions Eq. (1) can be used for analyzing the laser-sensing data of the sea surface. If the lidar beam is directed vertically downward, then $\theta_s = \theta_v = \beta = 0$. Using the R function assumes that the laser pulse duration is sufficiently large and at the same time a contribution to the reflected signal is made by all surface elements that satisfy the specular-reflection condition. If the duration of the laser pulse is short then the reflections from the surface elements located near the crest and near the trough occur at different points in time. In this case, it is necessary to take the distribution of reflecting elements by height into account [12].

When interpreting the results of laser sensing of the sea surface it is usually assumed that the two-dimensional slope distribution is isotropic and Gaussian [5, 11]. Under this assumption, it was obtained [10] that

$$R = -\frac{F_w(\beta)}{4\pi\sigma^2 \cos^4\beta} \exp\left(-\frac{\tan^2\beta}{2\sigma^2}\right), \qquad (2)$$

where

$$\sigma^2 = \sigma_x^2 + \sigma_y^2; \qquad (3)$$

σ_x^2 and σ_y^2 are the dispersions of orthogonal components of slopes, which are assumed to be equal. If the sensing is carried out by laser into the nadir, assuming that $\beta \approx 0$, we obtain $\tan\beta \approx 1$, $\cos\beta \approx 1$ and it follows from Eq. (1) that

$$R = F_w(0)/(4\pi\sigma^2). \qquad (4)$$

Full-scale measurements revealed that the slope field of the sea surface is not Gaussian and is not isotropic. We estimate the errors due to the calculation of the slope dispersion within the framework of the isotropic Gaussian field model.

2. DEVIATIONS OF SEA SURFACE SLOPE DISTRIBUTIONS FROM THE GAUSSIAN DISTRIBUTION

It was revealed by mathematical modeling that interwave interactions, dynamic effects of waves with longer wavelengths on shorter waves, and a number of other physical mechanisms lead to the deviation of the distribution of the characteristics of surface waves from a Gaussian distribution [13, 14]. This area is determined by the conditions $|\xi_c/\sigma_c| < 2.5$ and $|\xi_u/\sigma_u| < 2.5$ [15], which are always fulfilled during vertical laser sensing.

Field studies performed using various types of equipment revealed that the coefficients C_{22}, C_{04}, and C_{40} do not depend on wind speed. The magnitudes of these coefficients obtained as a result of processing aerial photographs [15] and processing the data of space-based optical scanners [7] in experiments carried out in marine environments with laser slope meters [20] are presented in the table.

In all of these experiments the average values of coefficients C_{22}, C_{04}, and C_{40} are positive. This means that the estimates of the dispersion σ^2 obtained by expression (4) according to the laser-sensing data have a systematic error corresponding to underestimation of its values. The average error magnitude calculated for the above average values of coefficients C_{22}, C_{04}, and C_{40} is in the range of 11–14%.

3. THE ANISOTROPIES OF SEA SURFACE SLOPES

The angular distribution of slopes according to direction is not isotropic. The dispersion of slopes oriented in the wind direction is higher than the dispersion in the transverse direction. The three-dimensionality index, which is equal to the ratio of the standard values of the slopes in the transverse σ_c and longitudinal σ_u directions, is used as a rule as the parameter that characterizes the anisotropy of the slopes [21]

$$\gamma = \sigma_c/\sigma_u.$$

The parameter γ approaches zero for the waves with a long crest, while for waves with short crests it approaches unity.

We analyze the influence of the slope anisotropy on the reflection characteristics during laser sensing. We first convert expression (5) from Cartesian to polar coordinates. For this, we represent two orthogonal components of the slopes in the form

$$\xi_c = \xi_m \sin\varphi, \quad \xi_u = \xi_m \cos\varphi,$$

where $\xi_m = \sqrt{\xi_u^2 + \xi_c^2}$ is the slope module and $\varphi = \arctan(\xi_c/\xi_u)$ is the azimuth angle. For the probability distribution function, the condition of transition to the new variables of other physical mechanisms leads to deviation of the distributions of the characteristics of surface waves from a Gaussian distribution [13, 14]. Experimental studies performed under field conditions confirmed that the distribution of slopes is quasi-Gaussian [7, 15, 16]. To describe the probability distribution function of such distributions the approximations based on the Gram-Charlier series are used [17].

The two-dimensional probability distribution function built for longitudinal ξ_u and transverse ξ_c slope components relative to the wind-speed vector was described by the model [15]

$$P(\xi_c,\xi_u) = P_G(\xi_c,\xi_u)\left[1-\frac{1}{2}C_{21}H_2\left(\frac{\xi_c}{\sigma_c}\right)H_1\left(\frac{\xi_u}{\sigma_u}\right) + \frac{1}{4}C_{22}H_2\left(\frac{\xi_c}{\sigma_c}\right)H_2\left(\frac{\xi_u}{\sigma_u}\right) - \frac{1}{6}C_{03}H_3\left(\frac{\xi_u}{\sigma_u}\right) + \frac{1}{24}\left(C_{04}H_4\left(\frac{\xi_u}{\sigma_u}\right) + C_{40}H_4\left(\frac{\xi_c}{\sigma_c}\right)\right)\right], \quad (5)$$

where $P_G(\xi_c,\xi_u) = \frac{1}{2\pi\sigma_c\sigma_u}\exp\left(-\frac{1}{2}\left(\frac{\xi_c^2}{\sigma_c^2}+\frac{\xi_u^2}{\sigma_u^2}\right)\right)$ is the Gaussian distribution, σ_u^2 and σ_c^2 are the dispersions of longitudinal and transverse slope components, and H_i are the Chebyshov–Hermite polynomials of the ith order. The first index of coefficient C_{ij} corresponds to the transverse slope component and the second index corresponds to the longitudinal slope component.

We estimate the errors in the determination of the dispersion of sea surface slopes caused by the calculations under the assumption that the distribution of slopes is Gaussian. During laser sensing the reflection in the spacecraft direction creates facets, whose orientation is close to horizontal; one can suppose that $\xi_u = \xi_c = 0$. The H_1 and H_3 polynomials are odd functions, so at low incidence angles the contribution of terms proportional to these polynomials can be neglected. The H_2 and H_4 polynomials are even functions. Taking the fact into account that $H_2(0) = -1$ and $H_4(0) = 3$, for $\xi_u \approx \xi_c \approx 0$ we obtain

$$P(\xi_c,\xi_u) \approx P_G(\xi_c,\xi_u)\left[1+\frac{C_{22}}{4}+\frac{C_{04}+C_{40}}{8}\right].$$

It should be noted that expression (5) correctly describes the probability distribution function of the sea surface slopes only in a bounded domain [18, 19].

$$p(\xi_m,\varphi) = \frac{\partial(\xi_c,\xi_u)}{\partial(\xi_m,\varphi)}P(\xi_c,\xi_u),$$

where $\frac{\partial(\xi_c,\xi_u)}{\partial(\xi_m,\varphi)} = \xi_m$ is the Jacobian determinant.

If the components of the slopes are oriented along and across the wind direction, expression (3) can be written in the form $\sigma^2 = (1+\gamma^2)\sigma_u^2$. We introduce the normalization $\tilde{\xi}_m = \xi_m/\sigma$. From expression (5) neglecting the terms proportional to polynomials H_i with odd indices i we obtain

$$p(\xi_m,\varphi) = p_{G\varphi}(\xi_m,\varphi)\left[1+\frac{1}{4}C_{22}H_2\left(\frac{\xi_m\sin\varphi}{(1+\gamma^{-2})^{-0.5}}\right)H_2\left(\frac{\xi_m\cos\varphi}{(1+\gamma^2)^{-0.5}}\right) + \frac{1}{24}\left(C_{04}H_4\left(\frac{\xi_m\cos\varphi}{(1+\gamma^2)^{-0.5}}\right) + C_{40}H_4\left(\frac{\xi_m\sin\varphi}{(1+\gamma^{-2})^{-0.5}}\right)\right)\right], \quad (6)$$

where $p_{G\varphi}(\xi_m, \varphi)$ is the distribution corresponding to the case where the components ξ_u and ξ_c are distributed according to the Gaussian law.

The beam reflected from the sea surface enters the photodetector aperture of lidar if the module of the slope ξ_m is less than some critical value ξ_{m0} regardless of the orientation of the slope φ. We exclude in expression (6) the dependence on φ and integrated $p(\xi_m, \varphi)$ over all directions $p_m(\xi_m) = \int_0^{2\pi} p(\xi_m,\varphi)d\varphi$.

Let the slope components be distributed according to the Gaussian law. In the case of $\gamma = 0$, which corresponds to a two-dimensional wave field, the probability distribution function of the slope module corresponds to the distribution of the module of a random variable distributed according to the normal law with zero mathematical expectation

$$p_{mG}(\tilde{\xi}_m,\gamma=0) = -\frac{2}{\sqrt{2\pi}\sigma}\exp\left(-\frac{\tilde{\xi}_m^2}{2}\right).$$

When $\gamma = 1$ the module slope $\tilde{\xi}_m$ conforms to the Rayleigh distribution

$$p_{mG}(\tilde{\xi}_m,\gamma=1) = 2\tilde{\xi}_m\exp\left[-\tilde{\xi}_m\right].$$

Here, the subscript (G) indicates that the distribution of the slope module was obtained for the case where the slope components are distributed according to the Gaussian law. If the two-dimensional slope distribution is described by expression (5), then the corresponding distribution of the slope module is denoted by the subscript N.

According to measurement data in the field conditions using a laser slope meter [16], the values of the three-dimensional index are within $0.66 < \gamma < 0.95$ with the average value of $\gamma = 0.8$. The dependences of the γ parameter on the wind speed was not observed. According to the measurements with optical scanners [7], the γ parameter changes from $\gamma = 0.9$ at a wind speed of 3 m/s, to $\gamma = 0.8$ at the wind speed of 15 m/s. The effect of changes of the three-dimension index on the probability distribution function of sea surface slopes is shown in Fig. 1. When the slope components ξ_u and ξ_c are distributed according to the Gaussian law, three models were built corresponding to the two-dimensional ($\gamma = 0$) and isotropic ($\gamma = 1$) fields of slopes, as well as to the wave field, for which $\gamma = 0.66$,

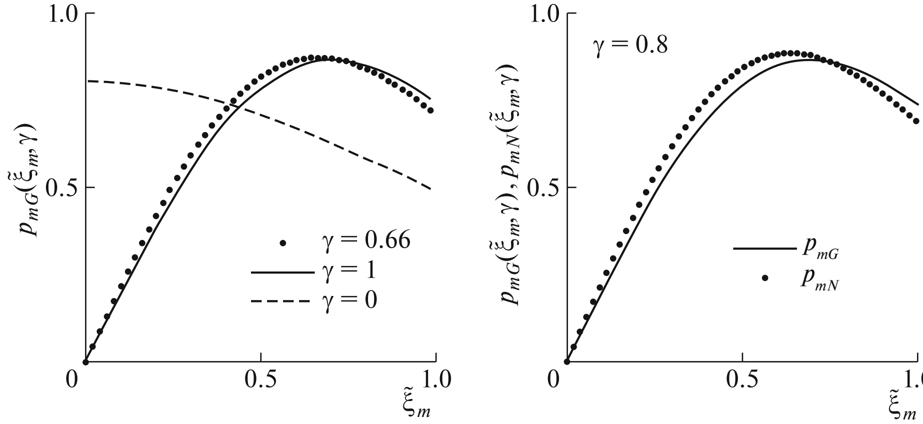

Fig. 1. The models of probability distribution function of the sea surface slope module.

that corresponds to the lower boundary of the observed values of γ parameter [16]. It is seen that with the reduction of the γ parameter the probability distribution function $p_{mG}(\tilde{\xi}_m, \gamma)$ in the region of small values ξ_m increases.

In addition, it was revealed that for the isotropic slope field the deviations of the slope components ξ_u and ξ_c from the Gaussian distribution in the region of small values of ξ_m lead to increasing the probability distribution function $p_{mG}(\tilde{\xi}_m, \gamma)$ (see Fig. 1). The calculations were performed for $\gamma = 0.8$, which corresponds to the average magnitude of the three-dimensionality index.

4. QUANTITATIVE ESTIMATES

During vertical sensing the laser beam reflected from the sea surface enters the photodetector aperture if the slope module ξ_m does not exceed a certain critical value ξ_{m0}. The amplitude recorded for the spacecraft signal is directly proportional to the probability

$$\xi_m \leq \xi_{m0}. \tag{7}$$

As the dispersion of the slopes depends on the wind speed, the different values of ξ_{m0} will correspond to the same value of $\tilde{\xi}_{m0}$. The laser beam is narrow. Thus, the half-width of the laser beam of the lidar of the CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) type installed on the CALIPSO spacecraft [5] is 5×10^{-5} rad. Accordingly, during vertical sensing the critical value of the slope module equals 5×10^{-5} rad. Sensing from CALIPSO was carried out at the incidence angle 5×10^{-3} rad (or = 0.3°). In this case the critical value of the slope module is defined by the expression $\arctan(\xi_{m0}) = 5.42 \times 10^{-3}$ rad.

Changes of the $\tilde{\xi}_{m0}$ parameter with increasing wind speed W when $\arctan(\xi_{m0}) = 5.42 \times 10^{-3}$ rad are shown in Fig. 2. The regression dependencies of the slope component dispersions on the wind speed obtained in [7] are used for the calculation,

$$\sigma_u^2 = 10^{-3} + 3.16\times10^{-3}W \pm 5\times10^{-4},$$
$$\sigma_c^2 = 3\times10^{-3} + 1.85\times10^{-3}W \pm 5\times10^{-4}.$$

When varying the wind speed within 1–15 m/s the values $\tilde{\xi}_{m0}$ vary from 0.055 to 0.019 if $\xi_{m0} = 5.42 \times 10^{-3}$ and from 5.3×10^{-3} to 1.8×10^{-4} if $\xi_{m0} = 5 \times 10^{-5}$.

To quantitatively estimate the effects caused by the fact that the field of short surface waves is not isotropic, we introduce the parameter

$$\varepsilon(\gamma) = F_G(\gamma)/F_G(\gamma = 1),$$

where F is the probability that the slope module ξ_m satisfies condition (7).

It is seen from Fig. 3 that in the region of small module slope values corresponding to the mentioned values of $\tilde{\xi}_{m0}$ the probability distribution function can

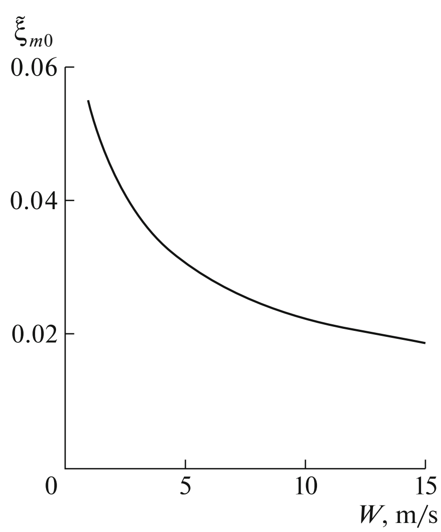

Fig. 2. The dependence of parameter $\tilde{\xi}_{m0}$ on the wind speed W for the conditions of CALIOP lidar sensing.

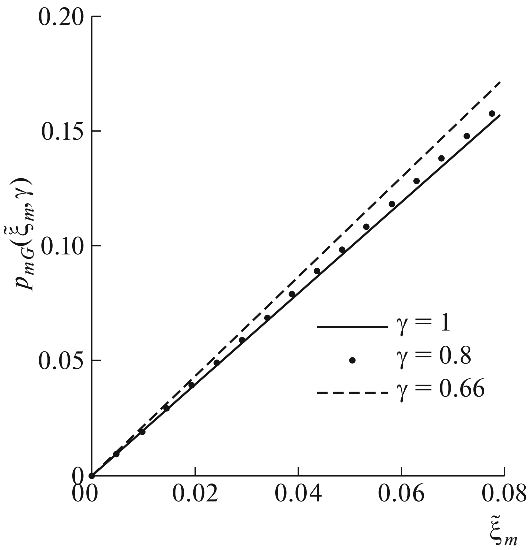

Fig. 3. The changes of the probability distribution function of sea surface slope module $p_{mG}(\xi_m, \gamma)$ in the region of small values of parameter ξ_m.

be approximated by a linear dependence. The slope angle of the approximation changes with changes in the γ parameter, respectively, the probability F changes. The calculations based on the measurement data obtained using a laser slope meter [16] revealed that at the average value of the three-dimension index $\gamma = 0.8$ parameter $\varepsilon = 1025$; when $\gamma = 0.66$ parameter $\varepsilon = 1088$. According to the measurement data with optical scanners [7] the values of the γ parameter change from 0.9 at the wind speed $W = 3$ m/s to $\gamma = 0.8$ at $W = 15$ m/s. For the mentioned values of the γ parameter calculated using regression equations (8) and (9) we have $\varepsilon \leq 1025$.

CONCLUSIONS

An analysis of measurement errors of the dispersion of sea surface slopes with space-based lasers was performed. The errors caused by deviations of the actual wave field from isotropic Gaussian surface were considered. The data obtained with laser slope meters, as well as with the optical space-based scanners, were used for the analysis.

It was found that unaccounted deviations of the slope distributions from the Gaussian distribution lead to a systematic error of 11–14%. The calculated values of the slope dispersion are underestimated. The anisotropy of the sea surface slope leads to an error, which systematically understates the values of the dispersion. The magnitude of this error is less than 3% on average and compared with the error due to the non-Gaussian nature of the distributions of slopes can be neglected.

REFERENCES

1. V. N. Nosov, S. Yu. Pashin, D. N. Khandogin, et al., Izv. Akad. Nauk SSSR, Fiz. Atmos. Okeana **26**, 206 (1990).
2. A. P. Aleksandrov and V. P. Legeza, Morsk. Gidrofiz. Zh., No. 6, 51 (1988).
3. N. E. Lebedev, A. A. Aleskerova, and E. M. Plotnikov, Sovrem. Probl. Distantsionnogo Zondirovaniya Zemli Kosmosa **13** (3), 136 (2016).
4. G. N. Khristoforov, A. S. Zapevalov, V. E. Smolov, and Yu. R. Feldman, Phys. Oceanogr. **5**, 461 (1994). doi 10.1007/BF02198512
5. Y. Hu, K. Stamnes, M. Vaughan, J. Pelon, et al., Atmos. Chem. Phys. **8**, 3593 (2008). doi 10.5194/acp-8-3593-2008
6. N. Ebuchi and S. Kizu, J. Oceanogr. **58**, 477 (2002). doi 10.1023/A:1021213331788
7. F. M. Breon and N. Henriot, J. Geophys. Res. **111**, C06005 (2006). doi 10.1029/2005JC003343
8. N. E. Lebedev, V. V. Pustovoitenko, K. V. Pokazeev, et al., Sovrem. Probl. Distantsionnogo Zondirovaniya Zemli Kosmosa **11** (3), 310 (2014).
9. A. S. Zapevalov and K. V. Pokazeev, Moscow Univ. Phys. Bull. **59** (5), 47 (2004).
10. B. van Ginneken, M. Stavridi, and J. J. Koenderink, Appl. Opt. **37**, 130 (1998). doi 10.1364/AO.37.000130
11. J. S. Barton and M. F. Jasinski, Remote Sens. **3**, 1492 (2011). doi 10.3390/rs3071492
12. K. V. Pokazeev, A. S. Zapevalov, and V. V. Pustovoytenko, Moscow Univ. Phys. Bull. **68**, 420 (2013). doi 10.3103/S0027134913050135
13. O. M. Phillips, J. Fluid Mech. **11**, 143 (1961). doi 10.1017/S0022112061000913
14. M. S. Longuet-Higgins, J. Phys. Oceanogr. **12**, 1283 (1982). doi 10.1175/1520-0485(1982)012<1283:OTSOSS>2.0.CO;2
15. C. Cox and W. Munk, J. Opt. Soc. Am. **44**, 838 (1954).
16. A. S. Zapevalov, Phys. Oceanogr. **12**, 24 (2002).
17. A. S. Zapevalov and N. E. Lebedev, Atmos. Oceanic Opt. **27**, 487 (2014). doi S1024856014060220
18. V. I. Tatarskii, J. Atmos. Oceanic Technol. **20**, 1697 (2003).
19. A. S. Zapevalov and V. V. Pustovoitenko, Radiophys. Quantum Electron. **53**, 100 (2010). doi 10.1007/s11141-010-9206-z
20. G. N. Khristoforov, A. S. Zapevalov, and M. V. Babii, Okeanologiya **32**, 452 (1992).
21. M. S. Longuet-Higgins, Philos. Trans. R. Soc., A **249**, 321 (1957).

Translated by M. Kromin