Influence of the sea foam coverage on the power of a lidar return from the sea surface sensed

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We present formula derived for describing the foam effect on the power of a laser signal, and compare it with numerically simulated results for different models of sea foam coverage. It is shown that the presence of foam on sea surface strongly influences the power of the laser signal. This effect strongly depends on foam model and viewing angles.

The methods of laser sensing are indirect and provide no possibility of measuring *in situ* the sea surface characteristics, the latter being, instead, determined from measurements of laser signal, which depends on many factors. One of such factors is the sea foam coverage (see, e.g., Refs. 1 and 2).

The power of a lidar return recorded in continuous interrogating the foam-covered sea surface has been studied by Belov et al.,[3] who derived an approximate formula which takes into account the foam effect on the received power. Below, we deduce a more exact formula describing the foam effect on the return signal power, and compare it with numerical results obtained using different models of the sea foam coverage.

The model of sea roughness is usually represented as a Gaussian random process (Gaussian distribution for the slopes of sea surface is close to that observed experimentally[4]). High winds lead to foam formation on the sea surface. Generally, the foam-covered regions are assumed to be isotropic reflectors (see, e.g., Refs. 1 and 2), located on the wave slopes. It is noteworthy, that if the wind is not very high, the foam spots are located almost parallel to wave slopes; therefore the foam slope distribution can be considered to be the same as the sea wave slope distribution.[2]

The mean power P received by lidar in sensing the sea surface partially covered with foam can be presented as[3]:

$$P = (1 - C_{\mathrm{f}})\, P_{\mathrm{sea}} + C_{\mathrm{f}} P_{\mathrm{f}}, \qquad (1)$$

where P_{sea} and P_{f} are mean sensed powers returned from sea surface free of and totally overcast with foam; and C_{f} is the fraction of the sea surface covered with foam.

The integral formulas for $P_{\mathrm{sea,f}}$ are obtained in Refs. 5 and 6:

$$P_{\mathrm{sea}} \cong V^2 \frac{q^4}{4q_z^4} \int_{-\infty}^{\infty} W(\zeta)\mathrm{d}\zeta \int_{S_0} \mathrm{d}\mathbf{R}_0 E_{\mathrm{e}}^{n}(\mathbf{R}'_{0\zeta}) \times$$

$$\times E_{\mathrm{r}}^{n}(\mathbf{R}''_{0\zeta}) W(\boldsymbol{\gamma} = \tilde{\boldsymbol{\gamma}}), \qquad (2)$$

$$P_{\mathrm{f}} \cong \frac{A}{\pi} \int_{-\infty}^{\infty} W(\zeta)\mathrm{d}\zeta \int_{-\infty}^{\infty} W(\boldsymbol{\gamma})\mathrm{d}\boldsymbol{\gamma} \int_{S_0} \frac{\mathrm{d}\mathbf{R}_0}{n_z} E_{\mathrm{e}}(\mathbf{R}'_{0\zeta}) E_{\mathrm{r}}(\mathbf{R}''_{0\zeta}), \qquad (3)$$

$$\tilde{\boldsymbol{\gamma}} = \left(-\frac{q_x}{q_z} - \frac{R_{0x}}{q_z} T, -\frac{R_{0y}}{q_z} s\right),$$

where

$$s = \frac{1}{L_{\mathrm{e}}} + \frac{1}{L_{\mathrm{r}}}; \quad T = \frac{\cos^2\theta_{\mathrm{e}}}{L_{\mathrm{e}}} + \frac{\cos^2\theta_{\mathrm{r}}}{L_{\mathrm{r}}};$$

$$E_{\mathrm{e}}(\mathbf{R}''_{0\zeta}) = E_{\mathrm{e}}^{n}(\mathbf{R}''_{0\zeta})(\mathbf{n}\mathbf{m}_{\mathrm{e}}); \quad E_{\mathrm{r}}(\mathbf{R}''_{0\zeta}) = E_{\mathrm{r}}^{n}(\mathbf{R}''_{0\zeta})(\mathbf{n}\mathbf{m}_{\mathrm{r}});$$

$$q_x = \sin\theta_{\mathrm{e}} + \sin\theta_{\mathrm{r}}; \quad q_z = -(\cos\theta_{\mathrm{e}} + \cos\theta_{\mathrm{r}});$$

$$q^2 = q_x^2 + q_z^2;$$

$$\mathbf{R}'_{0\zeta} = \{[R_{0x}\cot\theta_{\mathrm{e}} - \zeta]\sin\theta_{\mathrm{e}}, R_{0y}\};$$

$$\mathbf{R}''_{0\zeta} = \{[R_{0x}\cot\theta_{\mathrm{r}} - \zeta]\sin\theta_{\mathrm{r}}, R_{0y}\};$$

ζ, $\boldsymbol{\gamma} = (\gamma_x, \gamma_y)$, $\mathbf{n} = (n_x, n_y, n_z)$ are the random height, slope vector, and unit vector normal to sea surface; $E_{\mathrm{e,r}}^{n}(\mathbf{R})$ are the cross-beam intensities of illumination from actual and apparent (with parameters of receiver) sources; $\mathbf{m}_{\mathrm{e,r}}$ are the unit vectors defining the transmitting and receiving directions; $W(\zeta)$ and $W(\gamma)$ are distribution functions for surface heights and slopes; V^2 is the Fresnel reflection coefficient of foam-free sea surface; A is the albedo of foam-covered surface region; $L_{\mathrm{e,r}}$ are the slant distances from source and receiver to the surface; and $\theta_{\mathrm{e,r}}$ are the angles between normal to the plane $z = 0$ and optical axes of source and receiver.

In the integral expressions (2) and (3), the integration is being done over surface S_0 (the projections of random-irregular roughed sea surface onto the plane $z = 0$).

It is possible to evaluate the integrals in Eqs. (2) and (3) and derive the formulas for the power returned from sea surface free of foam and totally covered with foam.[3,5,6] Using these results, we can obtain an expression for the quantity

$$N = [(1 - C_{\mathrm{f}})\, P_{\mathrm{sea}} + C_{\mathrm{f}} P_{\mathrm{f}}]/P_{\mathrm{sea}},$$

equaling the ratio of received power with/without the account of the foam (when, as usual, it is satisfied that

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the root-mean-square wave slope be much larger than the source divergence angle and receiver field of view, and it is assumed that the source and receiver, and their optical axes, are in the same XOZ-plane), namely:

$$N \cong (1 - C_f) + C_f \frac{8Aq_z^4}{V^2 q^4} \exp\left(\frac{q_x^2}{2q_z^2 \overline{\gamma_x^2}} + \frac{1}{2a}\right) \frac{a}{4} \times$$

$$\times \sum_{k=0}^{\infty} \frac{a^{-k}}{k!} \left(\frac{\beta}{2}\right)^{2k} \left\{ \sin\theta_e \sin\theta_r a^{1/4} \frac{\Gamma(2k+2)}{\Gamma(k+1)} \times \right.$$

$$\times W_{-k-0.75,\ k+0.75}\left(\frac{1}{a}\right) - \sin\theta_e \sin\theta_r a^{-1/4} \frac{\Gamma(2k+3)}{\Gamma(k+2)} \frac{\beta}{2} \times$$

$$\times W_{-k-1.25,\ k+1.25}\left(\frac{1}{a}\right) + 2\cos\theta_e \cos\theta_r a^{-1/4} \times$$

$$\left. \times \frac{\Gamma(2k+1)}{\Gamma(k+1)} W_{-k-0.25,\ k+0.25}\left(\frac{1}{a}\right) \right\}, \quad (4)$$

where

$$a = 4\left(\frac{1}{\overline{\gamma_x^2}} + \frac{1}{\overline{\gamma_y^2}}\right)^{-1}; \quad \beta = \frac{a}{4}\left(\frac{1}{\overline{\gamma_x^2}} - \frac{1}{\overline{\gamma_y^2}}\right);$$

$\overline{\gamma_{x,y}^2}$ are the variances of the slopes of a roughed sea surface; $W_{n,m}$ is the Whittaker function; and $\Gamma(k)$ is the gamma function.

Expression (4) enters into the formula obtained in Ref. 3, provided that sea surface slopes are small ($\overline{\gamma_{x,y}^2} \ll 1$), and that only first term of series (4) is considered.

For calculation of N it is necessary to know the reflection characteristics of the foam and the value C_f. Numerous observations in different climatic zones of the world ocean have revealed different empirical relations for relative areas of the sea foam coverage (see, e.g., Refs. 7 and 8). These relations depend strongly on geography and sea surface temperature T_w. The results of statistical processing of observation data (in terms of three model dependences of $C_f(U)$) are presented in the Table.[7,8]

Dependence of C_f on the near-water wind

Model	T_w, °C	U, m/s	$C_f \cdot 10^2$
1	6–22	9–23	$C_f = 0.009U^3 - 0.329U^2 + 4.54U - 21.33$
2	3	9–16	$C_f = 0.189U - 1.285$
3	>14	$U > U_w$	$C_f = 2.95 \cdot 10^{-4} U^{3.52}$; $U_w = 3.36 \cdot 10^{-0.00309T_w}$

The parameter U_w in the third line of the Table is a certain value of near-water wind speed at which the foam starts to form. The parameter T_w is the sea surface temperature, governing U_w value in accordance with the empirical formula presented above.

The foam reflection was measured in Ref. 9, where it was shown that the foam albedo $A \approx 0.5$ in the wavelength region 0.5–1 μm.

Figure 1 shows how N varies for different wind speeds U. The calculations were made for the case of monostatic sensing (coaxial optical arrangement of the lidar receiver and transmitter) for foam models presented in the Table, assuming the following model parameters: $V^2 = 0.02$; $A = 0.5$; $\theta_e = \theta_r = 0$ (a) and $\theta_e = \theta_r = 40°$ (b).

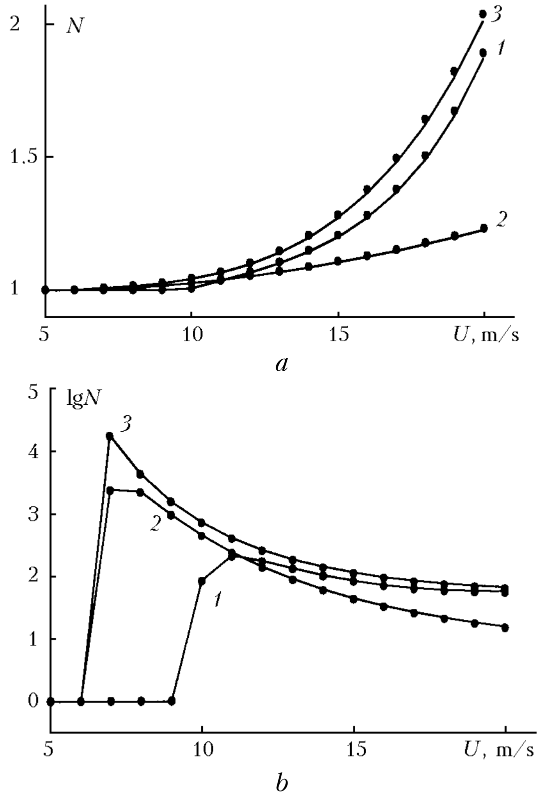

Fig. 1. Dependence of N on the near-water wind speed.

Variances of the surface slopes $\overline{\gamma_{x,y}^2}$ were calculated by Cox and Munk formulas.[4]

Solid lines show the calculations according to formula (4), and dots are for N calculated numerically using integral formulas (2) and (3). Formula (4) well fits the dependence of N on near-water wind speed: the plots calculated from analytical formula almost coincide with the numerical results.

From Fig. 1 it is seen that the presence of foam on sea surface strongly influences the power of lidar return signals. The degree of this influence significantly depends both on the foam model (i.e., the sea surface temperature, geography of measurements, etc.), and on the viewing angles, the tendency most clearly seen from comparison of Figs. 1a and b.

Figure 1a shows that, for a monostatic sensing vertically downward ($\theta_e = \theta_r = 0$), an increase of near-water wind speed U leads to an increase of N (equaling the ratio of received powers with and without the account of the foam effect), starting from a certain (characteristic of a foam model) value of the near-water wind speed, at which foam forms on the sea surface. Physically, this is because the reflection coefficient of foam-covered regions of the sea surface are much larger than that of foam-free regions.

For a monostatic slant sensing (Fig. 1*b*), the dependence of N on U is more complicated. When near-water wind is low (so that sea surface is free of foam yet), $N = 1$ (as in Fig. 1*a*). As near-water wind speed U increases (to a value leading to foam formation on the sea surface), the N value rapidly increases. Physically, this is because at low near-water winds (not leading to foam formation on the sea surface), at viewing angle $\theta_e = \theta_r = 40°$ the power received by lidar is very small (because at low U, the sea surface has near-mirror reflection); and once the foam has appeared on the sea surface (which has a diffuse character of reflection), the received power rapidly increases. With the further increase of U, N reaches a maximum and then decreases with the increasing near-water wind speed (though being still high in the sense that the received power with foam taken into account is larger than that without taking foam into account). This is because, at high near-water winds, the reflection from sea surface, even without taking the foam into account, approaches the diffuse one (due to an increase of the variance of the heights of sea surface slopes with growing near-water wind speed), what leads to a decrease of the foam effect on the return power.

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