LIDAR SOUNDING OF OIL FILMS ON THE SEA SURFACE

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The influence of foam on the sea surface, wind-driven sea waves, lidar parameters, and deviation of the lidar optical axis from the vertical direction on the lidar contrast in the system "oil film–clear sea surface" for pulse remote laser sounding is considered. Analytical expressions have been obtained for the lidar contrast in the system "oil film–clear sea surface" for nadir and slant sounding paths. It is shown that the lidar contrast in the system may substantially degrade for the foam-covered sea surface and deviation of the lidar optical axis from the nadir direction, but still remains fairly sharp at small sounding angles for wide ranges of variations of the driving wind velocity and laser pulse duration.

The important ecological problem that can be solved with the use of a lidar is monitoring of sea water areas to detect oil films on the water surface.

The oil films on the sea surface are reliably detected in the case of nadir sensing[1–3] when the driving wind velocity is small. For high driving wind velocities, the sea surface is covered with foam having high reflectance and influencing substantially the intensity of lidar return signals.[5] Moreover, in the case of remote sensing of extended water areas using scanners, lidar returns will depend strongly on the scanning angle and the driving wind velocity.[6] Acting together, these factors may substantially reduce the contrast of the oil film on the sea surface and thus make the interpretation of lidar measurements more difficult.

How oil-film detection on the sea surface is affected by the driving wind velocity and the scanning angle was studied in Refs. 2–4 for continuous laser sensing of the sea surface. Here, we study the lidar contrast in the system "oil film–clear sea surface," K, as a function of the characteristics of foam on the sea surface, sea surface roughness, lidar parameters, and nadir sensing angle in the case of pulse remote sensing.

Physically, remote detection of oil films on the sea surface by laser sensing method relies upon the contrast of the sea surface covered with oil film against the clear sea surface. Physical factors giving rise to the contrast are[1–4]: (1) different reflectance of oil film and water–air interface and (2) smoother sea surface covered with oil films. In particular, for an even sea surface covered with a thick oil film the highest contrast K (of the order of 80%) is reached in the range 8–12 μm for sensing in the nadir. Reasonably high contrasts (45–50%) are observed in the visible and near-IR wavelength ranges.[1]

The contrast estimates presented in Ref. 1 were obtained for calm weather conditions, when the driving wind velocity was zero and the second physical factor (smoothing of the sea surface) was ignored. For non-zero driving wind velocity, the sea surface becomes rough and the contrast increases several times at all wavelengths.[2] In pulse remote sensing, the contrast K depends strongly not only on the driving wind velocity, but also on the sensing scheme and the parameters of lidar's source and receiver.

First, let us estimate the contrast K in the case of pulse sensing strictly in the nadir.

We define the lidar contrast K in the case of pulse sensing as

$$K = P_{\text{oil}}/P_{\max},$$

where P_{oil} and $P_{\max}$ are the powers of lidar returns from the sea surface with and without oil film at the instant of peak lidar returns.

Using expression for the mean (over many sounding pulses) power of the return signal recorded by the lidar receiver in the case of monostatic sensing of the sea surface in the nadir,[5] we find $t_{\max}$, the time of arrival of the peak signal on the receiver, and $P_{\max}$, the peak power of lidar return

$$P_{\max} \cong c_1(c_2 + c_3)\pi^{-1/2}(N_0\, p^{1/2})^{-1}[1 - (2N_0^2\, p)^{-1}]^{-1} \times \exp\{-0.25(N_0^2 p)^{-1}\}, \quad (1)$$

where

$$c_1 = a_s\, a_r\, c\pi\tau/(2L^3), \quad c_2 = (1 - S_f)V^2/(8\pi(\gamma_x^2\, \gamma_y^2)^{1/2});$$

$$c_3 = AS_f/\pi, \quad N_0 = C_s + C_r, \quad p = \frac{\tau^2\, c^2\, L^2}{16} + 2\sigma^2 L^2,$$

σ^2 and $\gamma_{x,y}^2$ are the variances of the roughness elevations and slopes of the sea surface, L is the distance from the

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lidar to the sea surface, V is the Fresnel reflectance of the sea surface, τ is the duration of a sounding pulse, S_f is the fraction of the sea surface covered with foam, and A is the albedo of the sea surface element covered with foam.

For the transparent aerosol atmosphere[7]

$$a_s = P_0 \exp(-\tau_a)/(\pi\alpha_s^2), \quad a_r = r_r^2 \,\pi \exp(-\tau_a),$$

$$C_{s,r} = (\alpha_{s,r}\, L)^{-2},$$

where $2\alpha_{s,r}$ are the source divergence angle and the receiver field-of-view angle, respectively; P_0 is the power radiated by the source; r_r is the effective radius of the receiving aperture; and, τ_a is the optical depth of the atmosphere.

In the derivation of formula (1), we assumed that $\alpha_{s,r}^2 \ll \gamma_{x,y}^2$ and used asymptotic expansion of the Fresnel integral $\Phi(x)$ valid only when $x \gg 1$ ($x = N_0\, p^{1/2} - 0.5/N_0\, p^{1/2}$), which is easily fulfilled for airborne and spaceborne lidar sensing.

Although derived for the sea surface without oil film, formula (1) also can be used to estimate the lidar returns from the sea surface covered with oil film, considering that the oil film smooths the sea surface roughness (reducing the variances of the roughness elevations and slopes and preventing foam formation) and has different reflectance. In the case of the sea surface covered with oil film, the law of sea surface slope distribution is assumed normal[2,8] as that of the film-free sea surface, while the variance of the slopes is taken to be three times less.

Using formula (1), for sensing in the nadir we obtain

$$K = [V_2^2/(8\pi(\gamma_{2x}^2\, \gamma_{2y}^2)^{1/2})] \times$$

$$\times \{(1 - S_f)V_1^2/(8\pi(\gamma_{1x}^2\, \gamma_{1y}^2)^{1/2}) + S_f\, A_1/\pi\}^{-1} \times$$

$$\times [(\tau^2\, c^2/16 + 2\sigma_1^2)^{1/2}/(\tau^2\, c^2/16 + 2\sigma_2^2)^{1/2}] \times$$

$$\times \{[1 - (2N_0^2\, p_1)^{-1}]/[1 - (2N_0^2\, p_2)^{-1}]\} \times$$

$$\times \exp\{-(0.25/N_0^2)[(p_2)^{-1} - (p_1)^{-1}]\}. \qquad (2)$$

Here, the parameters V, A, γ, σ, and p with subscript 1 are for the sea surface without oil film, while those with subscript 2 are for the film-covered sea surface.

As the lidar optical axis deviates from the nadir, a returned signal recorded by the lidar rapidly decreases. The mean peak power of a signal recorded by lidar's receiver in the case of slant monostatic sensing of the sea surface is calculated from the formula[5]

$$P_{max} \cong b_1\, (b_2 + b_3), \qquad (3)$$

$$b_1 = 2a_s\, a_r\, \pi^{1/2} L^{-4}\, N_0^{-1}\, \Omega^{-1/2},$$

$$\mu = \sin^2\theta(N_0 - 16/(\tau c)^2),$$

$$\Omega = 1 + 2\sigma^2[N_0 \sin^2\theta + 16/(\tau c)^2 - \mu^2/N_0],$$

$$b_2 = (1 - S_f)(V^2/(8\pi(\gamma_x^2\, \gamma_y^2)^{1/2}) \times$$
$$\times \exp(-0.5q_x^2/(q_z^2\, \gamma_x^2)),$$

$$b_3 = S_f\, A \cos^2\theta/\pi,$$

$$q_x = 2\sin\theta, \quad q_z = 2\cos\theta.$$

In the derivation of formula (3), we assumed that $\alpha_{s,r}^2 \ll \gamma_{x,y}^2$ and the angle θ between the lidar optical axis and the nadir is small ($\theta \ll 1$) but much larger than the source divergence and the receiver field-of-view angles.

Using Eq. (3), for off-nadir sensing we derive

$$K = [V_2^2 \exp(-0.5q_x^2(q_z^2\, \gamma_{2x}^2))/(8\pi(\gamma_{2x}^2\, \gamma_{2y}^2)^{1/2})\ ] \times$$

$$\times\{(1 - S_f)V_1^2 \exp(-0.5q_x^2/(q_z^2\, \gamma_{1x}^2))/(8\pi(\gamma_{1x}^2\, \gamma_{1y}^2)^{1/2}) +$$

$$+ \cos^2\theta\, S_f\, A_1/\pi\}^{-1} \times$$

$$\times [(\tau^2\, c^2/16 + 2\sigma_1^2)^{1/2}/(\tau^2\, c^2/16 + 2\sigma_2^2)^{1/2}]. \qquad (4)$$

The best contrast K is obtained for wavelengths of 1.06 and 10.6 μm.

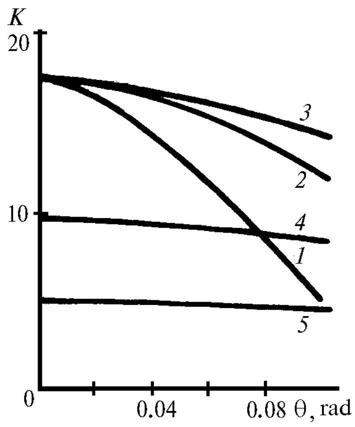

FIG. 1. Angular dependence of the contrast K for $\tau = 10^{-12}$ s.

The curves of the angular dependence of the contrast K for 1.06 μm are shown in Figs. 1 and 2. They were calculated by formulas (2) and (4) with the following parameter values: $L = 3$ km, $\alpha_s = 4\cdot10^{-4}$, $\alpha_r = 6\cdot10^{-4}$, $V_1^2 = 0.02$, $V_2^2 = 0.04$, and $U = 1$ (curves *1*), 5 (curves *2*), 9 (curves *3*), 17 (curves *4*), and 21 m/s (curves *5*).

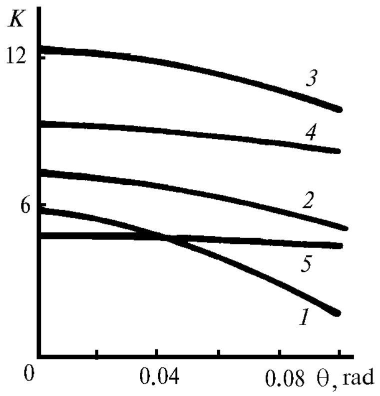

FIG. 2. The same as Fig. 1 but for $\tau = 10^{-8}$ s.

The parameters γ_{1x}^2, γ_{1y}^2, σ_1^2, and S_f were calculated as[8–10]

$$\gamma_{1x}^2 = 3.16\cdot 10^{-3}\, U, \quad \gamma_{1y}^2 = 0.003 + 1.92\cdot 10^{-3}\, U,$$

$$\sigma_1 = 0.016U^2,$$

$$S_f = 0.009\, U^3 - 0.3296\, U^2 + 4.549\, U - 21.33,$$

where U is the driving wind velocity (in m s^{-1}).

It was assumed that in the presence of oil films the variances of roughness slopes $\gamma_{x,y}^2$ and elevations σ^2 decrease by a factor of three and the albedo of foam is[11] $A_f \approx 0.5$.

Examination of the figures allows us to draw the following conclusions:

1. The contrast K depends strongly upon the driving wind velocity and the degree of coverage of the sea surface with foam. For small driving wind velocities, insufficient for foam formation, the greater the driving wind velocity, the higher is the contrast K (due to smoothing of the sea roughness by oil film). For the high driving wind velocity and the sea surface covered with foam, as the driving wind velocity increases, the contrast K considerably decreases, but remains still quite sharp. In this case, the contrast degradation with increasing driving wind velocity is observed because of larger area of water covered with foam (due to higher U), leading to a brighter sea surface and hence a worse contrast K.

2. The contrast K depends strongly on the sensing angle for small driving wind velocity. As lidar optical axis deviates from the nadir, the contrast decreases still remaining high for $\theta > 0.1$ rad in a wide range of variations of the sensing pulse duration.

3. The contrast K depends strongly on the sensing pulse duration. It increases markedly for short sensing pulses ($\leq 10^{-10}$ s). Physically, this is because not only reflectance and variance of sea surface slopes, but also variances of roughness elevations of the sea surface start to affect strongly the lidar contrast.

4. As driving wind velocity increases, the dependence of the contrast K on the sensing angle markedly weakens, especially for high driving wind velocities, leading to foam formation on the sea surface.

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