Two-wave laser method for remote detection of oil spills on rough sea surface

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We consider a two-wave sounding method for detecting oil spills on the sea surface. It is shown that the two-wave method allows one to distinguish between oil spills on the sea surface and areas with smoothed wind-induced wave (for example because of a slick on the water surface) and areas with high reflection coefficient (for instance, caused by a foam on the water surface) and thus to detect oil spills with high reliability.

Today, remote detection and measurement of oil film thickness on water surface from aircraft is most efficiently done by use of laser fluorescence and photometric methods (see, e.g., Refs. 1 and 2). Important advantages of the photometric methods are the simple instrumentation, and, therefore, relatively low cost.

Remote detection of oil spills on water surface with the use of photometric methods is usually performed using a lidar by determining the contrast between the intensity of laser radiation reflected from clear water surface and that from the surface covered with the oil film (see, e.g., Ref. 1). However, this method has one serious drawback as it may take clean water surface for oil-covered because there can occur strong reflectance from a smoothed wind wave (a slick on water surface, a wind shadow behind an island or a high coast) or this can be the area with a high reflection coefficient caused by foam.

To increase reliability of detecting oil spills one has to control simultaneously two effects, namely, the wave smoothing and variation of water surface reflectance (see, for example, Ref. 3). One of such methods (three-beam laser method) has been described in Ref. 4. Below we are describing a two-wave laser method of detecting oil spills that allows simultaneous control of wave smoothing and variation of water surface reflectance thus enabling one to correctly judge on the presence of oil spills.

Assume that a pulsed lidar is mounted onboard an aircraft and irradiates sea surface vertically down with a narrow beam at the wavelengths λ_1 and λ_2. The radiation wavelengths are in the infrared spectral region. The received signal is created by the radiation mirror-reflected from the sea surface.

To detect oil spills on the water area surveyed, we first find a reference portion of the surface, where the water is clean (free of oil spills). The data obtained then used as the criterion for normalization. If the chosen water area consists of the parts strongly different in terms of wave conditions, the reference surface areas must be found in each homogeneous part of the region (any method can be chosen to localize them depending on the situation in the region chosen).

Then lidar records return signals $P_{\rm w}(\lambda_1)$ and $P_{\rm w}(\lambda_2)$ from clean water (that is free from oil spills) at the two wavelengths λ_1 and λ_2. If the lidar pulse length is chosen to satisfy the inequality $\tau_{\rm s}^2 c^2/16 \gg 2\sigma_{\rm w}^2$ ($\sigma_{\rm w}^2$ is the variance of the heights of clean rough sea surface, $\tau_{\rm s}$ is the lidar pulse duration, c is the speed of light), then the powers $P_{\rm w}(\lambda_1)$, $P_{\rm w}(\lambda_2)$ are determined by the equation[5]

$$P_{\rm w}(\lambda_{1,2}) \cong \frac{V_{\rm w}^2(\lambda_{1,2})}{4\pi\left(\gamma_{{\rm w}x}^2\gamma_{{\rm w}y}^2\right)^{1/2}} \frac{a_{\rm s}(\lambda_{1,2})a_{\rm r}(\lambda_{1,2})\pi^{1/2}}{L^4(C_{\rm s}+C_{\rm r})}, \quad (1)$$

where $V_{\rm w}^2$, $\gamma_{{\rm w}x,{\rm w}y}^2$ are the coefficients of reflection and variance of slopes of clean sea surface; L stands for the distance from the lidar to the sea surface (the carrier flight altitude).

For a clear atmosphere

$$a_{\rm s}(\lambda) = P_{\rm s}(\lambda)\exp[-\tau_{\rm a}(\lambda)]/(\pi\alpha_{\rm s}^2);$$

$$a_{\rm r}(\lambda) = r_{\rm r}^2\exp[-\tau_{\rm a}(\lambda)]; \quad C_{\rm s,r} = (\alpha_{\rm s,r}L)^{-2}.$$

Here $a_{\rm s}(\lambda)$ is the illumination of water surface at the laser beam axis: $C_{\rm s,r}^{-1/2}$ are the effective radii of the laser beam cross section and that of lidar receiver's field of view on the water surface; $2\alpha_{\rm s,r}$ are the beam divergence angle and the field of view angle of the lidar receiving optical system; $P_{\rm s}(\lambda)$ is the power of radiation emitted from the source; $r_{\rm r}$ is the effective size of the receiving aperture; $\tau_{\rm a}(\lambda)$ is the optical depth of the atmosphere between the lidar and the sea surface.

Equation (1) was derived for pulsed sensing of sea surface. It determines the average power received at peaks in return signals (this is the power strictly averaged over possible realizations of rough sea surface and the power approximately average over any laser shots). Note that the laser pulse repetition rate can be hundreds hertz and even tens kilohertz. That is why the flight distances over which the received power will be averaged can be as small as several meters even at a high carrier speed.

The inequality $\tau_s^2 c^2/16 \gg 2\sigma_w^2$ for which Eq. (1) is true is not strict and can always be met at an appropriate lidar pulse duration. For example, at $\sigma_w \sim 1$ m (moderate sea, grade 3 on the swell conditions scale corresponding to the surface wind of $U \sim 5.3...7.4$ m/s on the wind force scale) and at $\tau_s = 50$ ns the left-hand side of the inequality is ~ 14 and the right-hand side is ~ 2.

During the aircraft overflight across the water area chosen, the lidar records the return signals $P(\lambda_1)$ and $P(\lambda_2)$ at two wavelengths λ_1 and λ_2:

$$P(\lambda_{1,2}) \cong \frac{V^2(\lambda_{1,2})}{4\pi\left(\gamma_x^2\gamma_y^2\right)^{1/2}} \frac{a_s(\lambda_{1,2})a_r(\lambda_{1,2})\pi^{1/2}}{L^4(C_s + C_r)}, \qquad (2)$$

where V^2, $\gamma_{x,y}^2$ are the coefficients of reflection and the variance of sea surface slopes in the area of interest.

The signals $P(\lambda_1)$ and $P(\lambda_2)$ are normalized to $P_w(\lambda_1)$ and $P_w(\lambda_2)$:

$$\tilde{P}(\lambda_{1,2}) = \frac{P(\lambda_{1,2})}{P_w(\lambda_{1,2})} = \frac{V^2(\lambda_{1,2})}{V_w^2(\lambda_{1,2})} \frac{(\gamma_{wx}^2\gamma_{wy}^2)^{1/2}}{(\gamma_x^2\gamma_y^2)^{1/2}}. \qquad (3)$$

Now, the signals $\tilde{P}(\lambda_1)$, $\tilde{P}(\lambda_2)$ are used to calculate the following quantity:

$$N = \frac{\tilde{P}(\lambda_1)}{\tilde{P}(\lambda_2)} = \left[\frac{V^2(\lambda_1)}{V^2(\lambda_2)}\right] \frac{V_w^2(\lambda_2)}{V_w^2(\lambda_1)}. \qquad (4)$$

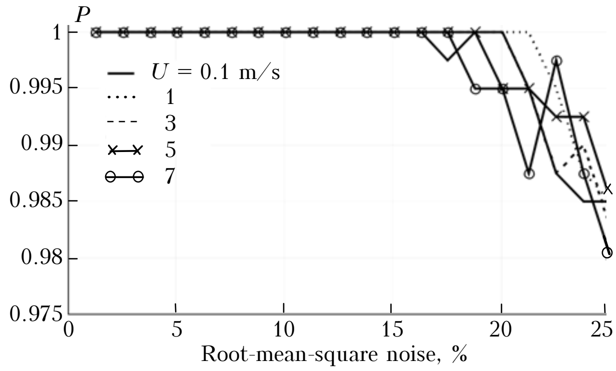
From Eqs. (3) and (4) one can see that the quantity N depends only on the reflection coefficients at the wavelengths $\lambda_{1,2}$ in the considered area and on the reflection coefficients of clean water, while $\tilde{P}(\lambda_{1,2})$ depends both on the reflection coefficients and on the variance of sea surface slopes. Thus, the value of N bears information on the reflection coefficient, while the value of $\tilde{P}(\lambda_{1,2})$ on the sea surface roughness in the area surveyed.

To determine whether or not there are oil spills on the sea surface, the values of N and $\tilde{P}(\lambda_{1,2})$ are compared with the threshold values $K_{1,2}$. If both inequalities, $N > K_1$ and $\tilde{P}(\lambda_{1,2}) > K_2$, are satisfied, the decision is made on the presence of oil spill on the surface.

Feasibility of this method was determined by mathematical modeling for a wide range of values of the parameters involved (the surface wind was varied from 0.1 to 7 m/s; the relative root-mean-square noise value ranged from 1 to 20%; the angles between the surface wind direction and the aircraft flight were 0–180°; wind speed variations for the time of measurements were (0 ... ±2) m/s); wind direction variations during the time of measurements were (0 ... ±0.7) rad).

For $K_{1,2}$ we used either *a priori* chosen values (for example, like in Ref. 6, we believed that in order to make a reliable prediction of an oil spill presence, the threshold must be ≥ 1.5) or the threshold values for $K_{1,2}$ for each particular pair of wavelengths chosen by the method of mathematical modeling. We proceeded from the values of correct detection probability (the probability of detecting the spills that really exist) and false alarm probability (positive response in no-spill situation).

The results obtained by mathematical modeling showed the efficiency of the algorithm that is based on the combined use of the requirements $N > K_1$ and $\tilde{P}(\lambda_{1,2}) > K_2$ and its high reliability in oil spills detection (see the Figure).



Note that the idea of using two-wave measurements with the purpose of detection of oil spills has been advanced earlier (see, e.g., Ref. 7). But this idea supposed such measurements are necessarily to be done at one wavelength near 3.4 μm, where the oil reflectance is roughly equal to that of water.

In practice there can be a lot of variations for the wavelength pairs for this method. The Table shows calculated values of $\tilde{P}(\lambda_2)$ and N for the following pairs: 1.43 and 3.35; 11 and 1.43; 2.5 and 1.06; 2.86 and 3.41 μm. The calculations were done for different water surface patterns: oil spill, slick, foam-covered surface, and clean water (free from oil contamination).

Calculated values of N and $\tilde{P}(\lambda_2)$

Water surface pattern	Wavelength, μm							
	1.43 and 3.35		11 and 1.43		2.5 and 1.06		2.86 and 3.41	
	N	$\tilde{P}(\lambda_2)$	N	$\tilde{P}(\lambda_2)$	N	$\tilde{P}(\lambda_2)$	N	$\tilde{P}(\lambda_2)$
Oil spill	2.36	2.85	2.1	6.7	1.42	6.7	1.71	3.93
Slick	1	10	1	10	1	10	1	10
Foam	14	0.12	0.085	1.68	0.23	3.32	1	0.12
Clean surface	1	1	1	1	1	1	1	1

The reflection coefficients of water and oil were calculated using data from Ref. 3, and the slope variance coefficients $\gamma^2_{x,y}$ were calculated using data from Ref. 8. We assumed for oil films that slope variances $\gamma^2_{x,y}$ reduce by three times (Ref. 8), while for slicks they would reduce by ten times. We took into account that the presence of foam hardly affects the sea surface reflectance at the wavelengths of 2.86, 3.35, and 11 μm. Foam reflection coefficients for the wavelengths of 1.06, 1.43, and 2.5 μm were determined using data from Ref. 9.

It is seen from the Table that both in the case of a slick or foam present on the sea surface, either the value of $\tilde{P}(\lambda_2)$, or that of N can much exceed unity. But only if there is an oil spill on the surface both $\tilde{P}(\lambda_2)$, and N exceed unity. Here, it is not necessary to use 3.4 μm wavelength or anyhow localize around it. However, computer simulation demonstrates that detection results are better if one of the wavelengths is chosen near 3.4 μm.

The Figure shows, for the wavelength pair of 2.86 and 3.41 μm the dependence of the correct detection probability P on the relative root-mean-square noise (the later being the relation between the root-mean-square noise and the mean received signal) at different surface wind velocities and $K_1 = K_2 = 1.5$. It is seen from the Figure that P does not differ from unity even if the relative root-mean-square noise reaches 15 percent. The probability of false alarm in the cases of clean water, a slick, or foam on the water surface is almost zero.

Thus, the two-wave laser sensing method definitely allows one to distinguish oil-polluted areas from those with smoothed wind waves and the areas with high reflectance and thus reliably judge on the presence of oil spills on the sea surface.

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