Method of measuring the thickness of thin oil films on water surface using tunable lasers

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A method of remote monitoring of oil films on water surfaces using a tunable laser is considered. The method is based on the approximation of the measured wavelength dependence of the return intensity by a preset function and the following fitting of the parameters of this function to the measured data. It is shown that the method allows precise reconstruction of the thickness of thin oil films on the water surface.

The active laser radar method is one of the most promising remote methods, which allows detection of oil films, mapping of polluted regions, and measurement of the thickness of oil films.

Consider reflection of a laser beam from a rough sea surface. Assume that the laser operates in the IR spectral region, where water is characterized by high absorption, so the main part of the echo signal is due to the light specularly reflected from the air / water interface, and the part of the light diffusely reflected by the sea depth can be neglected. Take into account that the laser wavelength is short as compared with the characteristic curvature radii and heights of the sea surface. Then, in the Kirchhoff approximation, the field $u(\mathbf{r}_\mathrm{r})$ of the laser beam reflected by the rough sea surface S can be represented as[1,2]:

$$u(\mathbf{r}_\mathrm{r}) = \frac{1}{4\pi i}\int\limits_S v(\mathbf{r},\, \mathbf{r}_r)V(\mathbf{r})u_0(\mathbf{r})[\mathbf{n}(\mathbf{r})\tilde{\mathbf{q}}(\mathbf{r})]\, \mathrm{d}\mathbf{r}, \qquad (1)$$

where

$$\mathbf{n}(\mathbf{r}) = \{n_x,\, n_y,\, n_z\}$$

is the unit vector normal to the rough sea surface S at the point $\mathbf{r}$;

$$\tilde{\mathbf{q}}(\mathbf{r}) = -k\nabla_S(|\mathbf{r} - \mathbf{r}_\mathrm{r}| + |\mathbf{r}_\mathrm{s} - \mathbf{r}|);$$

$\mathbf{r}_\mathrm{s}$ and $\mathbf{r}_\mathrm{r}$ are the vectors determining the positions of the source and the observation point; $u_0(\mathbf{r})$ is the field generated by the laser source on the surface S; $v(\mathbf{r},\, \mathbf{r}_\mathrm{r})$ is the field of the point source; $V(\mathbf{r})$ is the reflection coefficient; k is wavenumber.

Equation (1) was obtained ignoring shadowing and multiple scattering effects (they can be neglected at close-to-vertical sensing).

Using Eq. (1) and the results obtained in Ref. 2 and passing from integration over the randomly rough surface S to integration over its projection S_0 onto the plane $z = 0$, we obtain the following equation for the echo power recorded by a receiver at monostatic sensing of the rough sea surface by a laser beam in the nadir direction (vertically downward) (we assume that the optical axes of the source and the receiver are matched and lying in the plane XOZ of the ground-based coordinate system)[3]:

$$P = V^2 \int\limits_{S_0} \frac{\mathrm{d}\mathbf{R}_0}{n_z} E_\mathrm{s}(\mathbf{R}_0)\, E_\mathrm{r}(\mathbf{R}_0) \times$$

$$\times\, \delta\{K_x[R_{x0}s - 2\gamma_x]\}\, \delta\{K_y[R_{y0}s - 2K_x\gamma_x]\}, \qquad (2)$$

where

$$s = \frac{2}{L};\quad K_{x,y} = \frac{n_z}{\sqrt{1 - n_z^2\gamma_{y,x}^2}};$$

$\delta(x)$ is the delta function; $\mathbf{R}_0$ is the vector in the plane $z = 0$; $E_\mathrm{s}(\mathbf{R})$ and $E_\mathrm{r}(\mathbf{R})$ are the irradiance on the surface due to the actual source and the fictitious source with the receiver's parameters[4]; L is the distance from the center of the irradiated spot (on the sea surface) to the lidar; $\gamma = \{\gamma_x,\, \gamma_y\}$ is the vector of tilts of the rough sea surface S; V^2 is the coefficient of reflection from the smooth sea surface.

At monostatic sensing, the receiver receives the radiation reflected from only those parts of the sea surface, which are normal to the lidar optical axis. Thus, at vertical incidence of the radiation, V^2 in Eq. (2) is the reflection coefficient for elementary horizontal plane plates on the sea surface (i.e., the reflection coefficient for the smooth sea surface). For the homogeneous part of the surface (clear surface or surface covered by an oil film), the value of V^2 is independent of $\mathbf{R}_0$ and therefore it is factored out the integral sign. For the clear sea surface it is the reflection coefficient of the air / water interface, and for the sea surface covered by an oil film it is the reflection coefficient of the air / oil film / water system.

Equation (2) applies to the random (because of the random character of the sensed sea surface) power measured by the lidar receiver. The delta functions

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entering into Eq. (2) show that the received signal has a character of glints arising at mirror reflection of the laser beam from the sea surface.

Physically, the measurement of the thickness of oil films on the water surface by the method of active lidar is based on the dependence of the reflection coefficient of the air / oil film / water system on the film thickness and the radiation wavelength.

The reflection coefficient R_{ref} of the air / oil film / water system has the form[5,6] (under the vertically downward irradiation of the sea surface):

$$R_{\text{ref}}(\lambda, d) = \left| \frac{(Z_1+Z_2)(Z_2-Z_3)e^{-i\alpha(\lambda)d} + (Z_1-Z_2)(Z_2+Z_3)e^{+i\alpha(\lambda)d}}{(Z_1+Z_2)(Z_2+Z_3)e^{-i\alpha(\lambda)d} + (Z_1-Z_2)(Z_2-Z_3)e^{+i\alpha(\lambda)d}} \right|^2, \qquad (3)$$

where $Z_j = 1/m_j$ is the impedance of the jth medium; $m = n + i\kappa$ is the complex refractive index of the medium; n and κ are the refractive index and the absorption coefficient of the medium; $\alpha(\lambda) = 2\pi m_2/\lambda$, λ is the laser radiation wavelength; d is the thickness of the oil film; subscripts 1, 2, and 3 are, respectively, for air, oil, and water.

As is seen from Eq. (3), the reflection coefficient R_{ref} (and, consequently, the intensity of radiation recorded by the lidar receiver) depends on the thickness of the oil film d. Therefore, the value of d can be reconstructed from measurements of the intensity of the reflected radiation (given the oil refractive index and absorption coefficient).

The use of a tunable laser is promising for measurement of the oil film thickness. Figure 1 depicts the function $R_{\text{ref}}(\lambda)$ in the region of 9–11 μm (corresponding to the tuning range $\lambda_{\min} \ldots \lambda_{\max}$ of, for example, the CO_2 laser). The solid curve shows the dependence $R_{\text{ref}}(\lambda)$, and the dashed curve shows its approximation by a sinusoide function; λ_i is the position of extrema of the function $R_{\text{ref}}(\lambda)$.

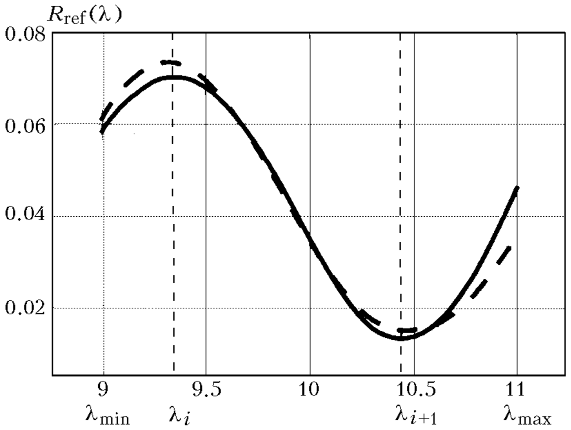

Fig. 1. Wavelength dependence of the reflection coefficient $R_{\text{ref}}(\lambda)$.

There exist some methods of measuring the oil film thickness with the use of tunable radiation and recording of the wavelength dependence of the intensity of reflected radiation.[7,8] In these methods, the oil thickness is determined from the analysis of the wavelength dependence of the echo intensity by measuring the distance between the extrema (maxima or minima) or the number of extrema in the laser tuning range. The film thickness is determined from the position of neighboring extrema as

$$d = \frac{1}{2n_2(\lambda_{i+1} - \lambda_i)} \lambda_i \lambda_{i+1} .$$

A disadvantage of these methods is the inability of measuring the thickness of thin films, when the number of extrema in the wavelength dependence of the echo intensity becomes less than two. To measure the thickness of thin oil films (when only one or even no an extreme is present in the laser tuning range), the processing algorithm based on the approximation of the measured wavelength dependence of the echo intensity by some preset function is used. This approximating function may be a function similar to Eq. (3) for the reflection coefficient of the three-layer air / oil film / water system or a sinusoidal function like

$$R_{\text{ref}}(\lambda) \cong A \sin\left(\frac{4\pi n_2(\lambda)\tilde{d}}{\lambda} + B\right) \exp\left(-\frac{4\pi\kappa_2(\lambda)\tilde{d}}{\lambda}\right) + C, \qquad (4)$$

where A, B, C, and $\tilde{d}$ are the approximation parameters.

Approximation is performed by the least-squares method through fitting to the echo readouts in the selected wavelength region. The global minimum of the function of the standard deviation between the approximating function and the measurements is sought. Approximation parameters (and, consequently, the film thickness) are determined numerically from the closest agreement between the measurements and the approximating function.

To check the efficiency of the described algorithm, the measurement of the thickness of oil films on the water surface was numerically simulated. The simulation was performed by a closed cycle: the thickness of the oil film d on the water surface was specified; the laser tuning range was selected; results of measurement at sensing wavelengths were simulated; for some current value of the film thickness $\tilde{d}$ the values of the approximating functions and their standard deviation $\xi(d, \tilde{d})$ from the “measurements” were calculated; the values of $\tilde{d}$, at which the function $\xi(d, \tilde{d})$ has minima, were determined; the global minimum was taken and the corresponding value of $\tilde{d}$ was thought to be the film thickness d_r reconstructed from the measurements.

In mathematical simulation, the tuning range was taken to be 9–11 μm, and the number of wavelengths in this range was equal to 100. The thickness d of the oil film on the water surface was taken equal to 6, 10, and 14 μm. In this case, the reflection coefficient $R_{\text{ref}}(\lambda)$ had no one extreme in the tuning range (for $d = 6$ μm), only one maximum (for $d = 10$ μm), and two maxima (for $d = 14$ μm).

The results of numerical simulation on reconstruction of the film thickness for approximation by Eqs. (3) and (4) and different rms values of the measurement noise are given in the Table.

These results show that the algorithm based on the approximation of the measured wavelength dependence of the echo intensity and fitting of the approximation parameters to the measured data allows reconstruction of the thickness of oil films on the water surface with acceptable accuracy. The accuracy of the reconstruction is especially high (less than 1%) for the approximation function in the form (3).

Table. Relative error $\Delta = |(d - d_r) / d| \cdot 100\%$ of determination of the film thickness

Relative rms noise	Approximation					
	Eq. (3)			Eq. (4)		
	Preset film thickness *d*, μm					
	6	10	14	6	10	14
0.05	0.085	0.055	0.031	17.2	10.2	0.77
0.2	0.37	0.23	0.10	17.3	10.1	1.59
0.4	0.73	0.47	0.20	13.4	6.3	3.21

In conclusion it should be noted that, in the case of high noise, pre-smoothing of the measured signals significantly decreases the errors of reconstruction of the film thickness by the method described in this paper.

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