Laser method for measuring the oil film thickness at the rough sea surface based on determination of the oil transmission coefficient

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The paper describes a three-wave remote laser method of measuring the oil film thickness at the rough sea surface based on the determination of the oil film transmission coefficient. Mathematical modeling shows that the method makes it possible to measure the oil film thickness between 5 and 140 μm. The mean error of the determination, in most cases, is no less than 15% in a series of 30 measurements at a relative root-mean-square value of measurement noise of 2%.

At present, the most effective methods for remote measurement of the oil film thickness at the sea surface are the laser fluorescence and spectrophotomety.[1,2] An important advantage of the spectrophotometry method is a relative simplicity of the equipment and, hence, its low cost. However, the disadvantage is the necessity of performing the multispectral measurements (with the use of several tens of wavelengths). Below we describe the spectrophotometry method of measuring the petroleum film thickness using only three wavelengths.

Assume that the lidar is mounted on board of the aircraft and irradiates the sea surface in nadir (vertically downwards) by a narrow beam.

To measure the petroleum product film thickness at the water area under study, a checking area is chosen with a pure (without oil pollutions) sea surface, which measurements are used for normalizing.[3] At the water area with a pure surface the lidar records the powers of lidar returns: $P_w(\lambda_1)$, $P_w(\lambda_2)$, and $P_w(\lambda_3)$ at the wavelengths $\lambda_{1,2,3}$. If the laser pulse duration is chosen so that the inequality $\tau_s^2 c^2/16 \gg 2\sigma_w^2$ (σ_w^2 is the dispersion of heights of pure rough sea surface; τ_s is the laser pulse duration; c is the light velocity) holds, then the powers $P_w(\lambda_{1,2,3})$ are determined by the following formula[3,4] (at moderate wind velocity adjacent water, when the foam formations are lacking at sea surface):

$$P_w(\lambda_{1,2,3}) \cong \frac{R_{w\mathrm{ref}}(\lambda_{1,2,3})}{4\pi(\gamma_{wx}^2\gamma_{wy}^2)^{1/2}} \frac{a_s(\lambda_{1,2,3})a_r(\lambda_{1,2,3})\pi^{1/2}}{L^4(C_s + C_r)}, \qquad (1)$$

where $R_{w\mathrm{ref}}(\lambda)$, $\gamma_{wx,wy}^2$ is the reflection coefficient (from the surface unperturbed by the sea swell) and the dispersion of tilts of pure sea surface; L is the distance from lidar to the surface (the height of a carrier); for the clear atmosphere:

$$a_s(\lambda) = P_s(\lambda)\exp[-\tau_a(\lambda)]/(\pi\alpha_s^2),$$

$$a_r(\lambda) = \pi r_r^2 \exp[-\tau_a(\lambda)]; \quad C_{s,r} = (\alpha_{s,r}L)^{-2};$$

$2\alpha_{s,r}$ is the angle of source divergence and the angular visual field of the receiving system; $P_s(\lambda)$ is the radiation intensity emitted by the source; r_r is the effective size of the receiving aperture; $\tau_a(\lambda)$ is the atmospheric optical thickness between lidar and sea surface.

Formula (1) was obtained at pulse sensing of the sea surface. It determines the mean received power at moments of lidar return peaks. The pulse repetition rate is hundreds of Hz and even tens of kHz. Therefore, the length of flight distances, at which the received power is averaging, can be short: some meters even at high velocity of the carrier flight. The inequality $\tau_s^2 c^2/16 \gg 2\sigma_w^2$, at which the formula (1) is valid, is not rigid and always can be made by choosing the appropriate pulse duration of the lidar.[3]

At the aircraft flight above the water area (polluted by petroleum products) the lidar records at three wavelengths λ_1, λ_2, and λ_3 of the power $P(\lambda_{1,2,3})$ of the lidar returns is

$$P(\lambda_{1,2,3}) \cong \frac{R_{\mathrm{ref}}(\lambda_{1,2,3},d)}{4\pi(\gamma_x^2\gamma_y^2)^{1/2}} \frac{a_s(\lambda_{1,2,3})a_r(\lambda_{1,2,3})\pi^{1/2}}{L^4(C_s + C_r)}, \qquad (2)$$

where $R_{\mathrm{ref}}(\lambda, d)$, $\gamma_{x,y}^2$ is the reflection coefficient and dispersion of tilts (of sea surface covered by oil film); d is the oil film thickness.

At vertical irradiation for $R_{\mathrm{ref}}(\lambda, d)$ we have:

$$R_{\mathrm{ref}}(\lambda, d) = \frac{r_{12}^2 + r_{23}^2 T^2(\lambda) + 2r_{12}r_{23}T(\lambda)\cos[2\beta(\lambda,d) + \delta_{23} - \delta_{12}]}{1 + r_{12}^2 r_{23}^2 T^2(\lambda) + 2r_{12}r_{23}T(\lambda)\cos[2\beta(\lambda,d) + \delta_{23} + \delta_{12}]}, \qquad (3)$$

where

$$r_{12} = \sqrt{\frac{[1 - n_2(\lambda)]^2 + k_2^2(\lambda)}{[1 + n_2(\lambda)]^2 + k_2^2(\lambda)}};$$

$$\delta_{12} = \pi + \arctan\left[\frac{k_2(\lambda)}{n_2(\lambda) - 1}\right] - \arctan\left[\frac{k_2(\lambda)}{n_2(\lambda) + 1}\right];$$

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$$\beta(\lambda,d) = \frac{2\pi d}{\lambda} n_2(\lambda);$$

$$\delta_{23} = \arctan\left[\frac{k_2(\lambda)-k_3(\lambda)}{n_2(\lambda)-n_3(\lambda)}\right] - \arctan\left[\frac{k_2(\lambda)+k_3(\lambda)}{n_2(\lambda)+n_3(\lambda)}\right];$$

$$r_{23} = \sqrt{\frac{[n_2(\lambda)-n_3(\lambda)]^2+[k_2(\lambda)-k_3(\lambda)]^2}{[n_2(\lambda)+n_3(\lambda)]^2+[k_2(\lambda)+k_3(\lambda)]^2}};$$

$$T(\lambda) = \exp\left(-\frac{4\pi k_2(\lambda)d}{\lambda}\right);$$

$n_{2,3}(\lambda)$, $k_{2,3}(\lambda)$ are the indices of refraction and the absorption of oil and water; r_{12}, r_{23} are the reflection coefficients at the "air–oil" and "oil–water" boundaries of the media.

The signals $P(\lambda_{1,2,3})$ are normalized to $P_w(\lambda_{1,2,3})$:

$$\tilde{P}(\lambda_{1,2,3}) = \frac{P(\lambda_{1,2,3})}{P_w(\lambda_{1,2,3})} = \frac{R_{\text{ref}}(\lambda_{1,2,3},d)}{R_{w\text{ref}}(\lambda_{1,2,3})}\frac{(\gamma_{wx}^2\gamma_{wy}^2)^{1/2}}{(\gamma_x^2\gamma_y^2)^{1/2}}. \quad (4)$$

The wavelength λ_3 is chosen to be equal to 3.41 μm, where the oil absorption peak exists.[5] Therefore, at $\lambda_3 \cong 3.41$ μm, because of large oil absorption (i.e., small value of T), when the oil film thicknesses is more than 4–5 μm, we have:

$$R_{\text{ref}}(\lambda_3,d) \cong r_{12}^2(\lambda_3).$$

Further we normalize the signals $\tilde{P}(\lambda_{1,2})$ to $\tilde{P}(\lambda_3)$:

$$\tilde{\tilde{P}}(\lambda_{1,2}) = \frac{\tilde{P}(\lambda_{1,2})}{\tilde{P}(\lambda_3)} \cong R_{\text{ref}}(\lambda_{1,2},d)K_{1,2}, \quad (5)$$

where

$$K_{1,2} = \frac{r_{13}^2(\lambda_3)}{r_{13}^2(\lambda_{1,2})r_{12}^2(\lambda_3)}.$$

The formula (5) for normalized signals $\tilde{\tilde{P}}(\lambda_{1,2})$ can be represented in the form:

$$\tilde{\tilde{P}}(\lambda_{1,2})K_{1,2}^{-1} \cong r_{12}^2(\lambda_{1,2}) + r_{23}^2(\lambda_{1,2})T^{2w_{1,2}} + $$
$$+2r_{12}(\lambda_{1,2})r_{23}(\lambda_{1,2})T^{w_{1,2}}\cos\left[4\pi n_2(\lambda_{1,2})d/\lambda_{1,2} + \Delta_1(\lambda_{1,2})\right]/$$
$$/\left\{1 + r_{12}^2(\lambda_{1,2})r_{23}^2(\lambda_{1,2})T^{2w_{1,2}} + 2r_{12}(\lambda_{1,2})r_{23}(\lambda_{1,2})T^{w_{1,2}} \times\right.$$
$$\left.\times\cos\left[4\pi n_2(\lambda_{1,2})\,d/\lambda_{1,2} + \Delta_2(\lambda_{1,2})\right]\right\}, \quad (6)$$

where $\Delta_{1,2}(\lambda) = \delta_{23}(\lambda) \mp \delta_{12}(\lambda)$; $T = T(\lambda_1)$; $w_1 = 1$; and $w_2 = k_2(\lambda_2)\lambda_1/[k_2(\lambda_1)\lambda_2]$.

The system of equations (6) contains only one unknown value (the film thickness d) but due to d entering trigonometric functions, we fail to determine it uniquely. However, equation (6) allow exclusion of the trigonometric functions, if λ_1 and λ_2 are chosen in some special way. Now we select λ_1 and λ_2 from the condition $2\varphi_1 = \varphi_2$, where

$$\varphi_1 = \frac{4\pi n_2(\lambda_1)d}{\lambda_1}, \quad \varphi_2 = \frac{4\pi n_2(\lambda_2)d}{\lambda_2}.$$

To fulfill this condition, we have

$$\cos\left[\frac{4\pi n_2(\lambda_2)d}{\lambda_2}\right] = 2\cos^2\left[\frac{4\pi n_2(\lambda_1)d}{\lambda_1}\right] - 1. \quad (7)$$

Using Eq. (7) for excluding trigonometric functions from Eq. (6), we can derive the relationship connecting the measurements at λ_1 and λ_2 with T. The precise type of this relationship occupies a large place, therefore its approximate expression is presented taking into account small values of $\delta_{12}(\lambda_2)$, $\delta_{12}(\lambda_1)$, and $\delta_{23}(\lambda_1)$:

$$(-1 + 2G_1^2)\cos[\delta_{23}(\lambda_2)] \pm$$
$$\pm\sqrt{1-(-1+2G_1^2)^2}\sin[\delta_{23}(\lambda_2)] = G_2, \quad (8)$$

where

$$G_{1,2} = -\left\{\tilde{\tilde{P}}(\lambda_{1,2})K_{1,2}^{-1}\left[1 + r_{12}^2(\lambda_{1,2})r_{23}^2(\lambda_{1,2})T^{2w_{1,2}}\right] - \right.$$
$$\left.-r_{12}^2(\lambda_{1,2}) - r_{23}^2(\lambda_{1,2})T^{2w_{1,2}}\right\}/$$
$$/\left\{2T^{w_{1,2}}\left|r_{12}(\lambda_{1,2})\right|\left|r_{23}(\lambda_{1,2})\right|\left[1 - \tilde{\tilde{P}}(\lambda_{1,2})K_{1,2}^{-1}\right]\right\}.$$

Equation (8) includes only one (and not trigonometric) function depending on the film thickness, (T is the oil film transmission at λ_1). Calculating from Eq. (8) the value of T, we can uniquely (neglecting the roots (8), which do not correspond to the physical meaning and measurements) determine d at the known absorption coefficient $k_2(\lambda)$.

Similarly to the above-mentioned procedures using analytical formulas, the numerical algorithm of d determination is based on the search for minimum of the discrepancy:

$$\left\{\left[\tilde{\tilde{P}}(\lambda_1) - \tilde{\tilde{P}}(\lambda_1,d)_{\text{mod}}\right]^2 + \left[\tilde{\tilde{P}}(\lambda_2) - \tilde{\tilde{P}}(\lambda_2,d)_{\text{mod}}\right]^2\right\}^{1/2}, \quad (9)$$

where $\tilde{\tilde{P}}(\lambda_{1,2})$ are the normalized values determined from the measurements; $\tilde{\tilde{P}}(\lambda_{1,2},d)_{\text{mod}}$ are the model values of quantities [Eq. (5)] depending on d.

The potentialities of the above method were investigated by the method of mathematical modeling for a "typical" oil.[5] Figures 1–3 show the most characteristic results of simulation for wavelengths $\lambda_1 = 5.76$, $\lambda_2 = 2.86$, and $\lambda_3 = 3.41$ μm (2.86 and 5.76 μm are connected by the condition $2\varphi_1 = \varphi_2$; $\lambda = 2.86$ μm corresponds to the peak of the reflection coefficient at the boundary "oil–water").

The numerical analysis algorithm (9) was used and the possible fluctuations of the film thickness at the water surface were considered (from the experimental data they were given ~ 8%).

Figure 1 shows the case of single measurements. Here the realization of the calculated value of the film thickness d depending on the real value (given at mathematical modeling) is shown. The presented realization corresponds to a certain realization of the noise at a relative root-mean-square value of the measurement noise σ, being equal to 2% (the value σ is determined as the ratio between the r.m.s. noise value and the mean value of the received signal). A straight line is the dependence, for which the calculated value of d coincides with the real value.

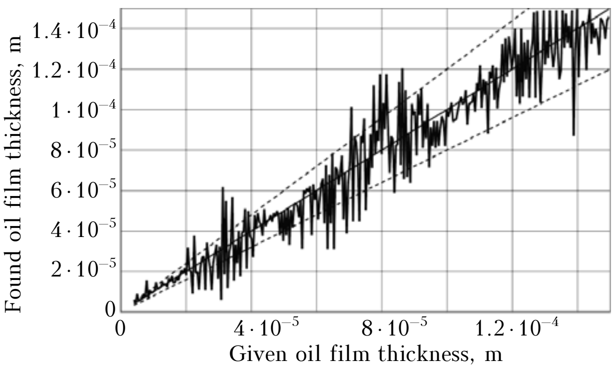

Fig. 1. The dependence of the found oil film thickness value on the real value of the thickness at individual measurements.

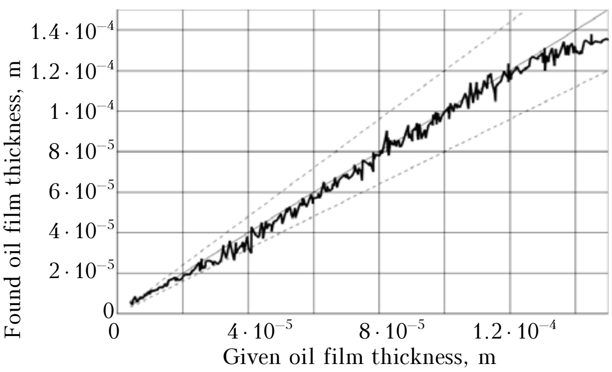

Fig. 2. The dependence of the found oil film thickness value on the real thickness value in the case of averaging the results over a series of 30 measurements.

Direct dot-dash lines show 20% difference of d from the real value. Figure 2 shows the case of results averaging over a series of measurements at σ = 2%. Here we can see the realization of the calculated value of the oil film thickness depending on the true value of the thickness for a series of 30 measurements. Figure 3 shows the mean relative error (%) of d determination. In Fig. 3 the line (*1*) corresponds to σ = 1%, (*2*) corresponds to σ = 4%.

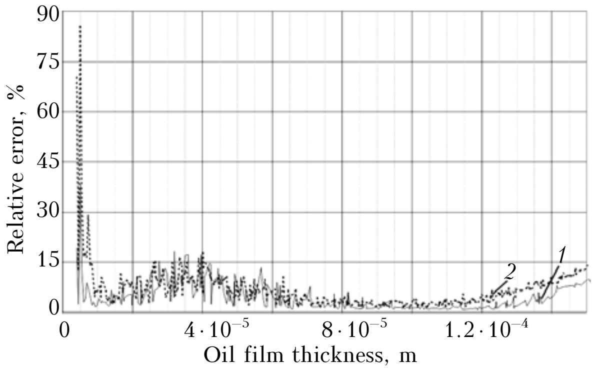

Fig. 3. The dependence of mean error of the determination of the oil film thickness on the real value of the thickness in a series of 30 measurements.

Results of numerical modeling have shown that the method, based on determination of the film transmission coefficient, makes it possible to conduct the measurements of the oil film thickness between 5 and at least 140 μm. The mean error of the film thickness determination in most cases is no worse than 15% for a series of 30 measurements and σ = 2%.

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