Determination of phase incursion difference in a film for sounding wavelengths as a base for a laser method of measurements of oil film thickness on a rough sea surface

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The remote laser method is considered based on determination of the difference of phase incursion in a film at sounding wavelengths and intended for measurements of thin film thickness on a rough sea surface. Mathematical simulation demonstrates that the method permits one to measure film thickness of units and tenth parts of micrometer by sounding at close wavelengths. For a collection of wavelengths: 0.767, 0.800, 0.792, and 1.600 μm, the range of measurements of film thickness is 0.1–6.4 μm. Mean error in determining film thickness in most cases is not worse than 5% for a series of 30 measurements and root-mean-square value of measurement noise of 1%.

Petroleum and its products are the most widespread pollutants of water area at our planet (see, for instance, Refs. 1, 2).

Accidents at tank ships, oil pipelines, and in oil storage tanks are most dangerous in frequency and spread of oil. Just after the spillage, the thickness of oil film can amount to several centimeters. After elapse of time, the film thickness decreases. The minimal mean thickness of the oil slick at which an oil pollution spot stops to exist as a unit is estimated between 4 and 100 μm.[3,4] At the same time (see, for instance, Refs. 5–7), the thickness of petroleum product films in some measurements was much less than 4 μm (down to 0.1 μm).

At present, the most efficient methods for remote measurement of oil film thickness on the water surface are the laser fluorescence and spectrophotometry (see, for instance, Refs. 6, 8).

Relative simplicity of equipment and, consequently, a low cost are the merit of the spectrophotometric method. However, the necessity of multi-spectral measurements (with the use of several tens of spectral measurement channels) is its disadvantage. A spectrophotometric method, using only three sounding wavelengths and permitting one to measure oil film thickness from 5 μm up to at least 140 μm is described in Ref. 9. Below we describe a spectrophotometric method for measuring oil film thickness. This method uses four sounding wavelengths and makes it possible to measure thickness of oil films from units to tenth parts of micrometer.

Let the aircraft-born lidar irradiate the sea surface vertically downwards by a narrow beam at four sounding wavelengths of the infrared range, so that the received laser signal is created by irradiation reflected from the sea surface.

At the part of the flight before the polluted sea area, the aircraft-born lidar registers and memorizes of echo-signal powers $P_w(\lambda_{1,2,3,4})$ at the wavelength $\lambda_{1,2,3,4}$ from the clean sea surface. When flying over the target sea area, the lidar registers echo powers $P(\lambda_{1,2,3,4})$.

In the block of data processing, the signals $P_w(\lambda_{1,2,3,4})$ and $P(\lambda_{1,2,3,4})$ are normalized by powers radiated by the lidar source at the corresponding wavelengths:

$$\hat{P}_w(\lambda_{1,2,3,4}) = P_w(\lambda_{1,2,3,4})/P_s(\lambda_{1,2,3,4}), \quad (1)$$

$$\hat{P}(\lambda_{1,2,3,4}) = P(\lambda_{1,2,3,4})/P_s(\lambda_{1,2,3,4}), \quad (2)$$

where $P_s(\lambda_{1,2,3,4})$ are lidar powers at the wavelengths $\lambda_{1,2,3,4}$.

The signals $\hat{P}(\lambda_{1,2,3,4})$ are respectively normalized in the block of data processing by $\hat{P}_w(\lambda_{1,2,3,4})$:

$$\hat{\hat{P}}(\lambda_{1,2,3,4}) = \hat{P}(\lambda_{1,2,3,4})/\hat{P}_w(\lambda_{1,2,3,4}). \quad (3)$$

The signals $\hat{\hat{P}}(\lambda_{1,3,4})$, in turn, are normalized by $\hat{\hat{P}}(\lambda_2)$ to eliminate influence of stochastic and unknown sounding characteristics of the surface roughness (the choice of a wavelength for normalization is not of principal importance; mathematical simulation demonstrates that the difference in results of film thickness measurements is insignificant at different wavelengths used in normalization):

$$\hat{\hat{\hat{P}}}(\lambda_{1,3,4}) = \hat{\hat{P}}(\lambda_{1,3,4})/\hat{\hat{P}}(\lambda_2). \quad (4)$$

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For definiteness, we suppose that sounding wavelengths lay in the near IR range of the spectrum where absorptive indices of water and oil are much less than unity. This permits one not to take into account phase shifts (excluding the phase incursion depending on the film thickness) arising at radiation reflection at the boundaries of the interfaces air–oil and oil–water and depending on optical characteristics of the media. The absorption coefficients are supposed to be small at sounding wavelengths only for simplicity of analysis of the formulas; actually, this requirement is not fundamental. Then the signals $\hat{\hat{\hat{P}}}(\lambda_{1,3,4})$ are defined by the following expressions[9]:

$$\hat{\hat{\hat{P}}}(\lambda_i) = A_i^{-1} \times$$
$$\times \frac{r_{12}^2(\lambda_i) + r_{23}^2(\lambda_i)T^2(\lambda_i) - 2r_{12}(\lambda_i)r_{23}(\lambda_i)T(\lambda_i)\cos[\varphi(\lambda_i)]}{1 + r_{12}^2(\lambda_i)r_{23}^2(\lambda_i)T^2(\lambda_i) - 2r_{12}(\lambda_i)r_{23}(\lambda_i)T(\lambda_i)\cos[\varphi(\lambda_i)]}, \tag{5}$$

where

$$i = 1,\ 3,\ 4;\ \ \varphi(\lambda_i) = \cos\left[\frac{4\pi n_2(\lambda_i)d}{\lambda_i}\right];$$

$$T(\lambda_i) = \exp\left(-\frac{4\pi k_2(\lambda_i)d}{\lambda_i}\right);\ \ T = T(\lambda_2);$$

$$A_i = \left(\frac{r_{13}^2(\lambda_i)}{r_{13}^2(\lambda_2)}\right)\times$$
$$\times \frac{r_{12}^2(\lambda_2) + r_{23}^2(\lambda_2)T^2 - 2r_{12}(\lambda_2)r_{23}(\lambda_2)T\cos[\varphi(\lambda_2)]}{1 + r_{12}^2(\lambda_2)r_{23}^2(\lambda_2)T^2 - 2r_{12}(\lambda_2)r_{23}(\lambda_2)T\cos[\varphi(\lambda_2)]};$$

$n_2(\lambda)$, $k_2(\lambda)$ are refractive index and absorption coefficient of oil (the lower indices of refractive index and absorption coefficient correspond to designations of media in the three-layer air–oil–water system: 1, 2, 3 mean, respectively, air, oil, and water; $n_1 = 1$, $k_1 = 0$); r_{12}, r_{23}, r_{13} are reflection coefficients at the air–oil, oil–water, and air–water boundaries; d is the film thickness.

By Eq. (5), taking into account that $T(\lambda_{1,2,3}) = T^{\lambda_2 k_2(\lambda_{1,3,4})/[\lambda_{1,3,4}k_2(\lambda_2)]}$, we obtain

$$\cos[\varphi(\lambda_i)] =$$
$$= \left\{\hat{\hat{\hat{P}}}(\lambda_i)A_i\left[1 + r_{12}^2(\lambda_i)r_{23}^2(\lambda_i)T^{2\lambda_2k_2(\lambda_i)/[\lambda_ik_2(\lambda_2)]}\right] - r_{12}^2(\lambda_i) -\right.$$
$$\left. - r_{23}^2(\lambda_i)T^{2\lambda_2k_2(\lambda_i)/[\lambda_ik_2(\lambda_2)]}\right\}\Big/\Big\{2r_{12}(\lambda_i)r_{23}(\lambda_i)\times$$
$$\times(-1)T^{\lambda_2k_2(\lambda_i)/[\lambda_ik_2(\lambda_2)]}\left[1 - \hat{\hat{\hat{P}}}(\lambda_i)A_i\right]\Big\}. \tag{6}$$

The sounding wavelengths $\lambda_{1,2,3}$ must be close to each other (this requirement is explained below).

Let us consider the case when the sounding wavelengths λ_1 and λ_3 are chosen symmetrically with respect to λ_2 so, that

$$\varphi_1 = \varphi_2 + \Delta\varphi \text{ and } \varphi_3 = \varphi_2 - \Delta\varphi$$

$$(\text{i.e., } \lambda_1 = \lambda_2 - \Delta\lambda \text{ and } \lambda_3 \cong \lambda_2 + \Delta\lambda,\ \lambda_2 \gg \Delta\lambda).$$

Here $\Delta\varphi$ is the difference of phase incursions in an oil film for the sounding wavelengths λ_1 and λ_2:

$$\left(\Delta\varphi = 4\pi d n_2(\lambda_2)\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right],\ \varphi_i = \varphi(\lambda_i)\right).$$

Then, by Eq. (6), we have

$$\cos\varphi_3 \pm \cos\varphi_1 = \frac{2\cos\varphi_2\cos\Delta\varphi}{2\sin\varphi_2\sin\Delta\varphi} =$$
$$= \left\{\hat{\hat{\hat{P}}}(\lambda_3)A_3\left[1 + r_{12}^2(\lambda_3)r_{23}^2(\lambda_3)T^{2\lambda_2k_2(\lambda_3)/[\lambda_3k_2(\lambda_2)]}\right] -\right.$$
$$\left. - r_{12}^2(\lambda_3) - r_{23}^2(\lambda_3)T^{2\lambda_2k_2(\lambda_3)/[\lambda_3k_2(\lambda_2)]}\right\}\Big/\Big\{2r_{12}(\lambda_3)r_{23}(\lambda_3)\times$$
$$\times(-1)T^{\lambda_2k_2(\lambda_3)/[\lambda_3k_2(\lambda_2)]}[1 - \hat{\hat{\hat{P}}}(\lambda_3)A_3]\Big\} \pm$$
$$\pm \left\{\hat{\hat{\hat{P}}}(\lambda_1)A_1\left[1 + r_{12}^2(\lambda_1)r_{23}^2(\lambda_1)T^{2\lambda_2k_2(\lambda_1)/[\lambda_1k_2(\lambda_2)]}\right] -\right.$$
$$\left. - r_{12}^2(\lambda_1) - r_{23}^2(\lambda_1)T^{2\lambda_2k_2(\lambda_1)/[\lambda_1k_2(\lambda_2)]}\right\}\Big/\Big\{2r_{12}(\lambda_1)r_{23}(\lambda_1)\times$$
$$\times(-1)T^{\lambda_2k_2(\lambda_1)/[\lambda_1k_2(\lambda_2)]}[1 - \hat{\hat{\hat{P}}}(\lambda_1)A_1]\Big\}. \tag{7}$$

The right-hand sides of Eq. (7) depend on the measured values [$\hat{\hat{\hat{P}}}(\lambda_3), \hat{\hat{\hat{P}}}(\lambda_1)$], optical characteristics of water and oil products [$r_{12}(\lambda_{1,2,3})$, $r_{13}(\lambda_{1,2,3})$, $r_{23}(\lambda_{1,2,3})$, $k_2(\lambda_{1,2,3})$], transparency of the film T and $\cos\varphi_2$. The left-hand sides of Eq. (7) depend on $\cos\varphi_2$ ($\sin\varphi_2$) and $\cos\Delta\varphi$ ($\sin\Delta\varphi$).

In principle, formulas (7) make it possible to determine oil film thickness on a water surface by measurements at only three close sounding wavelengths ($\lambda_{1,2,3}$). However, the solution of the system of equations (7) becomes unstable in the presence of noise.

The algorithm determining the film thickness by measuring in addition to three close wavelengths $\lambda_{1,2,3}$ also at λ_4 is more stable; λ_4 is chosen specially from the condition

$$\frac{n_2(\lambda_4)}{\lambda_4} = \frac{n_2(\lambda_2)}{2\lambda_2}. \tag{8}$$

Such a choice of λ_4 makes it possible to determine the cosine of phase incursion in the oil film at λ_2 from measurements at λ_2 and λ_4 (in this case $\cos\varphi_4 = \cos(\varphi_2/2)$ what makes it possible to find $\cos\varphi_2$ from the expression (6) for $i = 4$). This additional measurement makes the calculation algorithm for determination of film thickness significantly more stable. In this case, the uniqueness in d determination is provided by the initial interval of $\cos\Delta\varphi$ (or $\sin\Delta\varphi$) uniqueness. The condition determining the uniqueness interval has the form

$$\Delta\varphi \cong 4\pi d n_2(\lambda_2)\left[\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right] \le \frac{\pi}{2}$$

or

$$d \le \frac{\lambda_1\lambda_2}{8(\lambda_2-\lambda_1)n_2(\lambda_2)}.$$

This condition allows finding $\Delta\lambda = \lambda_2 - \lambda_1$ at the given d or the interval of unique determination of film thickness at the given $\Delta\lambda$.

For instance, at $\lambda_1 = 0.767$ μm, $\lambda_2 = 0.800$ μm, $n_2(\lambda_2) \approx 1.5$ we have $d \le 1.6$ μm.

The parameter T in Eqs. (6), (7) very few differs from 1 at the interval $d \le 1.6$ μm and chosen wavelengths 0.767, 0.800, 0.792, and 1.600 μm. It is replaced by 1 or by an *a priori* chosen value (for instance, it can correspond to the middle of a thickness interval 0–1.6 μm, and then it is determined more exactly after the first iteration step in the procedure of d determination from Eq. (7)).

A similar (to the described procedures, which are based on analytical formulas) numerical algorithm for d determination is based on minimization of residual:

$$\left\{\left[\bar{\bar{\bar{P}}}(\lambda_1)-\bar{\bar{\bar{P}}}(\lambda_1,d)_{\text{mod}}\right]^2+\left[\bar{\bar{\bar{P}}}(\lambda_3)-\bar{\bar{\bar{P}}}(\lambda_3,d)_{\text{mod}}\right]^2+\right.$$
$$\left.+\left[\bar{\bar{\bar{P}}}(\lambda_4)-\bar{\bar{\bar{P}}}(\lambda_4,d)_{\text{mod}}\right]^2\right\}^{1/2}, \qquad (9)$$

where $\bar{\bar{\bar{P}}}(\lambda_i)$ are determined from measurements; $\bar{\bar{\bar{P}}}(\lambda_i,d)_{\text{mod}}$ are model values of the corresponding functions depending on the film thickness d.

The uniqueness interval of the film thickness determination can be increased if $\Delta\lambda = \lambda_2 - \lambda_1$ is decreased (in this case, λ_1 and λ_3 need not be symmetrical relative to λ_2). However, it should be taken into account that the $\Delta\lambda$ decrease leads to some increase of error in determination of film thickness.

Possibilities of the described method for measurement of film thickness were studied by mathematical simulation for a "typical" petroleum.[10]

Particular values of wavelengths in calculations were chosen as follows: $\lambda_1 = 0.767$, $\lambda_2 = 0.800$, $\lambda_3 = 0.792$, and $\lambda_4 = 1.600$ μm (note that there are many possible collections of wavelengths and we present only one as an example).

For the chosen wavelengths, the condition, which defines the uniqueness interval has the form

$$\Delta\varphi \cong 4\pi d n_2(\lambda_2)\left[\frac{1}{\lambda_2}-\frac{1}{\lambda_3}\right] \le \frac{\pi}{2}$$

($\Delta\varphi$ is difference of phase incursions in a film for λ_3 and λ_2) or

$$d \le \frac{\lambda_3\lambda_2}{8(\lambda_2-\lambda_3)n_2(\lambda_2)}.$$

For $\lambda_3 = 0.792$ μm, $\lambda_2 = 0.800$ μm, and $n_2(\lambda_2) \approx 1.5$, $d \le 6.4$ μm.

Figures 1–3 present characteristic results of simulation for the case of averaged d with respect to a series of 30 measurements (without averaging, the errors in determination of film thickness are very large due to smallness of $\Delta\lambda = \lambda_3 - \lambda_2 = 0.008$ μm).

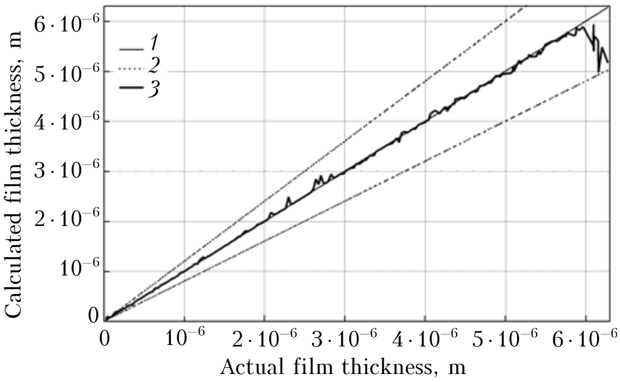

Fig. 1. Calculated film thickness as a function of actual thickness at σ = 1%: actual film thickness (curve *1*); 20% difference from the actual value of thickness (*2*); calculated value of film thickness (*3*).

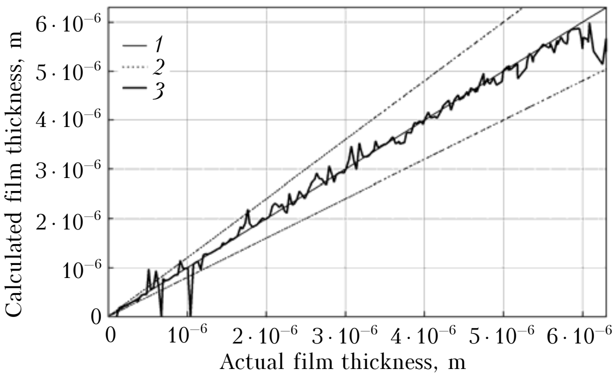

Fig. 2. Calculated film thickness as a function of actual thickness at σ = 2%: actual film thickness (curve *1*); 20% difference from the actual value of thickness (*2*); calculated film thickness (*3*).

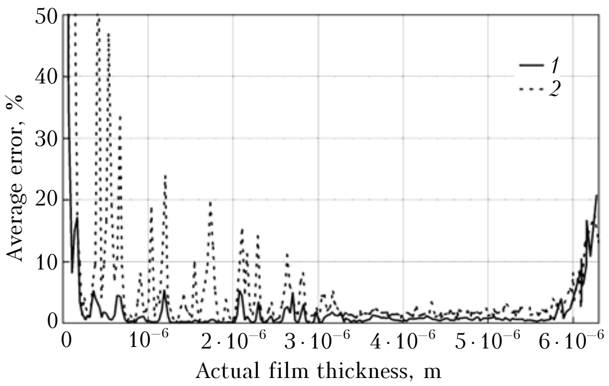

Fig. 3. Mean error of determination of film thickness as a function of the actual film thickness: σ = 1% (*1*), 2% (*2*).

These results were obtained by the numerical algorithm[9] for d determination. The processing program preanalyzed the data of "measurements" and took a decision on their applicability for determination of film thickness.

Figures 1 and 2 present the realizations (line *3*) of the calculated film thickness versus the real (given in mathematical simulation) value of the thickness with relative root-mean-square value of the measurement noise $\sigma = 1$ and 2%, respectively. Here the straight thin line *1* (diagonally crossing Figs. 1, 2) is the function, for which the calculated value of film thickness coincides with its real value. The straight dotted lines *2* show the 20% difference from the real value. As is seen from Fig. 1, it is possible to determine the film thickness with a high accuracy at $\sigma = 1\%$. For $\sigma = 2\%$ (see Fig. 2), the accuracy of determination is markedly lower. Figure 2 presents also dips up to zero in values of the obtained d. They correspond to points, in which the processing program refused to determine d because of bad data of "measurements". Note that appropriate accuracy of d determination can be provided at high noises by the increase of the averaged measurement series.

Fig. 3 presents the mean error in d determination as a function of the real value of the film thickness. Note that the largest errors fall to the range of the minimal film thicknesses.

The results of mathematical simulation show that measurement of the difference of oil film phase incursions permits one to determine the thin film thickness for oil products from units to tenth fractions of micrometer. For wavelengths of 0.767, 0.800, 0.792, and 1.600 μm, it is possible to determine oil film thickness in the range from 0.1 to 6.4 μm (with $\sigma = 1\%$ for the difference of 20% between calculated and real values of the film thickness). The difference between calculated values of film thickness and its real values exceeds 20% at the boundaries of this thickness range. Within the range, mean error for the determined film thickness is not worse than 5% for a series of 30 measurements at $\sigma = 1\%$.

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