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USING REMOTE LASER TECHNIQUE IN MEASURING OIL FILM THICKNESS ON WATER SURFACE IN THE EYE-SAFE SPECTRAL RANGE

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Abstract

Possibilities were studied of using a remote laser spectrophotometric method in measuring thickness of oil films on a wavy water surface with utilization of discretely tunable laser source operating at eye-safe narrow spectral range around ~ 2.1 μm. Laser spectrophotometric method is based on measuring reflection coefficient of the water surface on five probing wavelengths and finding thickness of the oil film by the quasisolution search method. It is proposed to use an optical parametric generator tunable along a wavelength in the 1.5–2.6 μm spectral range as a radiation source. Results of mathematical simulation are provided for the optical characteristics of typical oil and pure sea water with a mean square value of measurement noise of 1, 2 and 3 %. Results of mathematical simulation demonstrate that remote laser spectrophotometric method based on the quasi-solution selection technique makes it possible to measure oil films with a thickness from several micrometers to ~ 130 μm with an error of no more than 30 % for measurements with noise mean sguare error of 1–3 %

Keywords

Laser remote method, water surface, oil film, thickness measurement

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Introduction. Among the substances that contaminate seas and oceans, oil and oil products are the most common pollutants [1–3].

The most common causes of oil spills are tanker accidents, accidents at oil pipelines, oil and oil product storage facilities, fueling and pumping installations.

Spilled oil stays on water surface in the form of a film for a long period of time. Immediately after an accident, the oil film thickness on water surface could be of the order of several centimeters. After a certain period of time (under influence of gravity and surface tension), the oil film thickness decreases to 1–0.1 mm. Next, weathering of light fractions and oil partial dissolution in water is taking place.

Minimum oil film thickness, when an oil spill on the water surface still exists as a whole, is estimated by different authors from 4 to 100 microns [4, 5].

Offshore zone oil pollution is quickly detected by remote probing methods that make it possible to monitor water basins in a relatively short period of time. Remote probing methods have another important advantage, as they provide monitoring oil pollution at the film stage on water surface (i.e., in short time after the spill). Cleaning water surface from oil pollution at this stage could be carried out at the lowest cost [6].

Tasks in monitoring oil pollution of marine, lake and river water basins include identification and mapping oil contamination, as well as measuring film thickness of oil pollution on the water surface. Determination of oil pollution area and film thickness makes it possible to estimate the spilled oil amount and are the basis for decision making on taking measures to eliminate oil contamination.

There are many optical methods currently in measuring the film thickness on substrates, and they include spectral and angular reflectometric methods, interference methods, ellipsometry, laser triangulation, Fourier spectroscopy [7–16], etc. Analytical equipment developed on the basis thereof makes it possible to measure film thickness from nanometer units (and even less) to hundreds of nanometers (or more).

However, not all these methods could be modified for the task of measuring oil films on water surface. Measurements should be remote, monostatic (combined source and receiver); while the oil film thickness could appear in a wide range from micrometer units to micrometer tens and hundreds.

The most promising methods in remote detection and measurement of the oil film thickness on water surface are currently the lidar methods based on measuring laser induced fluorescence radiation, radiation Raman scattering and reflection coefficients on a number of probing wavelengths [3, 6, 17–27].

Disadvantage of the lidar methods based on measuring laser-induced fluorescence radiation and Raman scattering radiation lies in the possibility of monitoring the water surface only at the low (~ 100–150 m) flight altitude of the carrier, which leads to insignificant field of view over the water surface and, therefore, to low efficiency of these methods.

As of today, development of laser equipment to measure the oil film thickness from a high-altitude flying aircraft (to provide larger monitoring area and higher monitoring efficiency) is becoming more topical. To ensure operation of a high-altitude carrier in a wide range of weather conditions and regardless of time of the day, such equipment should be laser reflectometric (based on measuring reflection coefficients). Such laser equipment should ensure measurement of oil films with thicknesses from several micrometers to 100–150 microns.

Known laser reflectometry methods used in measuring the oil film thickness on water surface (providing measurement of the oil film thickness in the thickness range from several micrometers to 100–150 microns) involve utilization of either a laser source tunable in a wide spectral range (to provide several tens of probing wavelengths), or the use of a laser source tunable along the wavelength in the spectral range potentially hazardous to vision, or the use of several lasers with very different radiation wavelengths [25–27].

This work describes a new laser reflectometry method for remote measurement of the oil film thickness on water surface, where a single laser could be utilized with eye-safe wavelength and discretely wavelength tunable in the narrow spectral range.

Problem statement. It is assumed that laser locator is installed on a delivery aircraft and irradiates water surface vertically downward (for example, when probing from a delivery aircraft).

We assume that the near-water wind speed is not high, and there is no foam on the water surface. Then, optical radiation scattering on wavy water surface is described within the Kirchhoff method framework, which takes into account dependence of the wavy water surface reflection character on the degree of its unevenness and on the water optical parameters [28].

We assume that radiation wavelength is in the near IR or middle IR (laser signal registered by a receiver is mainly generated by radiation specular reflected from the surface). Let us take into account that radiation wavelength is low in comparison with the curvature characteristic radii and the sea surface height. Laser source is considered to be continuous (laser operation pulse mode would not affect description of the method under consideration).

In the Kirchhoff approximation, the $u(r_r)$ laser beam field reflected by the S wavy sea surface could be represented in the following form [6]:

$$u(r_r)=\frac{1}{4\pi i}\int_S v(r,r_r)R(\lambda,r)\,u_o(r)[n(r)\,\tilde{q}(r)]\,dr\,, \qquad (1)$$

where $\tilde{q}(r)=-k\nabla_S(|r-r_r|+|r_s-r|)$; $n(r)=\{n_x, n_y, n_z\}$ is the unit normal vector to the S wavy (randomly uneven) sea surface at the s point; r_s, r_r are the vectors that determine source position and observation point; $u_o(r)$ is the laser source field on the S surface; $v(r, r_r)$ is the point source field; $R(\lambda, r)$ is the reflection coefficient (depending in general on wavelength and spatial coordinates); k is the wave number.

Formula (1) was obtained without taking into account shading and effects of multiple scattering.

Passing from integration over the S randomly uneven surface to integration over its S_o projection (Fig. 1) and considering the water surface irradiated section to be homogeneous (in terms of its reflection characteristics), we obtain the following formula for the $P(\lambda)$ power detected by receiver at the vertical downwards laser beam monostatic location of the wavy sea surface [6, 28]:

$$P(\lambda) = R(\lambda)\int \frac{d\vec{R}_o}{n_z} E_s(\vec{R}_o)\, E_r(\vec{R}_o)\times$$
$$\times\ \delta\left\{K_x\left[R_{x\,o}s-2\gamma_x\right]\right\}\delta\left\{K_y\left[R_{y\,o}\,s-2\,K_x\gamma_y\right]\right\}, \qquad (2)$$

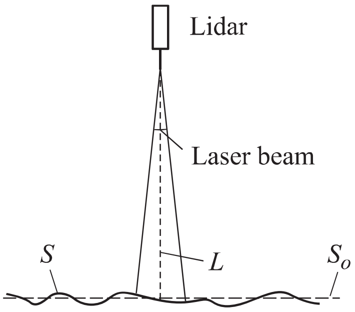

Fig. 1. Scheme of monostatic vertical probing

where $s=\dfrac{2}{L}$; $K_{x,y}=\dfrac{n_z}{\sqrt{1-n_z^2\,\gamma_{y,x}^2}}$; $R(\lambda)$ is the coefficient of reflection from an undisturbed water surface (covered with oil film or clean surface) at radiation vertical incidence; $\vec{R}_o$ is the vector in the S_o plane; $E_s(\vec{R})$ and $E_r(\vec{R})$ are illumination on water surface from a laser source and from a fictitious source with the receiver parameters [30]; $\vec{\gamma} = \{\gamma_x, \gamma_y\}$ is the S wavy water surface slope vector; n_z is the vertical component of the single normal vector to wavy water surface; $\delta(x)$ is the delta function; L is the delivery carrier flying height above water surface (above the S_o middle plane).

Delta functions included in expression (2) show that the signal registered by the locator receiver has the character of separate flares arising from specular reflections of laser radiation from water surface (if irradiated vertically downward, flares would occur when reflected from peaks and troughs of waves on surface).

When water surface is covered with a film of oil pollution, the $R(\lambda)$ value is reflection coefficient of the three-layer “air–oil pollution film–water” system and depends in a complex way (due to interference of radiation reflected from the “air–oil pollution film” and “oil pollution film–water” interface) on the λ radiation wavelength and the d film thickness.

Formula for $R(\lambda)$ in probing geometry shown in Fig. 1 has the following form [6, 29]:

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

where $\alpha(\lambda)=(2\pi/\lambda)m_2$; $Z_j=1/m_j$ is wave impedance of the j-th medium; $m = n + ik$ is the complex medium refraction indicator; n, k are the refraction and medium absorption indicators; indices 1, 2 and 3 relate to air, oil and water, respectively.

Radiation interference effect leads to the fact that the $R(\lambda)$ reflection coefficient measurement result on the λ wavelength ambiguously determines the d thickness of the oil pollution film.

This clearly could be seen from Fig. 2, which presents results of calculating the $R(\lambda)$ reflection coefficient dependence by formula (2) on the d film thickness for the probing wavelength of 1.54 μm.

Ambiguity in determining the d film thickness of the $R(\lambda)$ reflection coefficient value measurement at the λ single probing wavelength could be eliminated when measuring at several probing wavelengths and using special measurement data processing algorithms.

Laser spectrophotometric method used in measuring the oil film thickness on a water surface will be considered below; the method is introducing measurements on several wavelengths in the spectral range safe for vision.

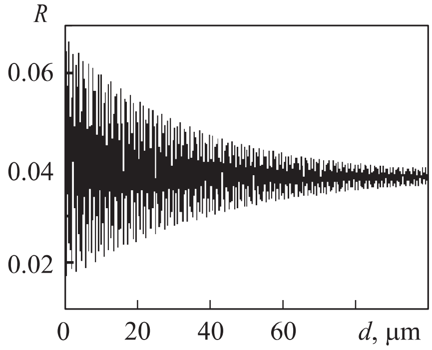

Fig. 2. $R(\lambda)$ reflection coefficient dependence on the film thickness for the probing wavelength of 1.54 μm

Selecting the probing wavelength tuning range safe for vision. Use of lasers for remote sensing is associated with eye danger. Moreover, the wavelength of a laser used in the monitoring system is of utmost importance.

Radiation in the visible and near IR ranges of 0.38–1.4 μm passing through the anterior eye media and affecting the retina is most dangerous* [30]. Laser radiation in the UV range with the 0.2–0.38 μm wavelength and in the near IR

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* State standard GOST 31581–2012. Laser safety. General safety requirements for development and operation of laser products. Moscov, Standartinform Publ., 2013 (in Russ.).

range with wavelengths of more than 1.4 μm is safer because it affects the anterior eye media.

Fig. 3 [30] makes it possible to assess radiation safety for vision in a wide spectral range from UV to mid-IR. Dependence is demonstrated here on the laser pulse energy radiation wavelength, which provides maximum safety for vision (at durations and repetition frequencies of radiation pulses characteristic of laser remote probing systems, i.e., pulse duration of 6 ns and laser pulse repetition frequency of 100 Hz).

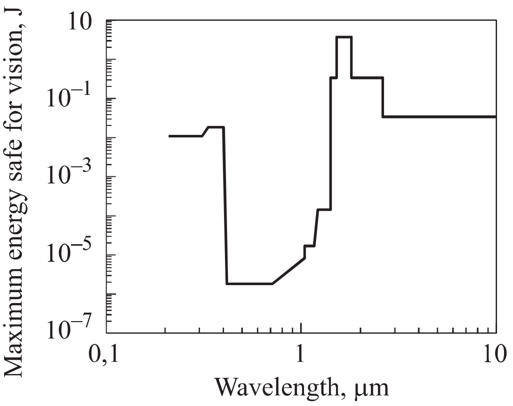

Fig. 3. Dependence on the laser pulse energy radiation wavelength that is maximum safe for vision

Fig. 3 shows that from the point of view of safety for the eyes, it is better to use sources of laser radiation in the spectral range of 1.4–2.5 μm.

Earth's atmosphere absorption in the near IR range is presented in Fig. 4 [31]. It follows from the Figure that from the point of view of atmosphere transparency it is better to use (in the spectral region of 1.4–2.5 μm) laser sources in the spectral range of 1.54–1.7 μm or 2.04– 2.35 μm in the laser remote probing systems.

Laser sources of these wavelengths and with pulse energy from units up to 10 MJ (suitable for remote laser probing) are currently quite affordable. For example, one of the suitable options could be optical parametric generator using the Nd:YLF laser (yttrium-lithium fluoride with neodymium doping) [32]. These radiation sources are adjusted in the spectral range of 1.5–2.6 μm, have pulse duration of 6–10 ns, and pulse repetition frequencies of 100–1000 Hz.

Laser method of determining oil film thickness on water surface using reflection coefficient measurement on several wavelengths. To determine film thickness, it is necessary to measure the reflection coefficient on several wavelengths and to solve the following system of nonlinear equations:

$$\begin{cases} R_{\text{mod}}\left(\lambda_1, d\right) = R_{meas}\left(\lambda_1\right); \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ R_{\text{mod}}\left(\lambda_n, d\right) = R_{meas}\left(\lambda_n\right), \end{cases} \tag{4}$$

where n is the number of probing wavelengths, where reflection coefficient is measured; $R_{meas}\left(\lambda_i\right)$ is the reflection coefficient value measured on the λ_i wavelength; $R_{mod}\left(\lambda_i, d\right)$ is the reflection coefficient theoretical (model) value on the λ_i wavelength.

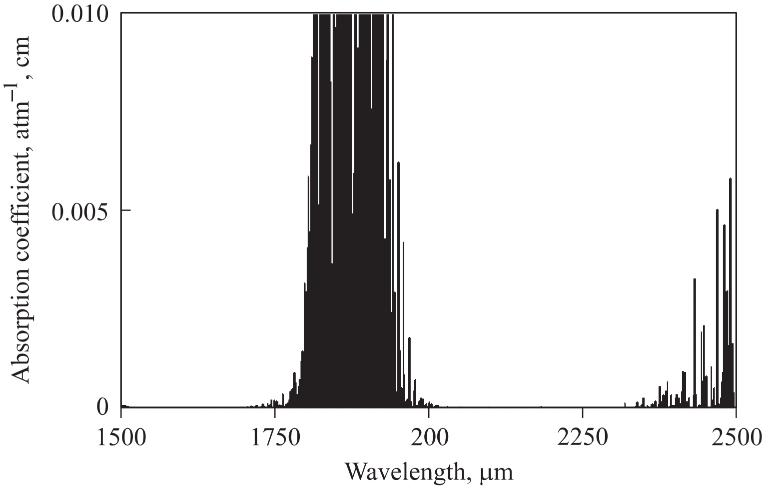

Fig. 4. Earth’s atmosphere absorption

Let us introduce the $E(d)$ discrepancy function

$$E(d) = \sum_{i=1}^{n} \left[R_{meas}\left(\lambda_i\right) - R_{\text{mod}}\left(\lambda_i, d\right)\right]^2. \tag{5}$$

The d film thickness value turning the $E(d)$ function to zero would be solution to the system of nonlinear equations (4).

However, not every set of the $R_{meas}\left(\lambda_i\right)$ values from the admissible values range (corresponding to the reflection coefficient physical meaning) would comply in the general case with the d film thickness, which is solution to the system of equations (4) and turns the discrepancy function (5) to zero. Even if insignificant measurement noise is present, it is possible that for the reflection coefficient measured values there would be no solution to the system of equations (4). Thus, inverse problem of determining the film thickness from the results of measuring the reflection coefficient on several wavelengths is an incorrectly posed mathematical problem [33, 34]. One of the most efficient in solving such problems is the quasisolution selection method [33, 34].

The concept of quasisolution is introduced for incorrectly posed problems Quasisolution selection mode in our case consists in looking for the $\tilde{d}$ film thickness that minimizes the $E(d)$ discrepancy between $R_{\mathrm{mod}}\left(\lambda_i, d\right)$ and $R_{meas}\left(\lambda_i\right)$. The $\tilde{d}$ quasisolution is found from the following condition:

$$E(\tilde{d}) = \inf\nolimits_{d\in M} \sum_{i=1}^{n} \left[R_{meas}\left(\lambda_i\right) - R_{\mathrm{mod}}\left(\lambda_i, d\right)\right]^2, \tag{6}$$

where $\inf_{d\in M}$ is the ρ value exact lower boundary for various values of the d film thickness belonging to the M region (region bounded by the d values having physical meaning for the problem being solved).

Thus, the problem of selecting a quasisolution to the system of equations (4) could be reduced to finding the $E(d)$ minimum discrepancy function in a certain limited range of d values determined by the problem physical meaning.

Mathematical simulation of the quasisolution selection method operation in the problem of measuring oil film thickness on water surface. Atmosphere transparency is slightly higher for a transparency window of 2.04–2.35 µm (than for the transparency window of 1.54–1.7 µm); therefore, let us select for determination a safe for vision radiation wavelength of 2.1 µm as the probing wavelength.

Mathematical simulation was carried out to study possibilities of the laser spectrophotometric method in measuring the oil film thickness using a laser source with eye-safe wavelength discretely tunable at a narrow spectral range around ~ 2.1 µm.

Optical characteristics of “typical” oil and pure sea water were used in the mathematical simulation [29]. Measurement noise was considered normal with a zero mean value and rms value in the range from 0 to 5 %.

Mathematical simulation carried out iteratively. Formula (3) was used as a model dependence of the reflection coefficient on the probing wavelength and on the oil film thickness. Reflection coefficient “measured” values were calculated by formula (3) for the given film thickness taking into account the measurement additive noise. Reflection coefficient “measurement” was carried out on five wavelengths: $\lambda_1 = 2.1 - 2\Delta\lambda$ µm, $\lambda_2 = 2.1 - \Delta\lambda$ µm, $\lambda_3 = 2.1 - \Delta\lambda$ µm, $\lambda_4 = 2.1 + \Delta\lambda$ µm, $\lambda_5 = 2.1 + \Delta\lambda$ µm, $\Delta\lambda$ was set from 0.001 to 0.01 µm. Finding of discrepancy function $E(d)$ minimum was carried out by exhaustive search.

Results of mathematical simulation of the quasisolution selection method operation for the problem of measuring the oil film thickness on water surface. Fig. 5–8 show mathematical simulation results of the quasisolution selection method operation for the problem of determination of the oil film thickness on water surface according to measurements of reflection coefficients on five wavelengths in the narrow spectral interval.

In Fig. 5–8, thick black line shows the film thickness determined value, thin black line shows the actual thickness value, and dashed black lines show the 30 % difference from the actual thickness value. Restored values of the oil film thickness are shown along the ordinate axis, and set values — along the abscissa axis.

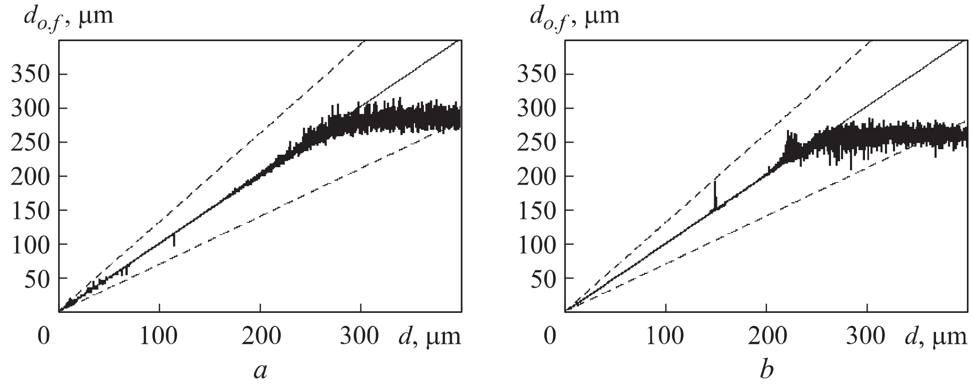

Fig. 5. Result of the oil film thickness restoration for σ = 1 %:
a at Δλ = 1 nm, *b* at Δλ = 10 nm

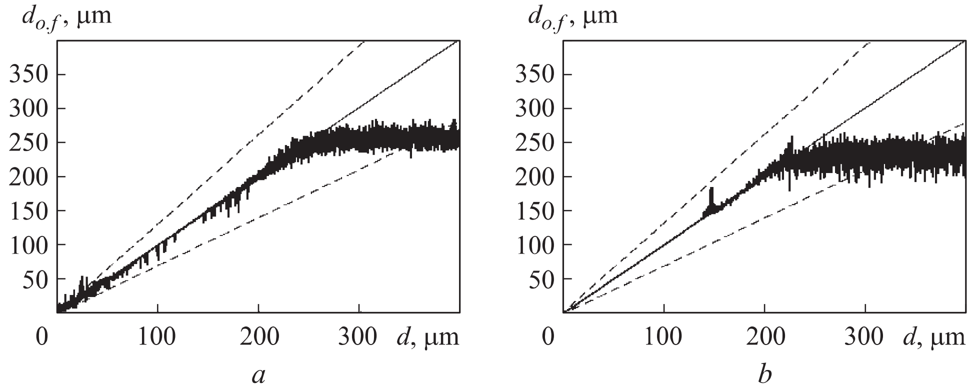

Fig. 6. Result of the oil film thickness restoration for σ = 2 % (*a, b*, see Fig. 5)

Fig. 5–7 show random realizations, i.e., results of restoring the oil film thickness values for the σ mean square measurement noise.

Fig. 5–7 demonstrate that the described algorithm using five probing wavelengths makes it possible to restore the oil film thickness in the range of up to ~ 130 μm from the measurement data with high accuracy (at Δλ = 10 nm).

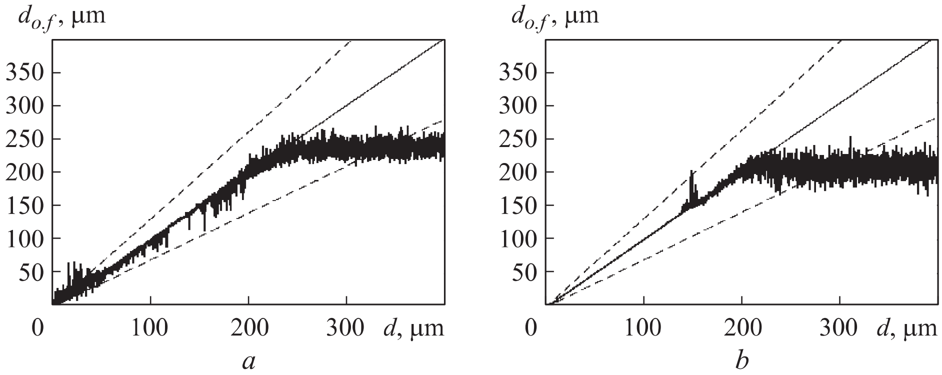

Fig. 7. Result of the oil film thickness restoration for σ = 3 % (*a, b*, see Fig. 5)

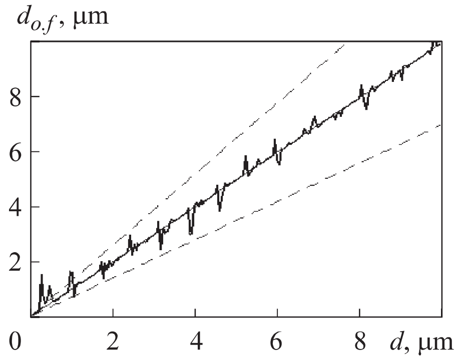

Fig. 8. Result of the oil film thickness restoration in the range 0–10 nm for σ = 2 %

The lower boundary in determining the oil film thickness could be estimated in Fig. 8, which shows random realization, i.e., result of restoring the oil film thickness value for Δλ = 10 nm and the mean square measurement noise of 2 % in the thickness range 0–10 nm. It could be seen that determination error is less than 30 % for films with thickness ranging from about few nanometers or more.

Conclusion. Possibilities were studied of using the remote method in measuring the oil film thickness on water surface using a laser with eye-safe wavelength, which is discretely tunable along five wavelengths at narrow spectral range around 2.1 μm. Results of mathematical simulation show that the remote laser spectrophotometric method based on the quasisolution selection technique makes it possible to measure oil films with a thickness from several μm to ~ 130 μm with an error of no more than 30 % for measurements with noise mean square error of 1–3 %.

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