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OPTICAL METHOD OF DETECTION OF OIL CONTAMINATION ON WATER SURFACE IN UV SPECTRAL RANGE

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ABSTRACT

Efficiency analysis of optical (photo and radiometric) method of oil contamination detection based on differences between reflective characteristics of clean and oil-contaminated water surfaces was conducted with sounding wave selection in UV, visible, near-infrared and medium-infrared regions of the spectrum. It is shown that, in terms of eye safety, width of thickness interval of detected oil films and atmospheric attenuation, the most promising type of sounding for monitoring of oil contamination is UV sounding at a wavelength of 0.355 μm, which allowing to detect oil films with thickness of at least 2 μm reliably with probability of correct detection exceeding 0.9 and probability of false alarms of 0.002 with relative measurement noise not exceeding 5 %.

Keywords: remote optical method, vision-safe radiation wavelengths, UV region of spectrum, oil contamination on water surface, detection

1. INTRODUCTION

The problem of environmental protection, first of all, the air and water environment, is one of the most important problems nowadays [1–6].

One of the top positions among contaminants of oceans, seas, lakes, and rivers of our planet is taken by oil and products of its processing. The main factors of oil contamination of sea, lake, and river spaces are disasters with vessels (especially tankers), offshore oil industry, oil pipeline accidents (especially at crossings of rivers, channels, lakes, and reservoirs), damage of underground oil product storages and leakages of their content, river flows, etc. [2, 4, 7–10].

In terms of frequency and volume of oil spillage, the most dangerous are accidents with oil carriers and accidents during offshore oil production as well as accidents with oil pipelines, oil storages, and oil products (when spillages are detected by monitoring instruments). In these cases, the fact of emergency spillages of oil is usually known, and the objective of mapping the oil stain and control of its evolution over time rises.

No less important is the objective to detect oil contamination, when spillages cannot be detected by monitoring instruments and in case of different accidents when corresponding information is not announced. For prevention of environmental consequences of such contaminations, it is preferable to detect them as soon as possible.

The topic of the article is the development of operative remote optical (photo and radiometric) detection method of oil contaminations on the water surface.

2. PROBLEM FORMULATION

A rapid growth of contamination of water environment with oil products results in necessity to develop the methods and equipment for their timely detection.

Remote methods that allowing to inspect large areas during a small period and to conduct both detection and mapping of contaminations comply with all requirements to oil contamination detection means to the fullest extent.

For operative remote detection of oil contaminations on the water surface, especially for near-shore regions of seas and during the early phase of spillage, planes fit the most.

Spillages of oil can be remotely detected using both passive and active methods [4, 10–20].

Using passive methods, solar radiation reflected from the sea surface, thermal radio radiation of surface in the microwave region or thermal radiation in the infrared region of the spectrum are registered. However, all passive methods of detection have disadvantages. Application of the first method is possible only during daytime and only in case of good weather, the main disadvantage of the second one is impossibility to detect films with thickness of less than 100 μm, and the disadvantage of the third one is that the temperature contrast between oil contamination and clean surface of water strongly depends on thickness of the film, hydrometeorological conditions, and period of the day and maybe both positive and negative.

With active methods, some radiation source is used for irradiation of the sea surface, e.g. radar station or optical radar. Detection of oil contaminations by radar method is based on decreasing of HF components of heaving by the oil film. Its main disadvantage is that there are other areas with lowered heaving on the sea surface (not related to oil contamination), which may be caused by subsurface waves, films of surface-activated substances, wind shadows behind islands or steep shore, etc. Therefore, the problem of distinguishing the areas of oil contamination from other surface areas with lowered heaving arises. Moreover, in case of still air and gentle wind, the radar method is not able to detect oil contaminations (in such conditions, there are no rips on the surface or those are very low). Detection of oil contaminations by active optical methods is possible throughout the day and is based on the difference between reflective or fluorescent characteristics of clean and oil-contaminated water surfaces.

The reviews of optical sounding systems state that their main disadvantage is strong dependence on atmospheric conditions. It is true if we speak about all optical sounding systems in general. However, this disadvantage is significantly mitigated for aviation systems (the atmosphere is non-isotropic along the vertical, and the main contribution in radiation attenuation is made by a relatively thin (50–100) m surface layer.

Nowadays, there is a number of known active optical methods of oil contamination detection. For example: 1) the fluorescent method allowing to detect oil contaminations on water surface, to measure thickness of oil films, and to categorise them, but the sounding distance (height) of the most of fluorescent lidars does not exceed (100–150) m; 2) the method of active optical detection based on differences of reflective characteristics of clean and oil-contaminated water surface, which is efficient for detection of oil contaminations. Its advantages are relative simplicity of equipment and capability to perform sounding from large heights.

The analysis of existing detection methods of oil contaminations of water surface [4, 10–20] shows that the equipment of remote optical sounding is the most efficient variant for an operative system of oil contamination monitoring. At the same time, integration of fluorescent radar with an optical locator allowing to perform analysis of reflective characteristics of the water surface from a height of several kilometres (with bigger flight height, the plane equipment provides larger monitoring strip on the water surface) is considered promising [4, 10].

Therefore, this article describes the development of a photo and radiometric detection method of oil contaminations on the water surface at a sight-safe wavelength (λ) of sounding.

3. OPTICAL METHOD BASED ON THE DIFFERENCE BETWEEN REFLECTIVE CHARACTERISTICS OF CLEAN AND OIL-CONTAMINATED WATER SURFACES

The physical basis of oil contaminations detection by the optical method is the contrast of the registered radiant flux of radiation reflected from the clean water surface and water surface with oil contamination.

The contrast is caused by two factors: oil contaminations increase reflectance (e.g. at $\lambda = 1.06\ \mu$m, the reflectance value of the clean water surface is equal to about 0.02, and the reflectance value of a thick oil film is about 0.04), and oil films lower heaving of the water surface [4, 21–24].

The contrast between the clean water surface and the oil-contaminated water surface K is usually determined using the formula:

$$K = \frac{P_{\text{oil}}}{P_{\text{w}}},$$

where P_w and P_{oil} are values of power of signals registered on the clean water surface and the oil-contaminated water surface respectively.

The formula of this contrast may be obtained using the formula of the average power registered by the optical radar in the course of the monostatic sounding of the wavy water surface:

$$K = K_V K_{\gamma,\sigma}, \tag{1}$$

where $K_V = \frac{V_2^2}{V_1^2}$,

$$K_{\gamma,\sigma} = \frac{\left(\gamma_{1x}^2\gamma_{1y}^2\right)^{\frac{1}{2}}}{\left(\gamma_{2x}^2\gamma_{2y}^2\right)^{\frac{1}{2}}}\exp\left\{-\frac{q_x^2}{2q_z^2}\left[\frac{1}{\gamma_{2x}^2}-\frac{1}{\gamma_{1x}^2}\right]\right\}$$

$$\left[\frac{\frac{\tau^2c^2}{16}+2\sigma_1^2+\sin^2\theta/(C_s+C_r)}{\frac{\tau^2c^2}{16}+2\sigma_2^2+\sin^2\theta/(C_s+C_r)}\right]^{\frac{1}{2}},$$

$q_x = 2\sin\theta$, $q_z = 2\cos\theta$, θ is the sounding angle (between the direction of the optical radar optical axis and the nadir direction), σ^2 and $\gamma_{x,y}^2$ are dispersions of heights and inclinations (along some of x and y axes) of heaving, V^2 is the reflectance of the flat (without heaving) area of the water surface, τ is the duration of the radar impulse, $C_{s,r} = (\alpha_{s,r}L)^{-2}$ (for transparent atmosphere), $2\alpha_{s,r}$ is the divergence angles of the radiation source and the field of view of the receiving optical system, L is the flight height.

The values of V, γ, σ with index 1 are related to the clean water surface and those with index 2 are related to the oil-contaminated water surface.

While obtaining the formula (1), it was presumed that the spindrift is not generated (the wind velocity is low), the inclinations of the water surfaces are low: $\gamma_{x,y}^2 << 1$, $\alpha_{s,r}^2 << \gamma_{x,y}^2$, the size of the illumination spot on the surface and the heaving height of the water surface are low as compared to L.

It should be noted that the formula (1) is obtained using the expressions for the average received power. Since the pulse repetition rate of the plane lidar may be equal to hundreds of Hz and even tens of kHz, the size of water surface areas, on which received power is averaged may be equal to first tens of metres even with high speed of the plane. For instance, with pulse repetition rate of 1 kHz and plane speed of 100 m/s (ordinary speed for measurements), in the registration time interval of 0.1 s (which is equal to 10 m along the flight route), 100 impulses will be accumulated (which is quite enough for estimation of the average value of the received power). The flight height is selected on the basis of the radiation source power (which, in its turn, depends on the pulse repetition rate) in this case.

In the formula (1): the term $K_{\gamma,\sigma}$ describes the contrast between the clean water surface and the oil-contaminated surface caused by lowering of the water surface heaving by the oil film; the term K_V describes the contrast between the clean water surface and the oil-contaminated surface caused by the difference between the values of reflectance of the clean water surface and the oil-contaminated water surface; the value V_2^2 is the reflectance of the three-layer-system "air–oil film–clean water surface" and the value V_1^2 is the reflectance of the two-layer-system "air–clean water surface".

The formulas for V_2^2 and V_1^2 have the following form (see, for instance, [4, 21]):

$$V_2^2 = \left|\frac{(Z_1+Z_2)(Z_2-Z_3)e^{-i\alpha(\lambda)d} + (Z_1-Z_2)(Z_2+Z_3)e^{i\alpha(\lambda)d}}{(Z_1+Z_2)(Z_2+Z_3)e^{-i\alpha(\lambda)d} + (Z_1-Z_2)(Z_2-Z_3)e^{i\alpha(\lambda)d}}\right|^2, \tag{2}$$

$$V_1^2 = \frac{(1-n_2)^2+k_3^2}{(1+n_2)^2+k_3^2}, \tag{3}$$

where $Z_j = \frac{2}{m_j}$; $\alpha(\lambda) = \frac{2\pi}{\lambda}m_2$; d is the thickness of the oil film on the water surface; n_j and k_j are the refractive and absorption indexes of j-th medium; $m_j = n_j + i\cdot k_j$ is the complex refractive index of j-th medium (for air, $m_1 = n_1 = 1$) and n_j and k_j are its real and complex parts respectively; the indexes 1, 2, 3 relate to air, oil, and water.

V_1^2 is defined only by the corresponding n_j and k_j, and V_2^2 complexly (due to the interference of radiation reflected from the air and oil film interface and oil film and water interface) depends on optical characteristics of water and oil products, λ of sounding and the thickness of oil film d.

Right after spillage of oil on the water surface (e.g. in case of an accident with oil pipeline or storage, wreck of oil carrier, etc.), the thickness of the film may be equal to several centimetres. Due to the

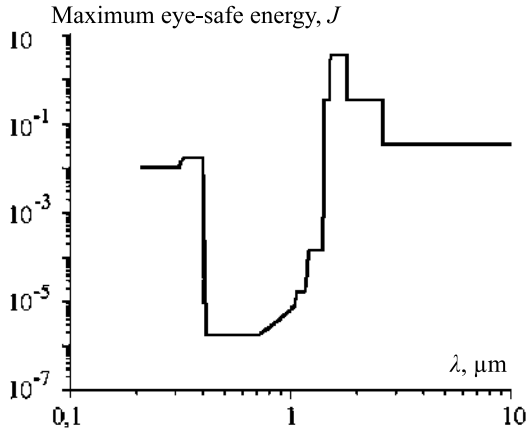

Fig. 1 Spectral dependence of maximum eye-safe energy of laser impulse

distribution of oil over the surface of the sea, the thickness decreases down to (1.0–0.1) mm and less. An important issue is the thickness of oil spillage after reaching of which the spillage stops being an integral whole [4]. Depending on oil grade, this thickness is usually estimated within the range between 4 and 100 μm. In the meantime, there are numerous data sets of thickness measurement of different oil and oil product grade films obtained both in-field and in laboratories, which obtained a lesser (than 4 μm) thickness of oil films [10].

In the simplest way, monitoring of oil contaminations is conducted registering the signal reflected from the water surface and determining the contrast between the level of power of the optical signal reflected from the clean water surface (which is registered, for example, while flying above clean water areas) and the one registered above the water surface along the flight route [4, 13, 25].

However, it is still not clear, which λ in the visible region is the most preferable for detection of oil contaminations: the contrasts between the clean water surface and oil contaminations complexly depend on λ, the thickness of oil film and type of oil product. Moreover, in the course of the development of optical equipment for remote sounding, it is necessary to take the degree of danger of laser radiation for sight into consideration.

4. SELECTION OF EYE-SAFE LASER RADIATION SOURCES

The functioning of active optical systems of remote sounding is always linked with danger to human organs of sight. However, the remote sounding system operates at still matters.

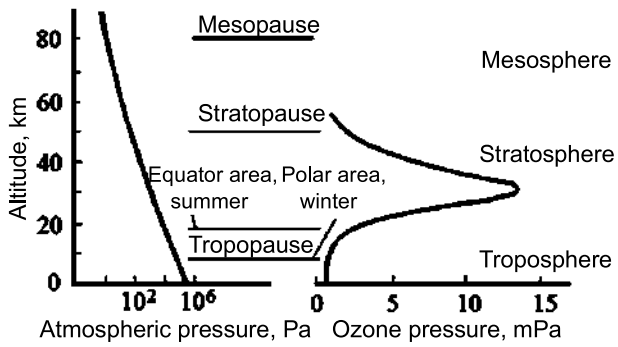

Fig. 2. Altitude distribution of atmospheric ozone

Radiation in visible and near-infrared spectral regions (0.38–1.4 μm) may cause damage to the retina and UV radiation within the range of λ of (0.18–0.38) μm and infrared radiation within the range of $\lambda > 1.4$ μm affect front ocular media and are considered safer [26, 27].

Fig. 1 [26] illustrates the safety of radiation for eyes at different λ (with equipment parameters specific for systems of active optical sounding, the pulse duration of 6 ns, the pulse repetition rate of 100 Hz and the optical beam diameter of 50 mm).

The requirement of eye-safety causes necessity of selection between UV (λ in range (0.18–0.38) μm), near-infrared, and medium-infrared ($\lambda >$ 1.4 μm) regions. The selection should be based on the efficiency analysis of application of these regions for detection of oil contaminations on the water surface.

In the said infrared regions, at λ>1.4 μm, due to high absorption by water and CO_2 vapours, the most promising λ of sounding are limited by atmospheric transparency windows of (1.5–1.8) μm, (2.1–2.4) μm (erbium-glass radiation sources, yttrium-aluminium garnet radiation sources with holmium addition, optical parametric oscillators) and (8–12) μm (CO_2-based radiation source).

Within the region of λ of (0.18–0.38) μm, due to absorption by oxygen and ozone (in the short-wave part of this region), the most prospective value of λ for remote sounding equipment is 0.355 μm (third harmonic of the yttrium-aluminium garnet radiation source with the addition of neodymium).

With pulse repetition rate ranging between hundreds of Hz and first kHz units and impulse duration of (5–10) ns, the impulse energy of the existing radiation sources with λ of 0.355 μm (e.g. *Ekspla NL230–100*) ranges between hundreds of μJ and first units of mJ, which allows us to perform sounding from the height of about several kilo-

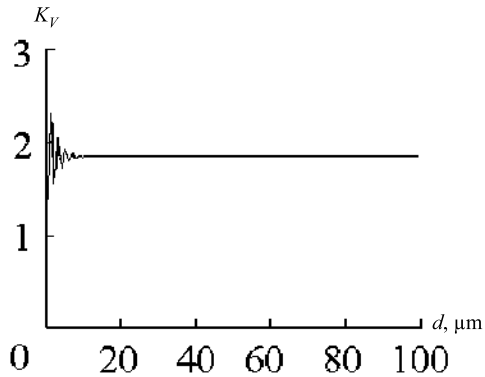

Fig. 3. Dependence of contrast K_V on film thickness d at λ of 0.355 μm

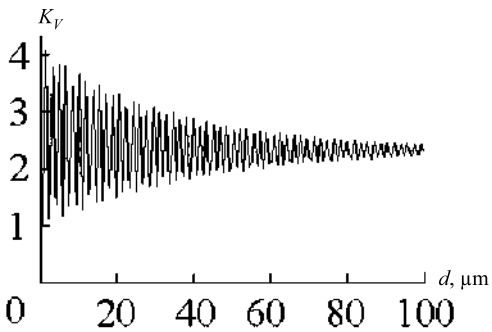

Fig. 4. Dependence of contrast K_V on film thickness d at λ of 1.54 μm

metres (with the receiving lens diameter of about (6–10) cm). The selection of the size of illumination spot on the sea surface is defined by requirements to the minimal detectable size of oil spillage on the sea surface.

It should be noted that UV spectral region is of interest for plane laser sounding systems as absorption of UV radiation by atmospheric ozone occurs mostly in the upper layers of the atmosphere. Fig. 2 [28] shows the general distribution of ozone in the atmosphere at different altitudes. In the lower layer of troposphere, the concentration of ozone varies depending on the place of monitoring but is maximum (units of mPa and less [29]).

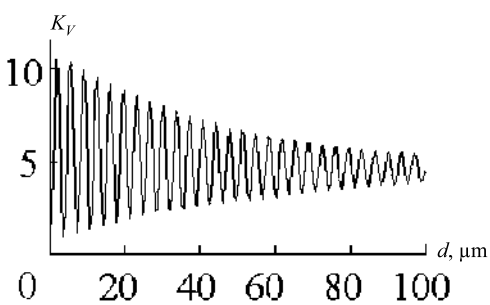

Fig. 5. Dependence of contrast K_V on film thickness d at λ of 10.6 μm

Below the contrasts between the clean water surface and oil contamination at eye-safe λ of sounding in a wide spectral band between UV and medium-infrared regions (0.355–10.6) μm are estimated.

5. ANALYSIS OF CONTRASTS BETWEEN CLEAN WATER SURFACE AND OIL CONTAMINATIONS AT EYE-SAFE RADIATION WAVELENGTHS IN UV, NEAR-INFRARED, AND MEDIUM-INFRARED SPECTRAL REGIONS

In Figs. 3–5, the dependencies of contrast K_V (caused by the difference of reflectance of the water surface covered with oil contamination film and the clean water surface) on the thickness of an oil film d at eye-safe λ of sounding of 0.355 m 1.54 and 10.6 μm respectively.

All the above-given figures show that, with an increase of oil contamination film thickness, the contrasts K_V oscillatory approximate some constant values, which are equal to contrasts of the two-layer medium "air–oil contamination" at corresponding λ. For sounding λ of 0.355, 1.54, and 10.6 μm, the values of this contrast equal to 1.84, 2.3, and 4.6 respectively.

Oscillatory nature of the dependence of contrast on oil contamination film thickness makes the operation of optical oil contamination detector (in real conditions of measurement noise) unstable in near-infrared and medium-infrared regions.

Fig. 6 shows the example of the mathematical modelling results of contrast dependence K_V on the thickness of oil contamination film d at sounding λ of 1.54 μm with a relative standard deviation of

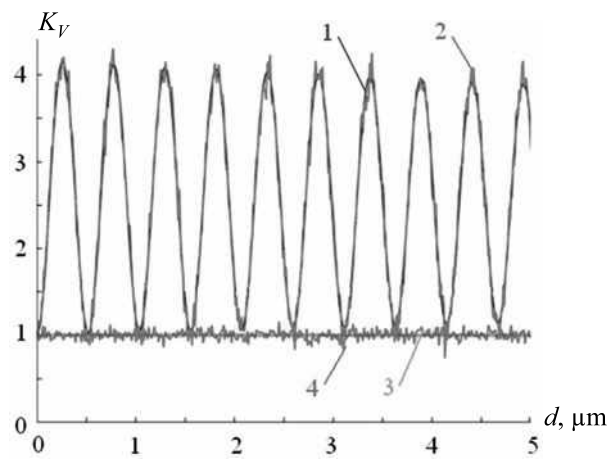

Fig. 6. Dependence of contrast K_V on oil thickness in conditions of noises with σ = 5 % at λ of 1.54 μm

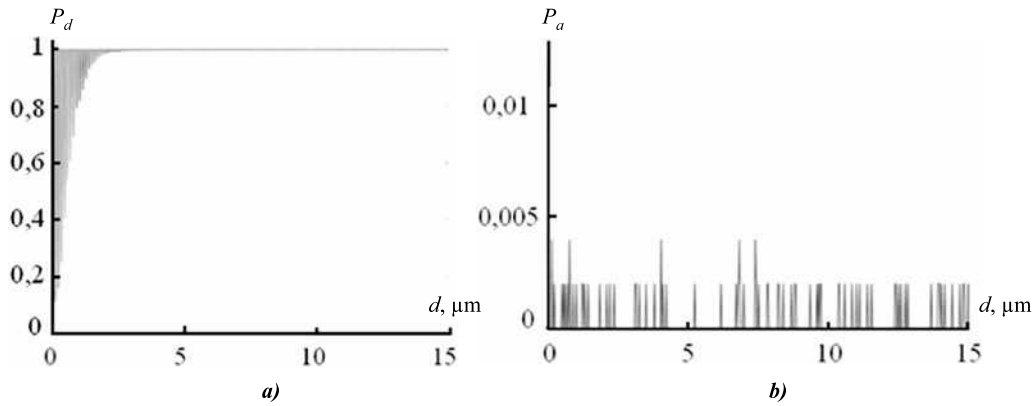

Fig. 7. Dependence of probabilities of correct detection P_d (*a*) and false alarms P_a (*b*) on oil film thickness at λ of 0.355 μm within the thickness interval of (0–15) μm

measurement noise of 5 %. In this figure, 1 stands for the contrast of oil contamination film without consideration of measurement noises, 2 stands for the contrast of oil contamination film with consideration of measurement noises, 3 stands for the contrast of the clean water surface $K_V \equiv 1$ without consideration of noises, and 4 stands for the contrast of the clean water surface with consideration of noises. It can be seen that, due to the noises, K_V of thin oil films occasionally becomes less than 1. At λ of 10.6 μm, this effect increases, it is seen to the least extent at λ of 0.355 μm.

Subsequently, despite the high values of the contrast of the two-layer medium "air–oil contamination" in the near-infrared and especially medium-infrared region, application of UV spectral region (λ of 0.355 μm) is more promising (in terms of reliability of measurements for thin oil films).

For estimation of operation reliability with measurement noises, mathematical modelling, and estimation of probabilities of correct detection and false alarms for detection of oil contaminations were conducted.

6. THE RESULTS OF MATHEMATICAL MODELLING OF OIL FILMS AND FALSE ALARMS CORRECT DETECTION PROBABILITIES

Mathematical modelling of correct detection probability P_d (probability of detection of oil contamination when it actually occurs) and probability of false alarms P_a (probability of detection of oil contamination when it does not actually occur) in conditions of measurement noises was conducted at eye-safe sounding λ in UV (0.355 μm) and near-infrared regions of the spectrum (1.54 μm).

The values of water and oil product refractive and absorption indexes at λ of 0.355 μm and 1.54 μm were taken from [21] (average characteristics of seawater and oil). It was assumed that measurement noise is normally distributed with zero average. The relative standard deviation of noises was set within the range of (1–10) %.

In the course of mathematical modelling, the values of oil films were set within the interval between 0.1 and 100 μm (thicker films are efficiently detected, for instance, by thermal radio methods). It was considered that the system of impulse active optical detection is capable (using spectral, spatial, and temporal filtering) to efficiently detect a signal among additive noises, and these noises influence the system operation only in the form of shot noise of photodetector (caused by it) [10]. Therefore, in the course of solution of the oil film detection task, the signals from the clean water surface and the oil-film contaminated surface registered by the receiver of the detector in conditions of noises were compared.

Availability of oil film was detected provided the condition $K_V > K_{th}$ was met (the contrast K_V between the studied area of the water surface and the invariably clean area of the water surface is higher than the threshold contrasts K_{th}). The value of K_{th} was selected (calculated before modelling) between 1 (the value of contrast when there are no oil-contaminations on the studied surface) and the minimal contrast (minimal value of K_V which is always more than 1) without noises and with set minimal thickness of films (which should be detected based on the remote sounding data).

Fig. 7 and Fig. 8 show the results of probability mathematical modelling of correct detection (P_d) and false alarms (P_a) with relative measurement

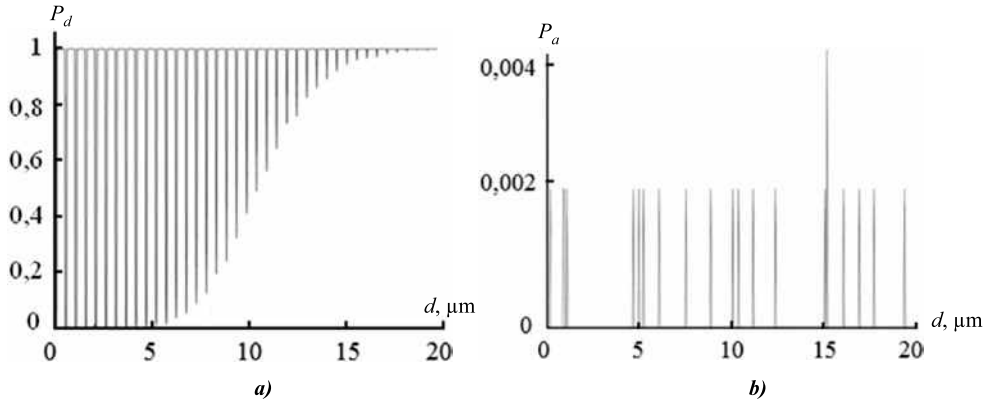

Fig. 8. Dependence of probabilities of correct detection P_d (*a*) and false alarms P_a (*b*) on oil film thickness at λ of 1.54 μm within the thickness interval of (0–20) μm

noise of 5 % (among 1000 samples of measurement noise) at sight-safe sounding λ in UV spectral region: at λ of 0.355 μm (Fig. 7, *a* and *b*) and in near-infrared spectral region: at λ of 1.54 μm (Fig. 8, *a* and *b*).

The figures show that with oil thicknesses more than 20 μm, probability of correct detection at sounding λ of both 0.355 μm and 1.54 μm is 100 %. However, in case of thinner films (which can be equal to units of μm and less) the situation is completely different: with sounding λ of 0.355 μm, it is possible to reliably detect oil films with thickness of at least 2 μm with acceptable P_d (more than 0.9) and P_a (less than 0.002) with relative measurement noise not exceeding 5 %. In the meantime, with sounding λ of 1.54 μm, P_d for oil films with a thickness of 2 μm may have any value ranging between 0 and 1 (depending on the random thickness of film in the sounding point).

7. Analysis of Oil Type Impact on Characteristics of Detection of Oil Contaminations on the Water Surface by Laser Method

The energy calculation of optical detector and mathematical modelling of P_d and P_a for detection of oil contaminations on the water surface are usually conducted for average characteristics of oil (see, for example, [4, 13, 25] and the above-listed results). However, different types of oil have significantly different optical characteristics.

For estimation of the impact of the oil type on the reliability of oil contaminations detection, mathematical modelling of P_d and P_a for different types of oil in conditions of measurement noises at sight-safe sounding λ of 0.355 μm was conducted.

It was assumed that measurement noise (during the registration of reflectance V_2^2 and V_1^2) is normally distributed with zero average and relative standard deviation δ =(1–10) %. Oil contamination was considered detected if the contrast $K_V = \frac{V_2^2}{V_1^2}$ was higher than K_{th}. The value K_{th} was selected between the value of K_V for oil contamination on the sea surface and $K_V = 1$ (the value of contrast for the clean water surface).

Table 1 (using formulas (1–3) and data from [30]) contains optical characteristics (*n* and *k*) and the results of mathematical modelling (among 1000 samples of measurement noise) of P_d and P_a with a thick oil film, relative standard deviation of measurement noise of 10 % and one threshold algorithm of detection for different types of oil. The types of oil products are given in the table line: 1 – diesel oil and 2–6 – different types of oil corresponding with different fields [30].

Table 1 shows that, despite P_d and P_a are different for different types of oil (with significant differences of *n* and *k*), these differences are non-significant.

Therefore, for detection of oil contaminations on the water surface by means of active optical detection at sight-safe λ of 0.355 μm, one detection algorithm may be used for all types of oil products.

8. CONCLUSION

Comparative analysis of efficiency of optical (photo and radiometric) method of oil contaminations detection on the water surface based on differences between reflective characteristics of clean and oil-contaminated water surfaces was conducted with sounding λ selection in UV, visible, near-in-

Table 1. The Results of Mathematical Modelling of Effect of Oil Type on Reliability of Detection of Oil Contaminations

Parameter	1	2	3	4	5	6
n	1.565	1.559	1.560	1.549	1.528	1.527
$k \cdot 10^3$	20.1	16.5	11.4	8.4	5.6	4.8
P_d	0.9991	0.9990	0.9989	0.9982	0.9967	0.9960
P_a	0.031	0.0308	0.0312	0.032	0.0338	0.0332

frared, and medium-infrared regions of the spectrum. It is shown that, in terms of eye-safety, the width of thickness interval of detected oil films and optical attenuation in the atmosphere, the most promising sounding method for monitoring of oil contamination is sounding in UV spectral region at λ of 0.355 μm. It allows to reliably detect oil films with a thickness of at least 2 μm with the probability of correct detection exceeding 0.9 and probability of false alarms of less than 0.002 with relative measurement noise not exceeding 5 %.

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