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The choice of spectral ranges of registration for the fluorescent method for detecting leaks in oil pipelines at an excitation wavelength of 355 nm

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Abstract. Mathematical modeling was carried out based on the experimentally measured fluorescence spectra of oil, vegetation and water to select the most effective spectral registration ranges for the fluorescent method for detecting oil leaks at an excitation wavelength of 355 nm. The results of mathematical modeling show that the probabilities of correct detection and false alarms for the problem of detecting oil leaks significantly depend on the type of oil and, accordingly, on the spectral channels selected for monitoring. For reliable detection of oil spills against the background of vegetation or water bodies, two or three spectral channels must be used. The highest probabilities of correct detection (>0.999) and small probabilities of false alarms (<0.04) can be achieved for oils with intensity maxima of laser-induced fluorescent radiation at wavelengths of ~ 420 and 550 nm (when using two spectral channels) and for oils with fluorescence intensity maximum at a wavelength of ~510 nm (when using three spectral channels). For oils with a maximum fluorescence intensity at a wavelength of about 475 nm (when using three spectral channels), the results are worse, although they remain acceptable (at a measurement noise of 10%, the probability of correct detection and false alarms, respectively, 0.94 and 0.11).

1 Introduction

Currently, oil and oil products continue to be the most common pollutants in the environment [1–7].

The greatest losses of oil are associated with its transportation from production areas. At the same time, pipeline transport is the most common.

Existing monitoring systems on pipelines [8] have a sensitivity from units to hundredths of a percent of the oil pipeline flow rate and leaks of lesser intensity are not recorded.

To date, the most effective method for detecting low-intensity oil leaks on the earth's surface is the laser-induced fluorescence method [9–11].

The laser fluorescent sensor makes it possible to detect oil pollution on the earth's surface caused by pipeline leaks at an early stage (with small oil pollution) and regardless of the time of day.

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The number of research works in the field of laser fluorescent monitoring of oil pollution is quite large. However, some questions remain unexplored. The issue of choosing the most effective spectral ranges for fluorescent radiation registration and their number for the task of monitoring oil pollution on the earth's surface remains unclear.

The task of laser monitoring of oil pollution on the earth's surface is difficult due to a large number of interfering factors - the influence of fluorescence of elements of the earth's landscape, and primarily vegetation [11-16] and water bodies [17-19]. This task is further complicated by the fact that for different grades of oil, the maxima of the laser-induced fluorescence spectra are in different spectral ranges [10, 19–26].

In the report, based on experimentally measured fluorescence spectra of oil, vegetation and water, mathematical modeling is carried out in order to select the most effective spectral detection ranges for the fluorescent method for detecting oil leaks at an excitation wavelength of 355 nm.

2 Analysis of fluorescence spectra of different grades of oil, vegetation and water

Examples of laser-induced fluorescence spectra of oil from different fields (at the oil fluorescence excitation wavelength of 355 nm) are shown in Figures 1 and 2 [10, 19, 26]. The fluorescence spectra [10, 19, 26] were obtained using different equipment in relative units, and therefore, for comparison, they are shown in Figures 1 and 2 in the same form (with the maximum value of the fluorescence intensity equal to one).

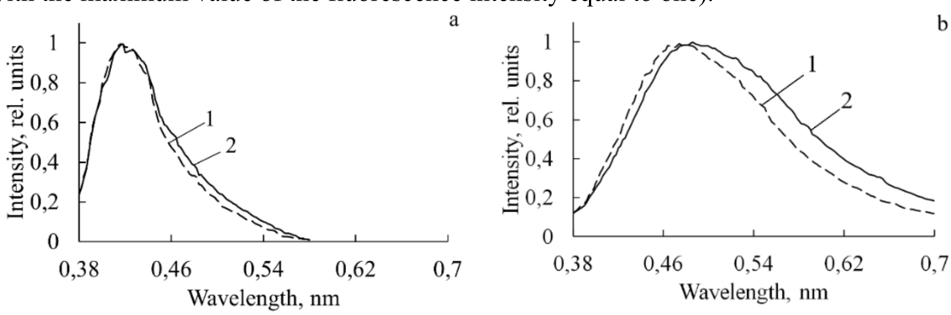


Fig. 1. Fluorescence spectra of oils with the maximum fluorescence intensity at a wavelength of ~420 nm (1a) and ~475 nm (1b). 1a: 1 - Super Light crude oil, 2 - Light crude oil. 1b: 1 - Jakutiya crude oil, 2 - West-Siberian crude oil.

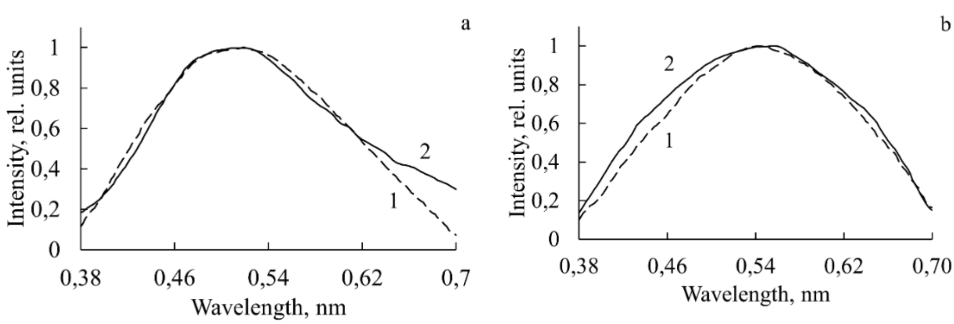


Fig. 2. Fluorescence spectra of oils with the maximum fluorescence intensity at a wavelength of ~510 nm (2a) and ~550 nm (2b). 2a: 1 - Nihian crude oil, 2 - Kapotny crude oil. 2 b: 1 - German crude oil, 2 - Arabian medium crude oil.

Figures 1 and 2 show that the fluorescence spectrum maxima of various types of oils are in different spectral ranges from ~ 420 nm to 550 nm.

The most significant factor affecting the detection of oil leaks by the laser-induced fluorescence method is the fluorescence of vegetation.

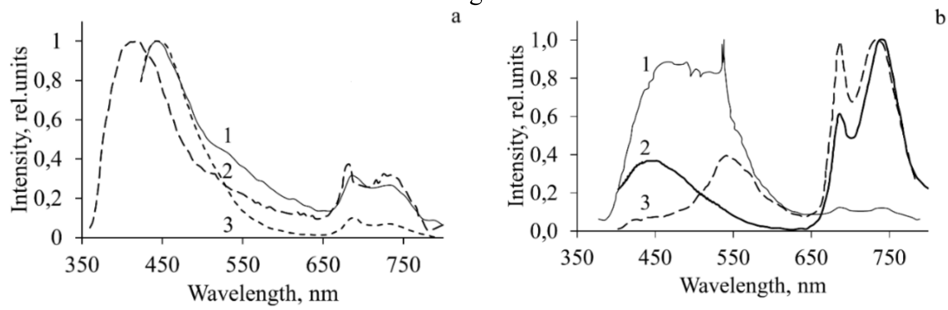


Fig. 3. Vegetation fluorescence spectra. 3a: 1 - hornbeam leaves, 2 - corn leaves, 3 - poplar leaves. 3 b: 1 - grass, 2 - wheat, 3 - soy.

Examples of the spectra of laser-induced fluorescence of vegetation (at the oil fluorescence excitation wavelength of 355 nm) are shown in Figure 3 [11, 27, 28].

Analysis of Figure 3 shows that the maximum of vegetation fluorescence falls on the spectral ranges ~ 400-550 nm and ~ 670-750 nm.

Along with vegetation, water bodies interfere with oil spill detection. Examples of laser-induced fluorescence spectra of different types of water bodies (at the oil fluorescence excitation wavelength of 355 nm) are shown in Figure 4 [11, 19, 20].

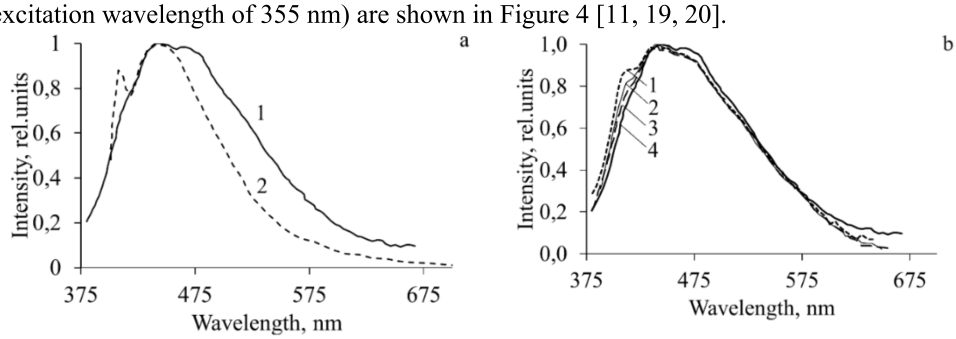


Fig. 4. Fluorescence spectra of water bodies. 4a: 1,2 - river water. 4b: 1-3 - sea water, 4 - river water.

It can be seen from Figure 4 that the maximum fluorescence of water bodies falls on the spectral range ~ 420-500 nm.

3 Determination of the spectral ranges of registration of laser-induced fluorescent radiation for the problem of monitoring oil pipeline leaks

Figures 1 and 2 above show that the maxima of the laser-induced fluorescence spectra of different types of oil lie in the range ~ 420 – 550 nm. However, in the same spectral range there can be intense laser-induced fluorescent radiation of vegetation and water bodies (see Figures 3 and 4).

The fluorescent signal from vegetation and water bodies can be a significant interfering factor for the problem of oil pipeline leak detection. This makes it problematic to use singlechannel spectral methods for monitoring oil spills, based on a significant excess of the fluorescent signal from an oil spill over the fluorescent signal from vegetation or water bodies in one spectral channel, which lies in the range of ~ 420 - 550 nm. For reliable detection of oil spills against the background of vegetation or water bodies, two or three spectral channels must be used.

But this is not the only difficulty. Since the maxima of the fluorescence spectra of different types of oils are in different spectral ranges: from ~ 420 nm to 550 nm, these spectral channels should be different for different types of oil.

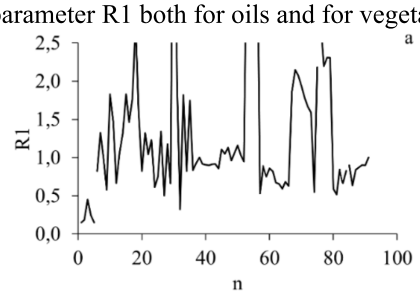
To determine the most promising (for the task of monitoring oil spills) spectral channels for detecting fluorescent radiation and to find quantitative characteristics of the efficiency of using these spectral channels, mathematical modeling was carried out (for different types of oil, for spectral channels with different central wavelengths and different spectral widths, different measurement noise receiving system).

The simulation results show that for oils with a maximum intensity of laser-induced fluorescent radiation at a wavelength of ~ 420 nm, the most effective are two spectral channels with central wavelengths of ~ 420 and 515 nm and a spectral width of ~ 60 nm. For oils with a maximum fluorescence intensity at a wavelength of about 550 nm, the most effective are two spectral channels with central wavelengths of ~550 and 625 nm and a spectral width of ~90 nm.

Fluorescent signals I1, I2 in the spectral channels (420 and 515 nm or 550 and 625 nm) were used to form the information parameter R1:

$$R1 = \frac{I2}{I1}.$$

Figure 5 shows the results of calculating the values of the information parameter R1 for oils with a maximum intensity of laser-induced fluorescent radiation at a wavelength of ~ 420 nm (Figure 5a) and oils with a maximum intensity of laser-induced fluorescent radiation at a wavelength of ~ 550 nm (Figure 5b). The figures show the values of the information parameter R1 both for oils and for vegetation and water.



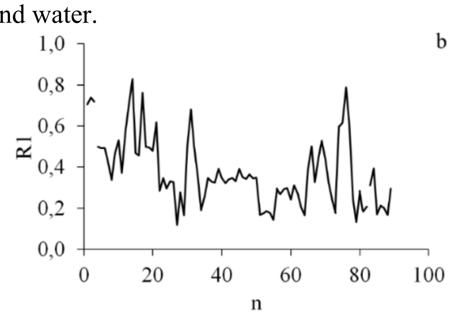


Fig. 5. The value of the information index R1. 5a: for spectral channels 420 and 515 nm. 5b: for spectral channels 550 and 625 nm.

In Figure 5 the value of the information parameter is plotted along the vertical axis, and n (number of the spectrum of oil, vegetation or water) is plotted along the horizontal axis. In Figure 5a, spectrum numbers 1-5 are different types of oil (1-crude oil (API gravity = 35.15), 2 - crude oil (API gravity = 28.48), 3 - crude oil from Azerbaijan, 4 - crude oil (API gravity= 24), 5 - crude oil (API gravity= 50.24). Spectrum numbers 6-84 - different types of vegetation (6.7 - green live and dry grass, 8.9 - green live and dry leaf, 10.11 - mustard in normal condition and after frosts, 12.13 - corn in normal condition and after oil pollution, 14-16 - hawthorn leaves green, yellow and brown, 17-19 - willow leaves green, yellow-brown and brown , 20-23 - live green grass, cut after 7 and 11 days and dry, 24-26 - various types of moss, 27 - sundew, 28 - rice, 29 - wheat, 30 - soybeans, 31 - grass, 32 - corn, 33 - moss, 34 - grass, 35 - mustard, 36 - tobacco, 37-52 - rice, 53 - pigeon peas (Cajanus cajan L.) in normal condition, 54-56 - pigeon peas (Cajanus cajan L.) with pollution soils with cadmium, 57 - corn, 58 - tobacco, 59 - magician nolia (M. denudata Desr.), 60 - willow (babylonica Linn), 61 - holly (L. chinensis Sims.), 62 - sundew (C. dielsiana), 63 - orchid (C. kotoense), 64 - annual plant C. serrulata, 65 - cherry (C. yedoensis), 66 - wheat, 67-73 - mustard, 74 - poplar, 75 - grass, 76 - 79 - wheat in the normal state and when cadmium is added to the soil, 80 - tobacco, 81 - corn, 82 - tobacco, 83, 84 - Campelia zanonia (green and white part of the leaf). Spectrum numbers 85-91 are various water bodies (85 is water in a navigation channel, 86 is water in a city pond, 87, 88 is sea water, 89 is water in the port area, 90 is water in a sea bay, 91 is river water).

In Figure 5b, spectrum numbers 1-3 are different types of oil (1 - crude oil Basra, 2 - crude oil Arabian, 3 - crude oil German. Spectrum numbers 4-82 - different types of vegetation (coincide with numbers 6-84 for Figure 5a). Spectra numbers 83-89 different water bodies (coincide with numbers 85-91 for Figure 5a).

Figures 5a and 5b show that for oils with a maximum intensity of laser-induced fluorescent radiation at wavelengths of ~420 nm and 550 nm, the information parameter R1 for oils differs greatly in value from the parameter R1 for water bodies and the vast majority of vegetation species. Thus, for these types of oil, the use of two spectral channels for registration fluorescent radiation (with central wavelengths ~ 420, 515 nm and 550 and 625 nm, respectively) allows solving the problem of reliable detection of oil spills against the background of vegetation and water, using a threshold algorithm to separate the values R1 for oils versus R1 for vegetation and water.

Analysis for other types of oil shows that for oils with a maximum intensity of laser-induced fluorescent radiation at wavelengths of ~ 475 nm and ~ 510 nm, the most effective are the use of three spectral channels with central wavelengths, respectively: ~ 475, 520, 735 nm (spectral width ~ 50 nm) and 510, 625, 680 nm (spectral width ~ 85 nm).

Statistical modeling was carried out to quantify the effectiveness of oil spill detection against the background of vegetation and water bodies. During modeling, additive noise was added to the values of fluorescent signals. It was assumed that the measurement noise was distributed according to a normal law with a zero mean value and different values of the relative standard deviation δ (from 0 to 10%). The simulation was carried out with 10^4 realizations of noise. Threshold values were set for information parameters.

During statistical modeling, the calculation was carried out:

- probability of correct detection of oil spills P_d - the ratio of the number of noise realizations, when the threshold algorithm correctly determines the oil spill (defines the "measured" value of the information parameter for oil as the information parameter of exactly oil), to the total number of realizations;

- probability of false alarms P_a - the ratio of the number of noise realizations, when the threshold algorithm incorrectly determines the oil spill (defines the "measured" value of the information parameter for vegetation or water as the oil information parameter), to the total number of realizations.

The probabilities of correct detection P_d and false alarms P_a for the task of detecting oil spills against the background of vegetation and water are given in Tables 1 and 2 for the spectral ranges of registration (central wavelengths, spectral range width) that provide the maximum value of the probability of correct detection. In tables 1 and 2, column 1 - probabilities for oils with a maximum intensity of laser-induced fluorescent radiation at a wavelength of ~ 420 nm, column 2 - with a maximum at a wavelength of about 475 nm, column 3 - with a maximum at a wavelength of about 510 nm, column 4 - with a maximum at a wavelength of about 550 nm.

Table 1. Probabilities of correct detection and false alarms for measurement noise of 0.1%.

Probabilities	1	2	3	4
P_d	>0.999	>0.999	>0.999	>0.999
P_a	0.013	0.103	0.011	0.034

Table 2. Correct detection and false alarm probabilities for measurement noise of 10 %.

Probabilities	1	2	3	4
P_d	>0.999	0.941	>0.999	>0.999
P_a	0.015	0.106	0.012	0.041

An analysis of the results of mathematical modeling given in tables 1 and 2 shows that the probabilities of correct detection and false alarms depend on the type of oil (oil fluorescence spectrum) and, accordingly, on the spectral channels selected for monitoring. The highest probabilities of correct detection (>0.999) and small probabilities of false alarms (<0.04) can be achieved for oils with intensity maxima of laser-induced fluorescent radiation at wavelengths of ~ 420 and 550 nm (when using two spectral channels for recording fluorescent radiation, respectively, 420, 515 nm and 550 and 625 nm) and for oils with a maximum fluorescence intensity at a wavelength of ~ 510 nm (when using three spectral channels for recording fluorescent radiation 510, 625, 680 nm). For oils with a maximum fluorescence intensity at a wavelength of about 475 nm (when using three spectral channels for detecting fluorescent radiation 475, 520, 735 nm), the results are worse, although they remain acceptable (with a measurement noise of 10% of the probability of correct detection and false alarms, respectively, 0.94 and 0.11).

4 Conclusion

Based on the experimentally measured fluorescence spectra of oil, vegetation, and water, the most effective spectral registration ranges for the fluorescent method for detecting oil leaks at an excitation wavelength of 355 nm were selected. It is shown that the probabilities of correct detection and false alarms for the problem of detecting oil leaks significantly depend on the type of oil (oil fluorescence spectrum) and, accordingly, on the spectral channels selected for monitoring. For reliable detection of oil spills against the background of vegetation or water bodies, two or three spectral channels must be used.

The highest probabilities of correct detection (>0.999) and small probabilities of false alarms (<0.04) can be provided for oils with intensity maxima of laser-induced fluorescent radiation at wavelengths of ~ 420 and 550 nm (when using two spectral channels, respectively, 420, 515 nm and 550 and 625 nm) and for oils with a maximum fluorescence intensity at a wavelength of ~ 510 nm (using three spectral channels 510, 625, 680 nm). For oils with a maximum fluorescence intensity at a wavelength of about 475 nm (when using three spectral channels 475, 520, 735 nm), the results are worse, although they remain acceptable (at a measurement noise of 10%, the probability of correct detection and false alarms, respectively, 0, 94 and 0.11).

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