Selecting laser fluorosensor detection band to monitor oil pipeline leaks

Yu V Fedotov, M L Belov\(^1\), D A Kravtsov, K S Titarenko and V A Gorodnichev
Bauman Moscow State Technical University (BMSTU), 2\(^{nd}\) Baumanskaya str.,
Moscow, 105005, Russia

\(^1\)E-mail: belov@bmstu.ru

Abstract. Detection bands of the laser fluorosensor to detect oil pipeline leaks have been studied at the fluorescence excitation wavelength 355 nm. It is shown that a diversity of the fluorescence spectra of different oils and plant species leads to the need to adapt the number and position of spectral detection bands of the laser fluorosensor for the specific types of the pipeline oil and vegetation along the pipe way. With no interfering factors (that emerge false alarms) to monitor along the pipe way, only one spectral channel (at maximum position of the oil fluorescence spectrum) can be used. However, there can be a need to use both the two spectral channels (the channel 1 at maximum position of the oil fluorescence spectrum, and the channel 2 at maximum position of the vegetation fluorescence spectrum within ~680…690 nm or ~730…740 nm) and the tree spectral channels (the channel 1 at maximum position of the oil fluorescence spectrum, the channel 2 at maximum position of the vegetation fluorescence spectrum within ~680…690 nm or ~730…740 nm, and the channel 3 in the spectral band of 625-650 nm).

1. Introduction
Presently, monitoring of oil pipeline leaks is a critical task because a significant amount of oil, travelling through the pipelines, is lost as a result of their worn-out state and mechanical damages [1,2]. The leak detection systems (LDS) available in the pipelines have LOD (a limit of detection) of a tenth of one percent from the oil-flow and the lower oil leaks are undetectable [3].

A promising operational method for monitoring the low oil-line leaks is to provide remote airborne monitoring of oil pollution on the ground surface along the pipe way.

Currently, the most efficient techniques for remote monitoring of oil pollution on the water and land surface are laser fluorescence methods [4-9].

The paper focuses on the study of possible detection spectral bands of a laser fluorosensor for oil pollution monitoring on the ground surface.

2. Problem description
A problem of LIF monitoring of oil pollution on the ground surface is more complicated than that of LIF oil pollution monitoring on the water surface.

A laser-induced fluorescence (LIF) signal from the oil pollution on the ground surface is less than the LIF signal from the oil spill on the water surface (oil is absorbed by the soil, flows downhill, contaminated areas are covered with dust, etc.). And still, the fluorescence signal from the oil spill on
the ground surface can be comparable in magnitude with the fluorescence signal from the landscape elements (generally from vegetation and water objects).

Therefore, to differentiate the oil pollution areas from the landscape elements (preselecting the usable detection spectral bands of the laser fluorosensor) it is necessary to involve data about a LIF spectrum shape both of oil and of vegetation and water objects.

To study possible detection spectral bands of the laser fluorosensor for monitoring the oil pollution on the ground surface, the LIF spectra of oil, vegetation and water objects have been experimentally investigated, and other authors’ experimental studies have been analysed [10-23].

A study of possible detection bands (their spectral position and number) for the LIF method to detect oil pipeline leaks using a fluorescence excitation wavelength of 355 nm is given below.

3. Experimental studies of LIF spectra of oil, vegetation, and water objects at excitation wavelength 355 nm

To measure the LIF spectra of oil, vegetation and water objects for the fluorescence excitation at the wavelength of 355 nm we used a laboratory setup (figure 1).

![Figure 1. Schematic diagram of the laboratory setup to study the LIF spectra.](image)

The laboratory setup employed a Q-switched diode-pumped solid-state pulse Nd: YAG laser at a wavelength of 1064 nm (pulse length <8 ns, repetition rate up to 500 Hz) and a module of the third harmonic (with the 0.8 mJ laser pulse at the third harmonic). A subsystem to detect fluorescence emission was based on the polychromator and the highly sensitive ICCD and enabled the fluorescence spectra detection in the band of 375 to 790 nm with the spectral resolution of 5 nm. A lens diameter of detector was 15 mm. The distance from the laser source to test item was ~ 1.4 m. A laser exciting beam diameter and detector's field of view in the test item plane were ~ 20 mm.

Equipment calibration involved a wavelength calibration of the polychromator and a detection limit calibration of the fluorescence detection system. To control the experimental laboratory setup calibration, we used a Raman-scattering spectrum of distilled water.

A laboratory setup management was based on software in visual development environment LabVIEW.

Figure 2 illustrates some examples of the LIF spectra of crude oils measured by the laboratory setup.
It is seen from figure 2 that for oils measured, the LIF spectra are maximum in the ~ 500 - 575 nm spectral band and have a wide spectral width.

Figure 3 (for exciting fluorescence wavelength 355 nm) shows the most typical examples of the experimental LIF spectra of other oils from different oilfields [10-15] (different authors measured spectra using various equipment, so to illustrate them in the same figure we have normalized a value at maximum of each spectrum).

Figure 3 shows the LIF spectra of oils, which are similar to those in figure 2 in terms of the maximum position (~ 500 - 575 nm) and the spectral width (curves 4,5). The other spectra in figure 3a (curves 1 – 3) have a slightly less spectral width, and their maximum position is appreciably shifted towards the shorter waves (~450 – 500 nm).

Figure 3b shows the fluorescence spectra, which are far different from those illustrated in figures 2 and 3a. They have a much lesser spectral width, and their maximum position can be within ~ 420 nm or ~ 490 nm.

Of course, for monitoring the oil pipeline leaks it is appropriate to choose the fluorosensor detection band at maximum position of the oil fluorescence spectrum. Because of a large variety of the oil fluorescence spectra from different oilfields (figures 2,3) a detection spectral band of the laser fluorosensor for monitoring the pipeline leaks should be adapted to the specific oil transported.

However, this is not the only difficulty to create a laser fluorosensor for monitoring the oil pipeline leaks. The key interfering factor for oil pollution monitoring on the ground surface (due to oil pipeline leaks) is vegetation. For a task of oil pipeline leaks monitoring, this interfering factor leads to the fact that employing the single-channel method to detect LIF (at oil fluorescence spectrum maximum position) can be non-optimum (due to high-risk of false alarms).

Illustrations below show LIF spectra of different species of vegetation measured by the laboratory setup (figure 4).
Figure 4. Fluorescence spectra of vegetation. 4a: leaves of hawthorn, 1 – green, 2 – yellow, 3 – brown; 4b: 1 – green grass, 2,3 – cut grass after 7 and 11 days, 4 – dried grass.

It is clearly seen from figure 4 that the LIF spectrum of live vegetation (figure 4a: curves 1-3, figure 4b: curves 1-3) has always typical maxima in the spectral bands of ~ 670…695 nm and ~ 720…745 nm.

The above data also show (that is well known) that in the spectral band of 375 - 650 nm the vegetation fluorescence is sometimes weak and is sometimes significant (i.e. there is fluorescence of vegetation in the spectral area of oil fluorescence). Herewith, in most cases (figure 4a: curves 1-3, 4b: curves 1-2) for live vegetation the fluorescence in the spectral band of ~ 670…695 nm and in the spectral band of 720…745 nm is more than in the spectral band of 375 - 650 nm.

Therefore, to differ the oil fluorescence from the vegetation one, two spectral detection bands (with the same spectral width) can be used: 1 – at maximum position of the fluorescence spectrum of a specific oil, 2 - ~ 670…695 nm or 720…745 nm.

For oils, a fluorescence signal in the spectral band of 670…695 nm or ~ 720…745 nm will be less than a fluorescence signal in the spectral band (with the same width) at maximum position of the oil fluorescence spectrum (figures 2,3).

For vegetation, in the spectral band of 670…695 nm or ~720…745 nm a fluorescence signal will be mostly more than a fluorescence signal in the spectral band (with the same spectral width) at maximum position of the oil fluorescence spectrum (figure 4a - curves 1-3, figure 4b – curves 1,2). The spectral curve 3 in figure 4b for vegetation can be also distinguished from the spectral curve of any kind of oil owing to introducing some threshold ratio of the fluorescence signal in the spectral band of 670…695 nm or ~ 720…745 nm to the fluorescence signal in the spectral band at maximum position of the oil fluorescence spectrum.

Figure 5 shows the most typical illustrations of the experimental spectra of other plants [16-23].

Figure 5. Fluorescence spectra of different plant species. 5a: 1 - sundew, 2- rice leave, 3 – wheat leave, 4 – soybean leave; 5b: 1 – grass, 2 – hornbeam leaves, 3 – maize leaves, 4 – poplar leaves.
It is seen from figure 5 that maximum position of spectrum vegetation (within 375 – 650 nm) can change in the band from ~ 440 to 540 nm (figure 5a).

And herein, there may be situations (like in figure 4) when the typical maximum in the spectral band of 375 - 650 nm can be significantly more than the typical (but weak) maximum in the spectral bands of ~ 680…690 nm or ~ 730…740 nm (figure 5b and curve 1 in figure 5a).

This leads to the fact that for a task of monitoring the oil pipeline leaks a dual-channel method (a channel 1 is at maximum position of the oil fluorescence spectrum, a channel 2 is at maximum position the of vegetation spectrum within ~ 680…690 nm band or ~ 730…740 band) as well can be non-optimum due to high-risk of false alarms.

In this case there may be a need to introduce the third channel in the spectral band of 625-650 nm (between the channels 1 and 2) in order to add-on monitoring the fluorescence spectrum of the area being monitored. The fluorescence signal for all plant species in the spectral band of 625-650 nm will be less or, at least, roughly the same as the signal in the spectral bands of ~ 670…695 nm or ~720…745 nm. At the same time, the fluorescence signal for all oils in the spectral band of 625-650 nm will be more than the signal in the ~ 670…695 nm or ~ 720…745 nm spectral bands.

As to the land-based water objects (rivers, ponds, lakes, puddles, etc.), fluorescence spectra of water objects may also resemble those of some oils. Figure 6 shows illustrations of the LIF spectra of various water objects (figure 6a – spectra of inland fresh water measured by the laboratory setup, figure 6b – spectra of river water [10,13]).

![Figure 6. Fluorescence spectra of water objects. 6a: 1 – green pond water, 2 – Moscow Canal water, 3 – Lebedyansky pond water (relatively clear) in Moscow; 6b: 1,2 – river water.](image)

However, a magnitude of the fluorescence signal from the water object (except for heavily polluted or turning green water objects) is significantly less than that of the fluorescence signal from oil (i.e. a threshold algorithm can be used just as for methods to detect oil pollution on the water surface).

Besides, the spectra shapes (of water objects and oil) are still different (different typical degrees of spectra growth and roll-off, position of maxima), and for specific oils and water objects they can be divided (moreover, in the fluorescence spectra of water objects there is a maximum caused by Raman-scattering of water at the wavelength of ~ 403 nm).

For instance, for oils which spectra are illustrated in figures 2 and 3a, to differentiate between oil and water objects, two channels can be used: the channel 1 at of the oil fluorescence spectrum (~500 – 575 nm) and the channel 2 in the spectral band of 625-650 nm (a fluorescence spectrum roll-off between the channels 1 and 2 for water is faster than for oil).

Thus, a diversity of the fluorescence spectra of different oils and plant species leads to the need to adapt the number and position of the spectral detection bands of a laser fluorosensor for oil pollution monitoring on the ground surface for the specific types of the pipeline oil and vegetation along the pipe way.
With no interfering factors (that emerge false alarms) to monitor oil pollution along the pipe way, only one spectral channel (at maximum position of the oil fluorescence spectrum) can be used. However, there can be a need to use both the two spectral channels (the channel 1 at maximum position of the oil fluorescence spectrum, and the channel 2 at maximum position of the vegetation fluorescence spectrum within ~ 680…690 nm or ~ 730…740 nm) and the tree spectral bands (the channel 1 at maximum position of the oil fluorescence spectrum, the channel 2 at maximum position of the vegetation fluorescence spectrum within ~ 680…690 nm or ~ 730…740 nm, and the channel 3 in the spectral band of 625-650 nm).

The number of detection channels, the central wavelengths of the spectral detection channels and their width can be finally selected only from results based on the experimental study of the pipeline oil and vegetation spectra in the oil piping region.

4. Conclusion

Thus, possible detection spectral bands of the laser fluorosensor to detect oil pipeline leaks have been studied at the fluorescence excitation wavelength 355 nm. It is shown that a diversity of the fluorescence spectra of different oils and plant species leads to the need to adapt the number and position of spectral detection bands of the laser fluorosensor for the specific types of the pipeline oil and vegetation along the pipe way. With no interfering factors (that emerge false alarms) to monitor along the pipe way, only one spectral band (at maximum position of the oil fluorescence spectrum) can be used. However, there can be a need to use both the two spectral bands (the band 1 - at maximum position of the oil fluorescence spectrum, and the band 2 - at maximum position of the vegetation fluorescence spectrum within ~ 680…690 nm or ~ 730…740 nm) and the tree spectral bands (the band 1 - at maximum position of the oil fluorescence spectrum, the band 2 - at maximum position of the vegetation fluorescence spectrum within ~ 680…690 nm or ~ 730…740 nm, and the band 3 - in the spectral range of 625-650 nm).

References

[1] Adejoh O F 2014 World Environment 4(3) 93
[2] Sivokon S and Andreev N 2012 Int. J. Corros. Scale Inhib. 1(1) 65
[3] Zhang J, Hoffman A, Kane A and Lewis J 2014 10th International Pipeline Conference 1 1
[4] Pashayev A, Tagiyev B, Allahverdiyev K, Musayev A and Sadikhov I 2015 Proceedings of SPIE 9810 981018-1
[5] Fedotov Yu V, Belov M L, Kravtsov D A and Gorodnichev V A 2019 Journal of Optical Technology 86(2) 23
[6] Sasano M 2012 Industrial applications of laser remote sensing ed T Fukuchi, T Shiina (Sharjah: Bentham Science Publishers Ltd) p 89
[7] Brown C E 2011 Oil Spill Science and Technology ed M Fingas (Burlington: Elsevier Inc.) p 171
[8] Steffens J, Landulfo E, Courrol L C and Guardani R 2011 Journal of Fluorescence 21(3) 859
[9] Utkin A B, Lavrov A and Vilar R 2011 Proceedings of SPIE 7994 799415-1
[10] Luedeker W, Guenther K P and Dahn H G 1995 Proc. SPIE 2504 426
[11] Malecha M, Bassant C and Saini S 2003 Appl. Spectrosc. 57(8) 1042
[12] Patsayeva S, Yuzhakov V, Varlamov V, Barbini R, Fantoni R, Frassanito C and Palucci A 2000 EARSeL eProceedings 1 106
[13] Karpicz R, Dementjiev A, Kupriions Z, Pakalnis S, Westphal R, Reuter R and Gulbinas V 2005 Lithuanian Journal of Physics 45(3) 213
[14] Palombi L, Lognoli D and Raimondi V 2013 Proc. of SPIE 8887 88870F-1
[15] Hegazi E, Hamdan A and Mastromarino J 2005 The Arabian Journal for Science and Engineering 30(1B) 3
[16] Lichtenhaler H K, Subhash N, Wenzel O and Miehe J 1997 Intern. geoscience and remote sensing symp. 4 1799
[17] Sne1s M, Guarini R and De11’Ag1io M 2000 Proc. of SPIE 4070 100
[18] Meyer S, Cartelat A, Moya I and Cerovic Z G 2003 Journal of Experimental Botany 54(383) 757
[19] Mishra K B and Gopal R 2005 *Gen. Appl. Plant Physiology* 31(3-4) 181
[20] Maurya R and Gopal R 2008 *Applied spectroscopy* 62(4) 433
[21] Mishra K B and Gopal R 2008 *International Journal of Remote Sensing* 29(1) 157
[22] Mo C, Kim M S, Kim G, Cheong E J, Yang J and Lim J 2015 *J. of Biosystems Eng.* 40(4) 335
[23] Yang J, Gong W, Shi L, Du L, Sun J, Song S, Chen B and Zhang Z 2016 *Scientific Reports* 6(1) 28787