Comparative capability analysis of laser multispectral methods for measuring oil slick thickness

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Abstract. The remote laser multispectral method capabilities to measure the thickness of the oil slicks on the sea surface in various spectral bands have been analysed. The best option (in terms of the band and the recovery accuracy of the oil film thickness on the water surface) is to use the eye-safe spectral band of about 2.1 μm. It is shown that a use of the discretely wavelength-tunable laser for 5 wavelengths in spectral interval about 2.1 μm and the quasi-solution search method for measurement data processing, enables us, with the mean square value of measurement noise 2 %, to recover the thickness of the oil slicks on the sea surface from ~ units μm to ~ 200 μm with an error of no more than 30%.

1. Introduction
Oil tanker accidents, offshore oil production, underwater oil pipeline accidents are main oil pollutant sources on the sea surface [1,2].

Right after spilling (tanker accident), a slick thickness on the water surface can be within the order of several centimetres. After a while, the slick thickness decreases up to 1-0.1 mm. Next, the weathering of light oil fractions and oil sub-solution in water occur. Different authors differently estimate a minimum slick thickness at which an oil spill is still available as a single one (the minimum estimate is units of μm) [1].

Laser remote sensing methods can operationally provide oil pollution monitoring on the sea surface. The most promising for remote detection and measurement of an oil slick thickness on the water surface are currently laser methods based on measurements of laser-induced fluorescence (LIF) emission, Raman-scattering emission, and reflection coefficients at a number of sensing wavelengths [1,3-7]. A drawback of lidar methods based on measuring LIF and Raman scattering emissions is that water surface monitoring is possible only at low (~ 100 – 150 m) aircraft altitude thereby resulting in the modest-sized field-of-view across the water surface and, as a consequence, in low efficiency of these methods.

To provide a large field-of-view and a high monitoring efficiency, the laser method based on the measurement of the reflection coefficient holds promise.

The paper concentrates on the capability analysis of the remote laser multispectral method in various spectral ranges for measuring a thickness of the oil slicks on the water surface, which uses an eye-safe wavelength laser that is a discretely wavelength-tunable (several wavelengths-tunable) laser in a narrow spectral band.
2. Problem description

We believe that a lidar irradiates the oil slick water surface vertically down (for instance, in airborne sensing).

Because of radiation interference, reflected from the interfaces “air – oil slick” and “oil slick – water”, a reflection coefficient of the three-layer system “air – oil slick – water” depends, in a complicated way, on the light wavelength \( \lambda \) and on the slick thickness \( d \) and is written as [8]:

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

where: \( \alpha(\lambda) = \frac{2\pi}{\lambda} m_j \); \( Z_j = \frac{1}{m_j} \) - impedance of the j-th medium; \( m = n + ik \) - complex refractive index of medium; \( n, k \) – refraction and absorption indices of medium; 1,2,3 indices are applicable to air, oil, and water, respectively.

The light interference effect leads to the fact that a measurement result of the reflection coefficient \( R(\lambda) \) at the wavelength \( \lambda \) ambiguously determines the slick thickness \( d \) of oil pollution. This is well seen in figure 1, which shows calculation results of the reflection coefficient \( R(\lambda) \) dependence on the slick thickness \( d \) at the sensing wavelength of 1.54 \( \mu \)m by formula (1).

![Figure 1. Reflection coefficient \( R(\lambda) \) of the three-layer system “air – oil slick - water” versus oil slick thickness \( d \) on water surface at the laser sensing wavelength of 1.54 \( \mu \)m.](image)

A determination ambiguity of the slick thickness \( d \) from the measurements of the reflection coefficient \( R(\lambda) \) at one sensing wavelength \( \lambda \) can be eliminated when measuring at several sensing wavelengths and by using the special measurement data processing algorithms.

3. Algorithm for recovering oil slick thickness using reflection coefficient measurements at several wavelengths by quasi-solution search method

To determine a slick thickness it is necessary to measure a reflection coefficient at several wavelengths and solve the following system of nonlinear equations:

\[
\begin{align*}
R_{\text{mod}}(\lambda_1, d) &= R_{\text{meas}}(\lambda_1) \\
&\vdots \\
R_{\text{mod}}(\lambda_n, d) &= R_{\text{meas}}(\lambda_n)
\end{align*}
\]

(2)
where \( n \) - the number of sensing wavelengths at which a reflection coefficient is measured; \( R_{\text{meas}}(\lambda_i) \) - reflection coefficient value measured at the wavelength \( \lambda_i \); \( R_{\text{mod}}(\lambda_i, d) \) - theoretical (model, formula (1) - determined) reflection coefficient value at the wavelength \( \lambda_i \).

Introduce a residual function \( E(d) \):

\[
E(d) = \sum_{i=1}^{n} \left[ R_{\text{meas}}(\lambda_i) - R_{\text{mod}}(\lambda_i, d) \right]^2.
\] (3)

A slick thickness value \( d \), which vanishes function \( E(d) \), will be a solution to the system of nonlinear equations (2).

However, in the general case not every set of values \( R_{\text{meas}}(\lambda_i) \) out of a tolerance region will be in line with the slick thickness \( d \), which is a solution to the system of equations (2) and vanishes the residual function (3). Even with a little measurement noise available, a situation is possible when for the measured values of the reflection coefficient there will be no solution to the system of equations (2). Thus, an inverse problem of determining the slick thickness based on the measurement data of reflection coefficient at several wavelengths is the ill-posed mathematical problem [9]. One of the most efficient approaches to solve such problems is a quasi-solution search method [9].

In our case the quasi-solution search method consists in finding the slick thickness \( \tilde{d} \) that minimises the residual function \( E(d) \). The quasi-solution \( \tilde{d} \) can be found from the condition:

\[
E(\tilde{d}) = \inf_{d \in M} \sum_{i=1}^{n} \left[ R_{\text{meas}}(\lambda_i) - R_{\text{mod}}(\lambda_i, d) \right]^2,
\] (4)

where \( \inf_{d \in M} \rho \) - the exact lower bound for value \( \rho \) at various slick thickness \( d \) values, in the region \( M \) (region limited by values \( d \), which have a physical significance for the problem to be solved).

Thus, a problem of searching quasi-solution to the system of equations (2) can be reduced to the search of the residual function \( E(\tilde{d}) \) minimum in a certain bounded region of values determined by the physical significance of the problem.

Based on the measurement data of the reflection coefficients, a recovery error of the oil slick thickness substantially depends on many factors the most of which are: a spectral band, the number of sensing wavelengths, and a spectral distance between the sensing wavelengths.

The sensing wavelengths have to meet the following conditions: they must be in the atmospheric transparency windows: less than 0.85 \( \mu \text{m} \); 0.95 – 1.06 \( \mu \text{m} \); 1.2 – 1.3 \( \mu \text{m} \); 1.5 – 1.8 \( \mu \text{m} \); 2.1 – 2.4 \( \mu \text{m} \); 3.3–4.1 \( \mu \text{m} \); 4.6-4.8 \( \mu \text{m} \); 8-12 \( \mu \text{m} \) [10].

Besides, the sensing wavelengths have to be eye-safe. In the visible and near infrared (NIR) band of 0.38 – 1.4\( \mu \text{m} \), laser emission passing through the anterior ocular media and affecting the amphibiestrodes is an eye-safety problem [11]. It is shown that in terms of eye-safety, it is better to use laser sources in the spectral bands of 0.2 – 0.38 \( \mu \text{m} \) and above 1.4 \( \mu \text{m} \). However, a spectral band of \( \sim 1.5 – 2.5 \mu \text{m} \) is the best option [11].

Mathematical modelling has been performed to select the best option for the spectral band, the number of sensing wavelengths, and the spectral distance between the sensing wavelengths and analyse the capabilities of the laser multispectral method for measuring the oil slick thicknesses on the water surface.

4. Mathematical modelling of the algorithm for recovering oil slick thickness using reflection coefficients measurements at several wavelengths by quasi-solution search method

Mathematical modelling has been conducted for the spectral bands with the central wavelengths \( \lambda_c \) of 0.38; 1.54; 2.1; 4; 4.6 и 10 \( \mu \text{m} \), being within the atmospheric transparency windows and eye-safe.
Modelling used optical characteristics of typical oil and clean seawater. Noise was thought to be Gaussian random variable with zero-mean and mean square value in the range from 0 to 5\%.

It was closed-loop mathematical modeling. Formula (1) was used as a model dependence of the reflection coefficient on the sensing wavelength and on the oil slick thickness. Values of “measured” reflection coefficients for the specified slick thickness were calculated by formula (1) taking into account the additive noise of the measurement. The reflection coefficient was “measured” at five wavelengths: \( \lambda_1 = \lambda_c - 2\Delta\lambda \) \( \mu \)m, \( \lambda_2 = \lambda_c - \Delta\lambda \) \( \mu \)m, \( \lambda_3 = \lambda_c \) \( \mu \)m, \( \lambda_4 = \lambda_c + \Delta\lambda \) \( \mu \)m, \( \lambda_5 = \lambda_c + 2\Delta\lambda \) \( \mu \)m, \( \Delta\lambda \) was specified from 5 to 70 nm. The search method was used to find a residual function \( E(d) \) minimum.

Figure 2 shows the mathematical modelling results of the quasi-solution search method used for recovering the water surface oil slick thickness from the measurement data of the reflection coefficients at five wavelengths in the narrow spectral interval in various spectral bands at the mean square value of measurement noise 2\% and \( \Delta\lambda = 5 \) nm. In figure 2 a, b, c, d are shown, respectively, \( \lambda_c = 0.38 \mu m \), \( \lambda_c = 2.1 \mu m \), \( \lambda_c = 4.6 \mu m \), \( \lambda_c = 10 \mu m \).

In all figures a heavy black line depicts a recovered value of the oil slick thickness. A thin black line displays a conventional true value of the thickness, while the black dash-lines show a 30% difference from the conventional true value of the thickness. The Y-axis shows the recovered values of the oil slick thickness, and the specified values are given in the X-axis.

It is seen from figure 2 that the spectral band with a central wavelength of 2.1 \( \mu m \) is the best option (in terms of the band and the recovery accuracy of the oil slick thickness).

![Figure 2. Result of recovering oil slick thickness on water surface at various spectral bands.](image)
The mathematical modeling results for various \( \Delta \lambda \) (at five sensing wavelengths and the mean square value of measurement noise 2 %) are shown in figure 3: \( \Delta \lambda = 10 \text{ nm} \) (a), \( \Delta \lambda = 40 \text{ nm} \) (b), \( \Delta \lambda = 50 \text{ nm} \) (c), \( \Delta \lambda = 70 \text{ nm} \) (d).

![Figure 3](image)

**Figure 3.** Result of recovering oil slick thickness on water surface at various values of \( \Delta \lambda \).

Figure 3 shows that \( \Delta \lambda = 40 \text{ nm} \) is the best option (in terms of the band and the recovery accuracy of the oil slick thickness on water surface).

It is seen that the above mentioned algorithm, using five laser sensing wavelengths in the narrow spectral band about 2.1 \( \mu \text{m} \), at \( \Delta \lambda = 40 \text{ nm} \), based on the measurement data, allows us to recover the oil slick thickness \( d \) on water surface with the error no more than 30% in the band up to \( \sim 200 \mu \text{m} \).

Thus, the mathematical modelling results show that the laser method for measuring an oil slick thickness on the water surface, using an eye-safe discretely wavelength-tunable laser for 5 wavelengths in a narrow spectral band about 2.1 \( \mu \text{m} \), enables us, with the mean square value of measurement noise 2 %, to measure the oil slick thicknesses from \( \sim \) units \( \mu \text{m} \) to \( \sim 200 \mu \text{m} \) with an error of no more than 30%.

5. **Conclusion**

The remote laser multispectral method capabilities to measure the thickness of the oil slicks on the water surface have been analysed. The best option (in terms of the band and the recovery accuracy of the oil slick thickness) is to use the eye-safe spectral band of about 2.1 \( \mu \text{m} \). The mathematical modelling results show that a use of the discretely wavelength-tunable laser for five sensing wavelengths in a narrow spectral interval about 2.1 \( \mu \text{m} \) and the quasi-solution search method for
mesurement data processing, enables us, with the mean square value of measurement noise 2 %, to recover the oil slick thicknesses on the water surface from ~ units μm to ~ 200 μm with an error of no more than 30%.

References
[1] Measures R M 1992 Laser Remote Sensing. Fundamentals and Applications (Malabar. Florida: Krieger Publishing Company)
[2] Hofer T N 2008 Marine Pollution: New Research (New York: Nova Science Publishers Inc.)
[3] Fingas M and Brown C 2014 Marine Pollution Bulletin 83(1) 9
[4] Sergievskaya I and Ermakov S 2012 Proc. of SPIE 8532 85320P-1
[5] Dolenko T A, Fadeev V V, Gerdova I V, Dolenko S A and Reuter R 2002 Applied Optics 41(24) 5155
[6] Kozintsev V I, Belov M L, Gorodnichev V A, Smirnova O A, Fedotov Yu V, Khroustaleva M 2005 Proc. of SPIE 5829 255
[7] Bukin O A, Proshchenko D Yu, Chekhlenok A A and Korovetskiy D A 2019 Atmospheric and Ocean Optics 32(4) 459
[8] Brekhovskikh L M 1976 Waves in Layered Media (New York London Toronto Sydney San Francisco: Academic Press)
[9] Tikhonov A N and Arsenin V Y 1977 Solutions of Ill-posed Problems (Washington: Winston)
[10] Fenn R W, Mill J D, Clough S A, Rothman L S, Gallery W O, Shettle E P, Good R E, Volz F E and Kneizys F X 1985 Handbook of geophysics and the space environment (Springfield. VA: AFGL) pp 18-1–18-80
[11] Corbett J and Woods M 2013 International Laser Safety Conference (Orlando. FL: LIA) Paper #303 1