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Technical Note

Modelling the Spectral Index to Detect a Baltic-Type Crude Oil Emulsion Dispersed in the Southern Baltic Sea

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Abstract: Information was obtained on the possibility of detecting oil-in-water emulsions located under the sea based on the modelling of the directional distribution of the radiance field above the water surface. The optical sea model used applies to the southern Baltic Sea, while the oil emulsion model is based on the optical properties of crude oil extracted in this region of the sea. The analyses were carried out while taking into account eight wavelengths in the range 412–676 nm, assuming different thicknesses of the layer contaminated with oil. The most favourable combination of two wavelengths (555/412 nm) for the determination of an index related to the polluted sea area compared to the same index for oil-free water (difference index) was identified, the value of which is indicative of the presence of the oil emulsion in water. Changes in the difference index depending on the viewing direction are shown for almost the entire upper hemisphere (zenith angles from 0° to 80°). The observation directions for which the detection of emulsions should be the most effective are shown.

Keywords: oil-in-water emulsion; seawater; oil pollution detection; radiance reflectance; spectral index

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1. Introduction

Detecting oily substances in the marine environment is difficult when they are located below the sea surface. In such a situation, information about their presence in the water column can only be transferred to the above-water detector in visible light, because all other types of electromagnetic waves are mostly absorbed by the water. Although intensive studies have been carried out on the propagation of radio-real electromagnetic waves in water [1], it is not known how an oil-in-water emulsion may influence their propagation in the marine environment. However, the interaction of visible light with oil droplets dispersed in seawater is relatively well analysed. The oil droplets, together with the natural components of seawater, affect the directional and spectral distribution of light coming from the sea depths to the atmosphere and further to a potential detector detecting the presence of oil in the water column. Of course, only oil in the upper layers of the sea can be detected in this way. Baszanowska et al. analysed water with an average content of suspended matter (several meters) [2] and presented the results of modelling the visibility of oil-in-water emulsions using data on the optical properties of the southern Baltic waters and crude oil extracted in this area. Moreover, the value of the optical contrast of the oily area in relation to the oil-free area as a function of the wavelength of the light and the viewing angle of the sea surface is shown. The question remains, however, whether other, non-oily suspensions may similarly affect the contrast. Therefore, this paper presents the results of additional analyses of using an appropriate spectral index for the detection of the oil suspension.

2. Materials and Methods

In the modelling, the inherent optical parameters (IOPs) of seawater and the oil suspension were used as in the aforementioned paper [2]. The modelling method also remained the same. The lighting conditions were based on a clear sky, and the angle of incidence of rays directly from the sun was 30°. The water surface was wavy as a result of a wind speed of 5 m/s, based on the Cox and Munk model [3].

3. Results and Discussion

As the modelling was performed for eight wavelengths (412, 440, 488, 510, 532, 555, 650 and 676 nm), 28 indices were determined, i.e., for all possible combinations of two wavelengths. The index calculations refer to the radiance reflectance determined for the observation direction perpendicular to the water (the radiance reflectance is frequently called remote sensing reflectance). The thickness of the polluted water layer was 30 m, and the results are presented in Figure 1.

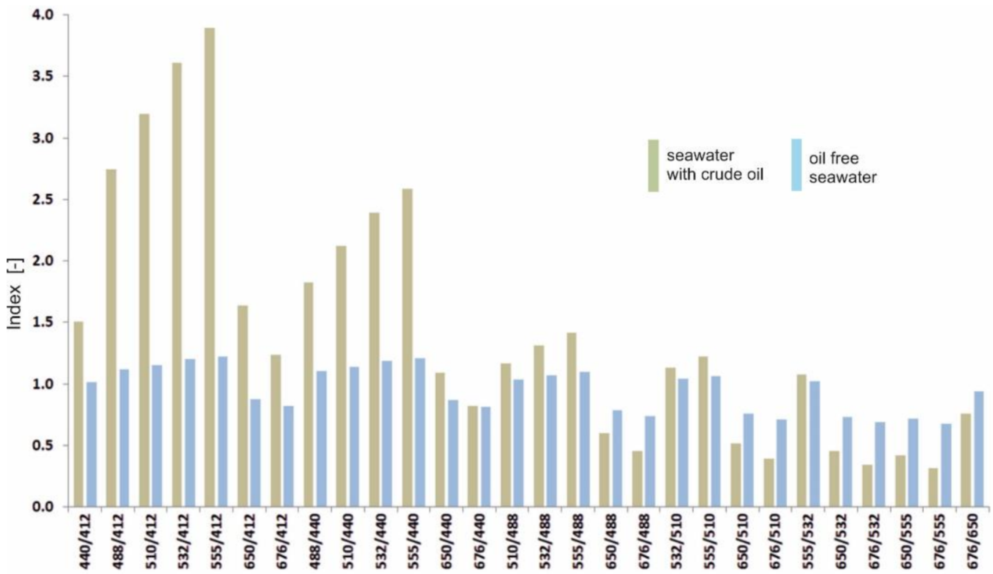

Figure 1. Spectral indices of the sea free of oil and in conditions of dispersed oil pollution.

The highest value of the index for oil-polluted water appears at the wavelength combination 555/412. However, it is important to relate this index to the index for oil-free water. Therefore, the differences between the spectral indices for oily water and water without oil were determined, and are shown in Figure 2. It was determined that the spectral index related to oil-free water falls between the wavelengths of 555/412. Therefore, further analyses were carried out for such an index.

In the next step of the research, as a result of the simulation of the above-water radiance field, the distribution of the spectral index difference was obtained for 1,620 directions of sea surface viewing angles—45 angles for zenith (from 0° to 80°) and 36 for azimuth (every 10 degrees), although the analyses were limited to the previously determined spectral index 555/412. The maximum index difference between oily water and oil-free water clearly occurs at the 555/412 ratio.

Observing the graphs in Figure 3, it can be seen that the index difference for the thickness of the contaminated layer greater than 5 m changes insignificantly. This effect is due to the fact that sunlight poorly penetrates the water to a depth of several meters. At the same time, it should be noted that this conclusion applies to waters with inherent optical properties (IOPs) of the southern Baltic. In the case of transparent ocean waters, this relationship would probably be different.

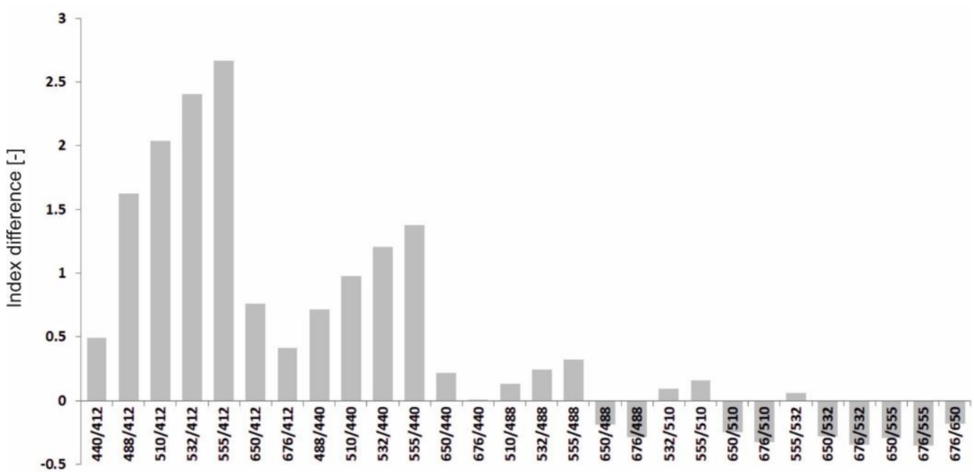

Figure 2. Differences between the values of spectral indices of water polluted with dispersed oil and values of indices of oil-free water. In the case analysed in this paper, a layer of oily water at a depth of several meters would not be noticed.

Observations regarding the visibility of the sea region in which the dispersed oil is located are for very light oiling (10 ppm). With such a low content of oil, the seawater visually observed in the glass vessel is transparent. In real conditions, the concentrations of dispersed oil may be higher, especially at the edges of the oil spot floating on the surface. Qingzhi et al. [4] demonstrated, using the 2010 Gulf of Mexico spill, that satellite optical data allow for the distinguishing between surface-contaminated sea areas and areas with water contaminated with an oil emulsion. Dispersed oil appears in the marine environment, not only as a result of natural processes but also because the use of chemical agents to disperse the oil [5] in a large mass of water is one of the methods of combating spillage.

With such a low oil content as was found in the analyses presented in this paper for an oily water layer of 0.5 m (upper graph in Figure 3), it is impossible to notice it. However, the modelling results indicate that a weak signal indicating the presence of an oil emulsion could exist. The two-meter layer (second graph from the top in Figure 3) of oily water already provides an opportunity to see the contaminated area.

The results of the analysis presented in Figure 3 concern the situation when the sea surface is wind-roughened. As a result of sunlight reflections on wave slopes, the detector receives flashes of light, disturbing the measurement. This effect is shown in Figure 3, which shows how the index difference significantly decreases if the sea surface is observed in the range of angles close to the direction of the specular reflection of light coming directly from the sun. The shape of the graphs in Figure 3 shows that the optimal observation direction is the zenith angle as the sun's zenith angle, but in a plane perpendicular to the plane of incidence of the sun's rays. This conclusion applies only to the index difference measurements, because when determining the contrast there is no such effect, which is illustrated by the juxtaposition of the contrast graph with the index difference graph (Figure 4).

In the process of determining the wavelength for the difference index, inherent optical properties (IOPs) are used for both seawater and oil-in-water emulsions for different wavelengths. There is little information on this subject. The different index used in this study is for a specific sea region and a specific type of oil.

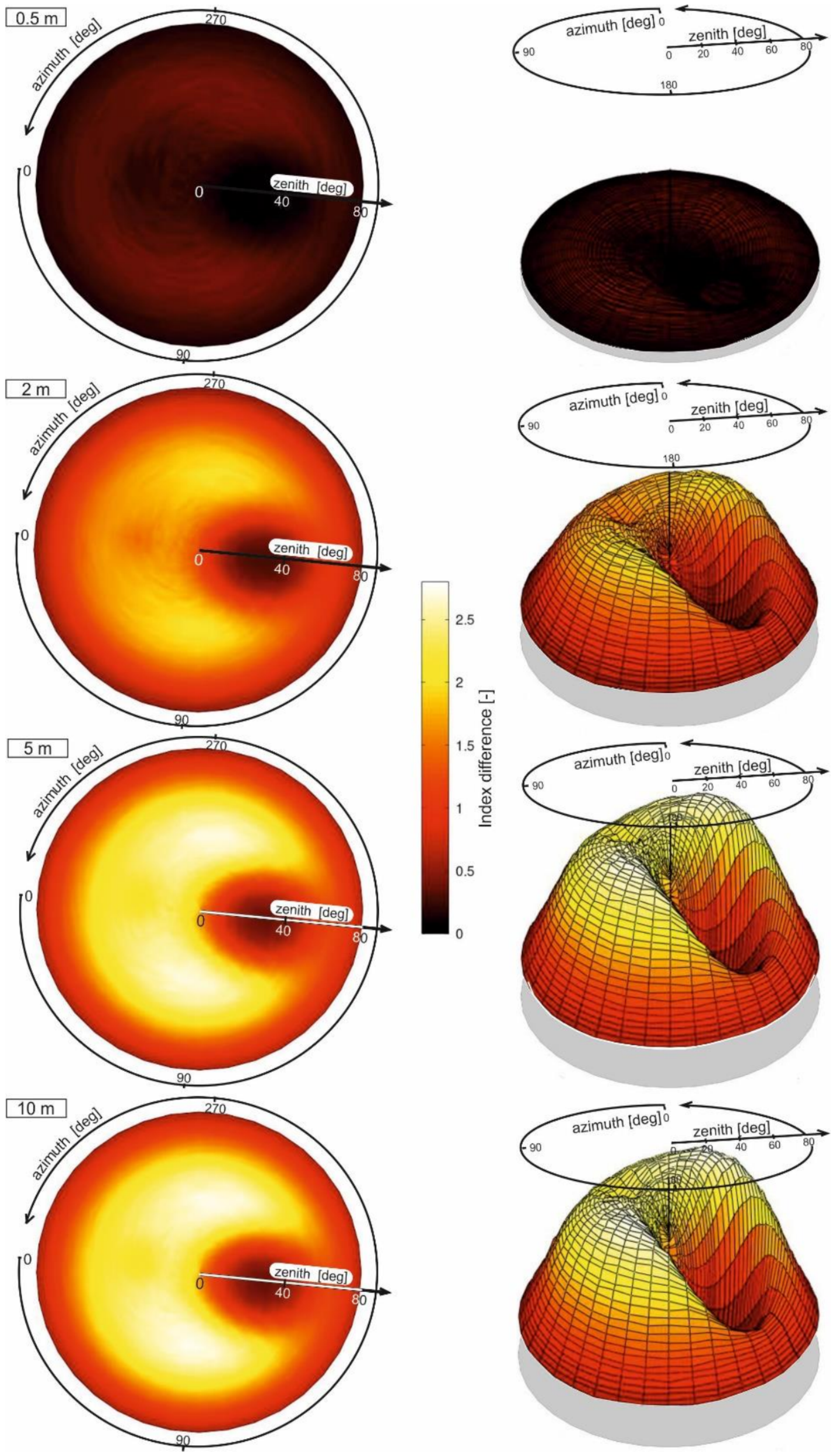

Figure 3. Spectral difference index depending on the thickness of the oil-polluted layer for various viewing angles.

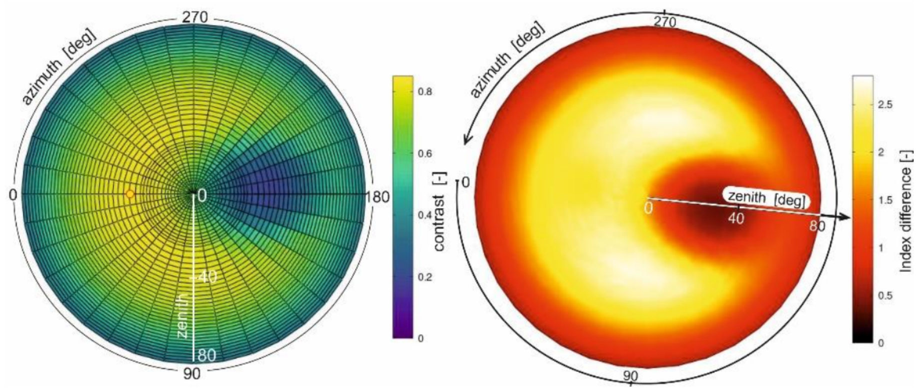

Figure 4. Compilation of the contrast distribution (left, after being extracted from [2]) and the difference in the spectral index (right, extracted from Figure 3) depending on the viewing angle. The thickness of the oily layer is 5 m and the sea surface is wavy due to a wind speed of 5 m/s.

In paper [6], the authors proposed index 650/440 as optimal and universal for various types of oil indices for oil detection. Such an index was calculated, taking into account the data corresponding to the Gulf of Gdańsk (Baltic Sea) and two types of crude oil with extremely different optical properties. The reflectance was determined for the direction of observation of the sea surface perpendicular to the water. However, in studies with the use of the same data, but for the analysis of reflectance for different directions of observation in the plane of incidence of sunlight [7], 650/412 was adopted as the optimal index. In the current paper, index 555/412 was signalled as optimal if it was certain that the water contained Petrobaltic-type oil (extracted in the southern Baltic Sea).

In view of the above statements, the proposed index 555/412 certainly cannot be treated as universal for various sea areas, and the information contained in this paper constitutes supplementary data in relation to the previous paper [2].

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References

1. Singh, G.; Kumar, M. Performance analysis of electromagnetic (EM) wave in sea water medium. *Wirel. Netw.* **2020**, *26*, 2125–2135. [CrossRef]
2. Baszanowska, E.; Otremba, Z.; Piskozub, J. Modelling the Visibility of Baltic-Type Crude Oil Emulsion Dispersed in the Southern Baltic Sea. *Remote Sens.* **2021**, *13*, 1917. [CrossRef]
3. Cox, C.; Munk, W.H. Statistics of the sea surface derived from sun glitter. *J. Mar. Res.* **1954**, *13*, 198–227.
4. Lai, Q.; Xie, Y.; Wang, C.; Wang, M.; Tan, J. Multiband directional reflectance properties of oil-in-water emulsion: Application for identification of oil spill types. *Appl. Opt.* **2021**, *60*, 6902–6909. Available online: https://www.osapublishing.org/ao/abstract.cfm?URI=ao-60-23-6902 (accessed on 30 September 2021). [CrossRef]
5. Merlin, F.; Zhu, Z.; Yang, M.; Chen, B.; Lee, K.; Boufadel, M.; Isaacman, L.; Zhang, B. Dispersants as marine oil spill treating agents: A review on mesoscale tests and field trials. *Environ. Syst. Res.* **2021**, *10*, 37. [CrossRef]
6. Baszanowska, E.; Otremba, Z.; Piskozub, J. Modelling Remote Sensing Reflectance to Detect Dispersed Oil at Sea. *Sensors* **2020**, *20*, 863. [CrossRef] [PubMed]
7. Baszanowska, E.; Otremba, Z.; Piskozub, J. Modelling a Spectral Index to Detect Dispersed Oil in a Seawater Column Depending on the Viewing Angle: Gulf of Gdańsk Case Study. *Sensors* **2020**, *20*, 5352. [CrossRef] [PubMed]