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INTEGRATED METHODOLOGY FOR TRACING OIL SLICKS USING SENTINEL-1 AND SENTINEL-2 DATA: BACKWARD MODELLING, METEOROLOGICAL CORRECTION, AND VISUALIZATION ANALYSIS

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Abstract
Modern satellite systems such as Sentinel-1 (SAR) and Sentinel-2 (optical spectrum) offer valuable tools for detecting the spatial morphology of marine pollution, including dark cores on SAR images that indicate thin surface films or emulsified oil layers. Unlike traditional spill detection, locating the underwater pollution source requires backward trajectory analysis accounting for wind and hydrodynamic conditions. This study presents an integrated methodology for backward tracing of oil slicks, combining satellite image analysis, vertical particle rise modeling, and drift vector correction using Meteoblue data. Special attention is given to the comparative evaluation of EO Browser visualization scripts used to enhance the detection of surface films and improve signal-to-noise ratios on Sentinel-1 and Sentinel-2 images. The method was tested using the case of the "Volgoneft" tanker incident in the northwestern Black Sea (December 2024). The results demonstrate the applicability of this approach for operational source localization under conditions of limited visibility, complex geopolitics, or military conflict.

Key words: *oil spill, marine area, environmental monitoring, Sentinel-1, Sentinel-2, SAR imagery, dark core, drift modeling, meteocorrection, remote sensing.*

Introduction

Modern satellite observation systems, such as Sentinel-1 (SAR) and Sentinel-2 (optical spectrum), enable the detection of the spatial morphology of pollution, particularly the presence of dark core areas in radar imagery, which indicate thin oil films or emulsified inclusions. However, unlike classical slick detection, identifying the coordinates of an underwater spill source requires a backward analysis of the slick's trajectory, taking into account wind and hydrodynamic conditions [3, 4].

This study presents an integrated methodology for the backward tracing of fuel oil slicks, combining satellite image analysis, vertical particle ascent modelling, and meteorological correction of the drift vector using Meteoblue data [7]. Special attention is given to the comparative assessment of the effectiveness of visualization scripts in EO Browser, which are used to enhance the detection of film formations and improve the signal-to-noise ratio in Sentinel-1 and Sentinel-2 imagery [8]. The methodology was tested using the case of the "Volgoneft" tanker accident in the northwestern part of the Black Sea (December 2024).

The proposed approach is suitable for use in environmental monitoring systems under conditions of limited visibility, complex geopolitical circumstances, or military conflict, where the rapid localization of a pollution source is of critical importance [6].

Materials and Methods

Sentinel-1 radar images (IW mode, VV+VH polarization, spatial resolution ~5 m × 20 m) were processed using EO Browser (Sentinel Hub). Sentinel-2 optical images (processing level L2A, resolution 10 m/pixel) were used for verification. Georeferencing of debris and contaminated zones was performed manually using Google Earth Pro (coordinate anchoring) and Umap (for building an interactive map), which enabled visualization of the drift zones and construction of the tracing model. To account for the influence of atmospheric conditions and underwater currents, archived meteorological data from Meteoblue (wind fields, currents, turbulence) were additionally used for drift direction correction and source coordinate estimation.

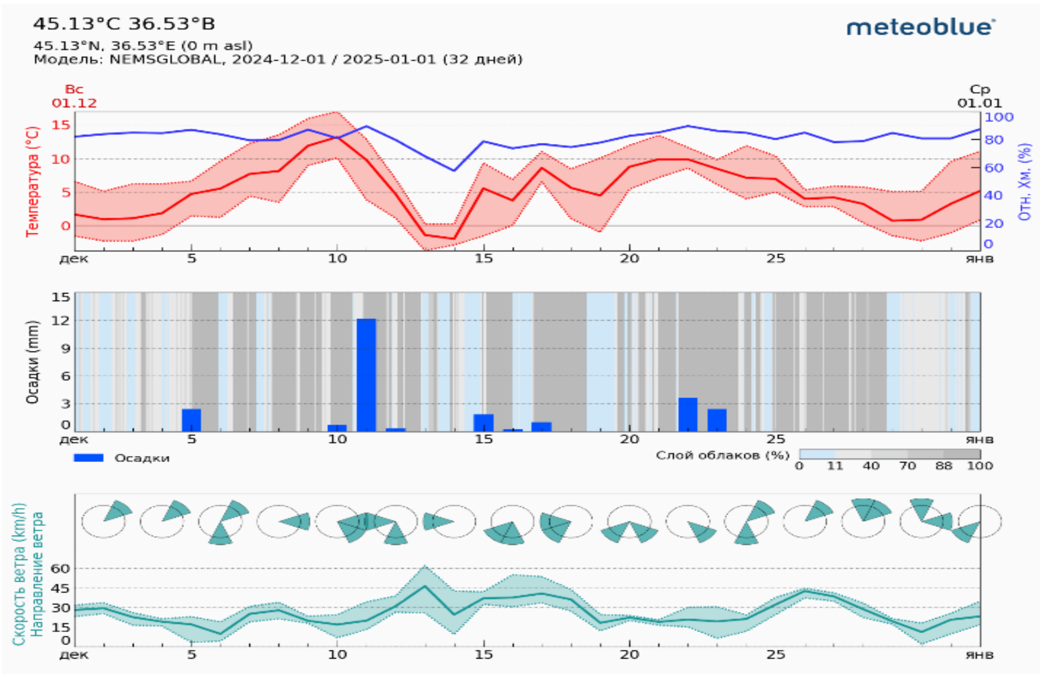

Fig 1. *Archived meteorological data from Meteoblue (45.13°N, 36.53°E) for the period from December 1, 2024, to January 1, 2025, were analyzed*

The chart displays daily averages of temperature, cloud cover, precipitation, wind direction, and wind speed. Weather conditions throughout December 2024 were consistently cloudy, with variable wind directions and short periods of calm. These data were used for meteorological correction of the dark core drift model.

To improve the accuracy of detecting film slicks and dark core areas, the effectiveness of EO Browser scripts was analyzed. For Sentinel-1, 18 scripts were tested, including customized variants with modified display channels. The highest performance was demonstrated by the script VV - Linear Gamma0 – 50% green. For Sentinel-2, indices such as NDWI, SWIR, False Color Urban, and others were evaluated—these proved most suitable for verifying surface objects and pollution boundaries.

The methodology is based on detecting dark core areas—stable zones of SAR signal absorption, which are interpreted as surface markers of underwater leakage [1].

The displacement of the slick head was calculated based on the coordinates of the dark core center and the direction of the submarine current (Figure 1):

$$Lh=(h\times vh)/wr, \quad (1)$$

where: Lh — horizontal displacement magnitude (m), h — source depth (m), vh — horizontal current velocity (m/s), wr — particle rise velocity (m/s) [2].

The location of the source was determined using the following formula:

$$P\_source=P\_head-Lh\times dir, \quad (2)$$

where: P_source — calculated coordinates of the source, P_head — coordinates of the dark core (determined from SAR), dir — normalized vector of horizontal current direction [**Помилка! Джерело посилання не знайдено.**].

A morphological analysis of the slick (tapering pattern) was then performed, followed by backward tracing to the dark core, correction using archived meteorological data (Meteoblue), and verification with Sentinel-2 optical imagery (presence of signal buoys, debris) (Figure 2). A complicating factor is the potential coalescence of slicks from multiple sources, which is considered as a morphological indicator.

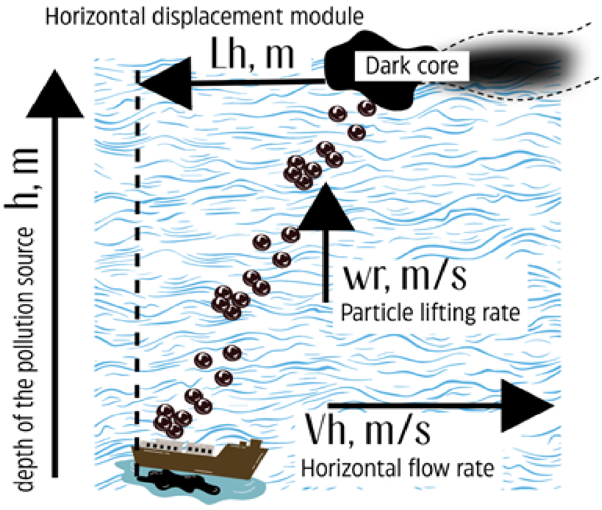

Fig. 2. *Scheme of dark core displacement relative to the underwater pollution source under the influence of the current*

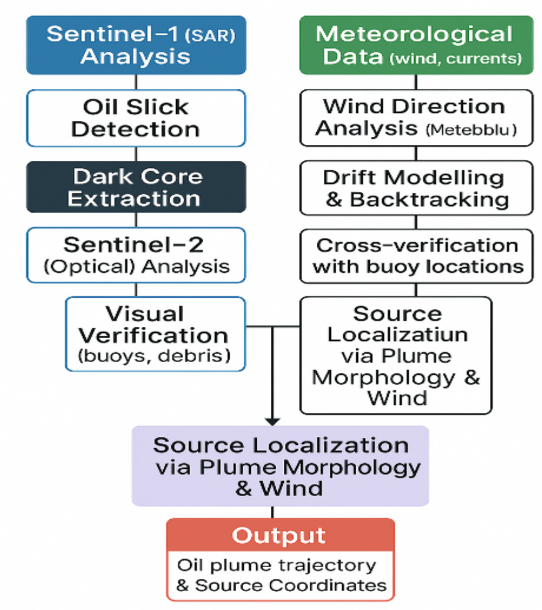

Fig. 3. *Block diagram of the integrated methodology for tracing an oil slick*

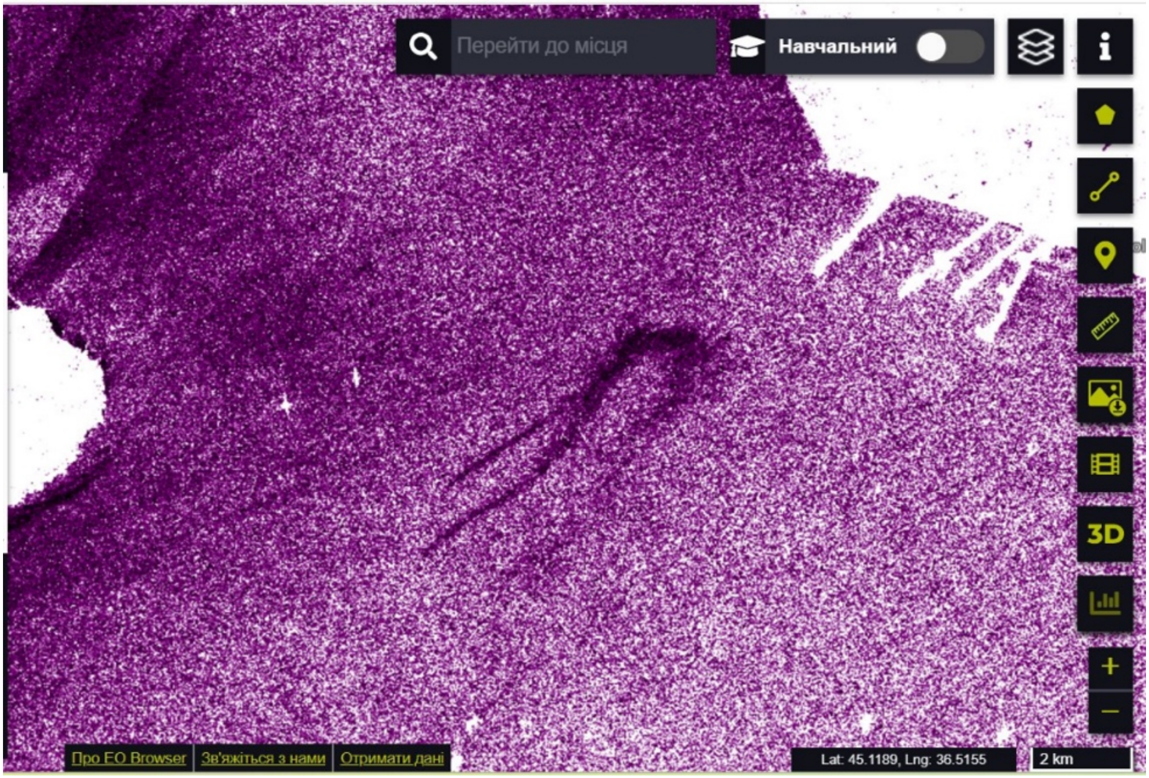

Fig. 4. *SAR visualization of the fuel oil slick using the script VV - Linear Gamma0 – 50% green (Sentinel-1, March 13, 2025)*

The dark core on Fig.4 is clearly distinguishable against the water surface due to reduced surface roughness. Manual attenuation of the green channel enhances the signal-to-noise ratio without compromising the slick's morphology.

Results

Sentinel-1: Evaluation of EO Browser Script Effectiveness. A total of 18 EO Browser scripts were tested for visualizing fuel oil slicks in Sentinel-1 SAR imagery. The focus was placed on VV polarization mode, as it is the most sensitive to changes in water surface micro-roughness.

The highest effectiveness was demonstrated by the script VV - Linear Gamma0 – 50% green, in which the green channel is attenuated to reduce background noise. This script provided the best signal-to-noise ratio and clear delineation of the dark core and film slick boundaries across a wide range of contrast settings.

Other highly effective scripts included:

– VV - Gamma0 (decibels) — a basic high-contrast SAR visualization option;
– SAR Urban — provides colored display of slicks and surface objects (e.g., buoys, debris) against the water background.

Scripts that used VH polarization or were designed for land-based objects did not yield high-quality results under conditions of film pollution. Some scripts were technically unsuitable due to EO Browser code size limitations.

The evaluation was based on the following criteria: contrast of the dark core, noise resistance, boundary detail of the oil film.

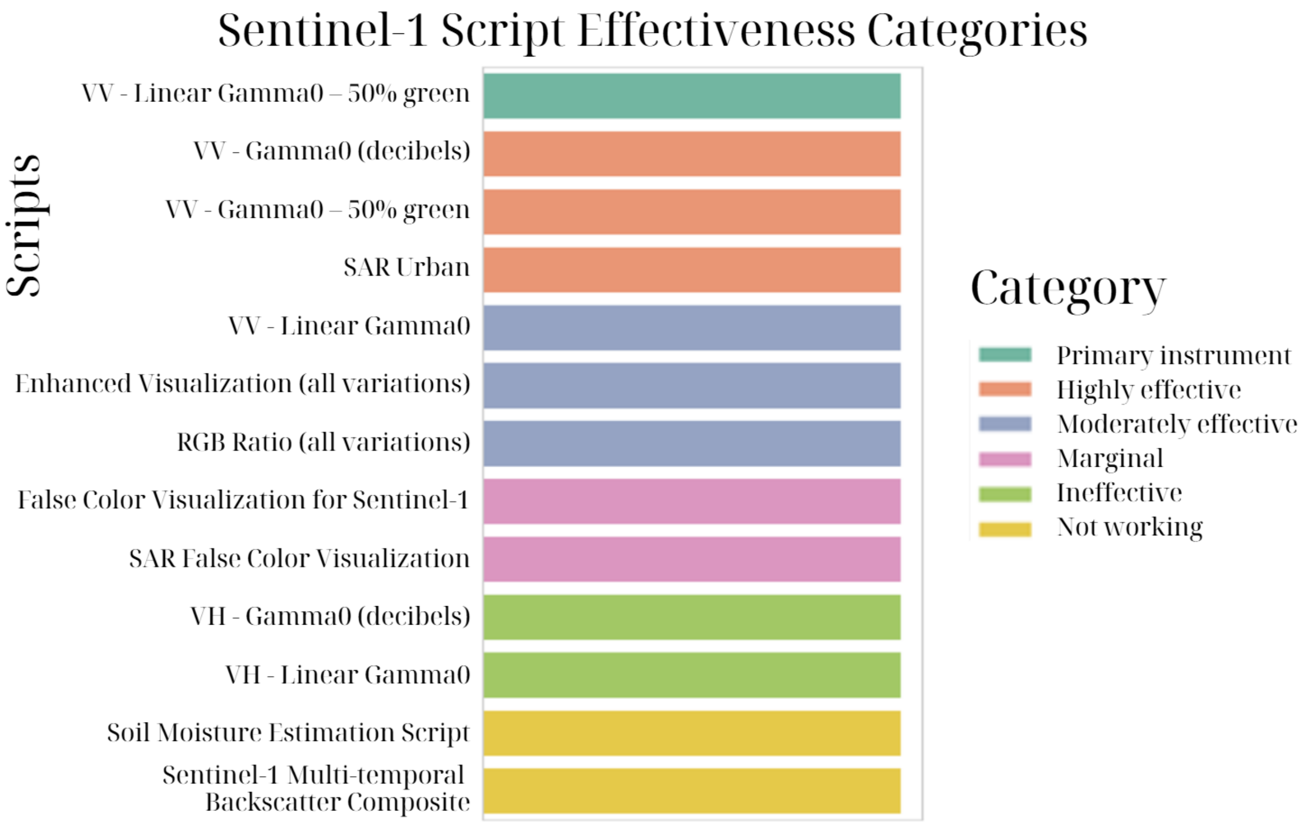

***Fig. 5.** Categories of EO Browser script effectiveness for Sentinel-1 in visualizing fuel oil slicks*

The classification was based on the quality of dark core detection, contour clarity of film slicks, and signal-to-noise ratio in Sentinel-1 SAR images (VV/VH).

Sentinel-2: evaluation of EO Browser script effectiveness. To visualize film-like fuel oil pollution in Sentinel-2 optical imagery, 10 EO Browser scripts were tested, utilizing visible, near-infrared, and SWIR bands. The focus was placed on the NDWI index, SWIR composites, and Urban Color visualizations. The best results were shown by:

– NDWI — enabled clear delineation of the slick boundary up to 7.4 km from the debris under good lighting conditions;
– SWIR (Shortwave Infrared) — enhanced contrast between oil films and the water surface;
– False Color Urban — provided the most intuitive interpretation of surface objects, particularly debris and buoys.

A significant number of scripts required manual adjustment of the sensitivity threshold due to the relatively low dynamic range of the reflected signal. It was also found that during the winter-spring period, Sentinel-2 is limited in the number of high-quality images due to cloud cover, especially in the case of thin oil films.

The evaluation was based on the following criteria: visibility of slick boundaries, detail of surface objects, and stability of results under varying atmospheric conditions.

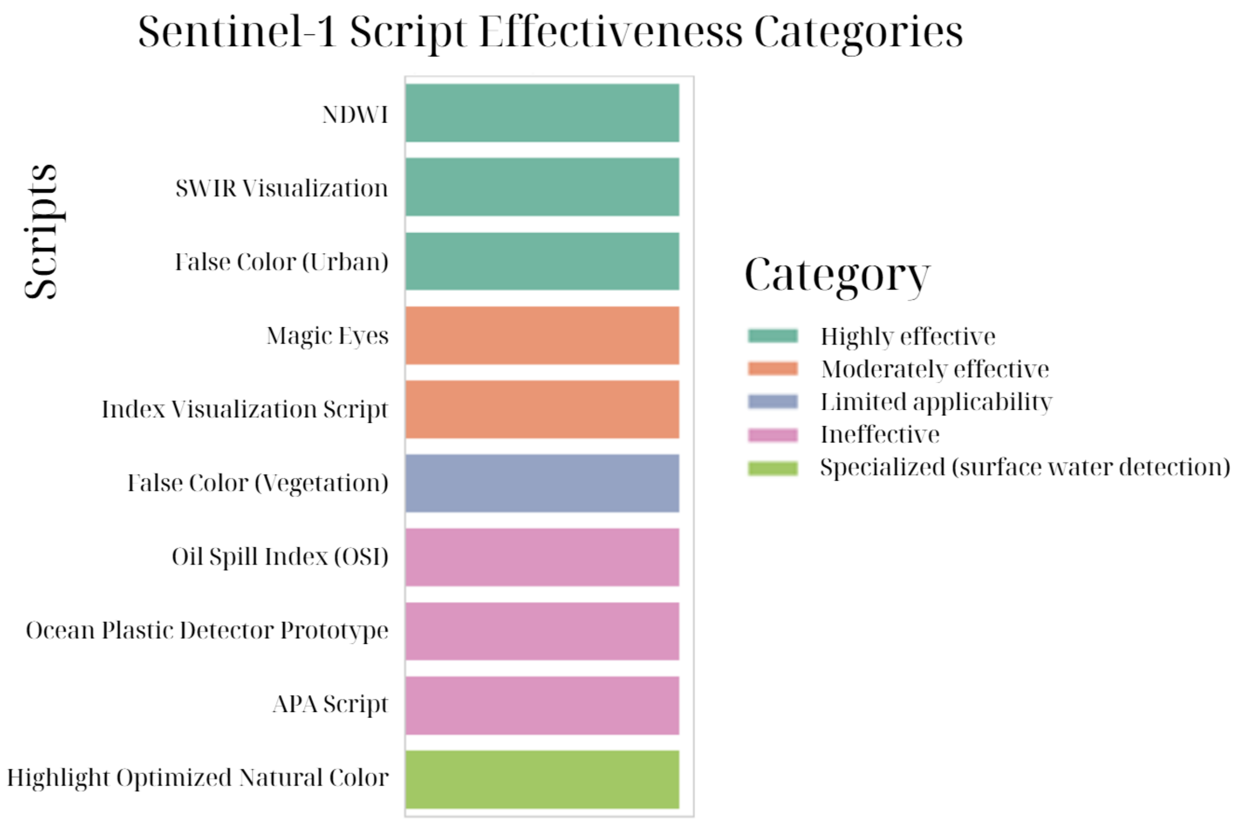

Fig. 6. *Categories of EO Browser script effectiveness for Sentinel-2 in visualizing fuel oil pollution*

The classification was based on the quality of slick boundary detail, the ability to identify surface objects, and the stability of results in Sentinel-2 optical imagery (L2A, 10 m/pixel).

Comparison of Sentinel-1 and Sentinel-2 platforms. A comparative analysis showed that Sentinel-1 radar imagery provides significantly higher effectiveness in detecting extended fuel oil slicks, particularly dark core areas. It was observed that the slick boundary could be traced on SAR images at a distance of over 14.8 km from the debris, whereas on the best available Sentinel-2 optical image, this boundary was limited to approximately 7.4 km.

Additionally, during the winter-spring period, Sentinel-1 provided at least twice as many images suitable for analysis, as it is not affected by cloud cover. This ensured stable retrospective monitoring.

Sentinel-2 optical imagery proved valuable for verifying surface objects—such as debris, buoys, and localized emulsified accumulations. NDWI and SWIR composites were particularly informative. However, their high dependence on weather conditions limited their practical utility for tracing in crisis situations.

Thus, Sentinel-1 should be considered the primary platform for backward slick tracing, while Sentinel-2 serves as a complementary source for confirming pollution morphology when high-quality images are available.

The comparison results served as the basis for the practical application of the methodology during the analysis of the "Volgoneft-212/239" tanker accident, which made it possible to:

– localize the underwater spill sources;
– determine coordinates with an estimated accuracy of 40–150 meters, depending on the depth of the source, the speed of underwater currents, and the quality of SAR georeferencing [3] (Table 1);

– build an interactive map of debris and slick drift; detect film slicks up to 20 km in length; confirm the effectiveness of the dark core displacement model combined with meteorological correction [4].

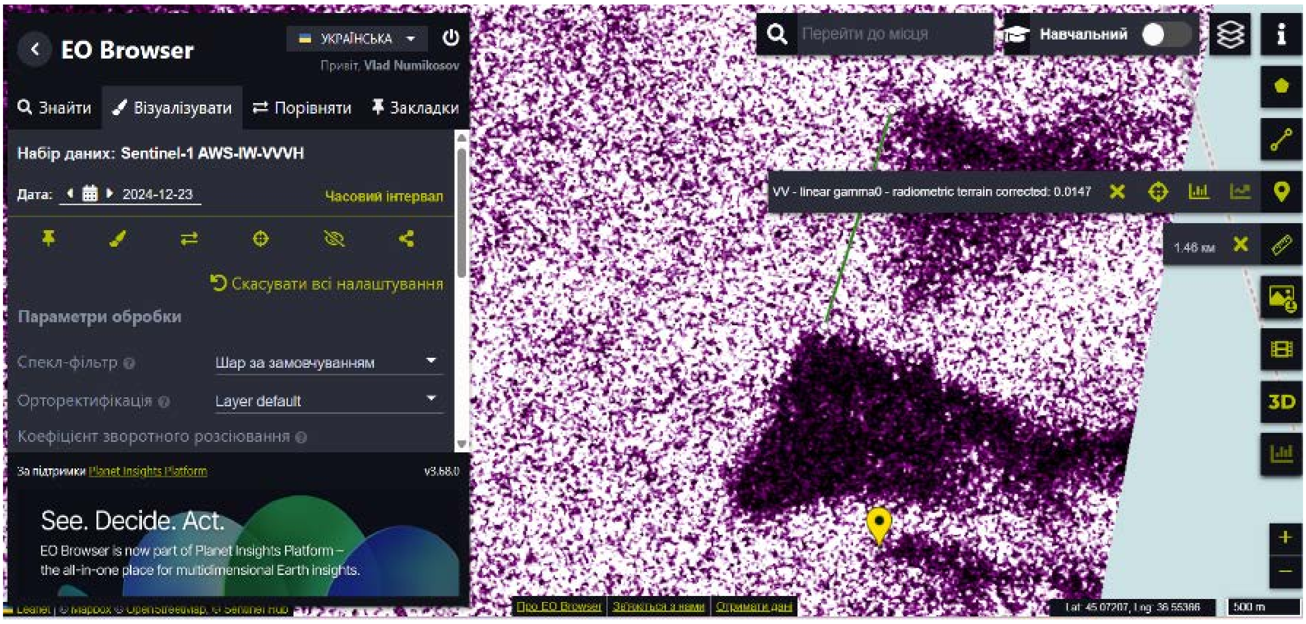

Fig. 7. *Localization of submarine spill sources based on the stable dark core zone in the Sentinel-1 SAR image (VV, 23.12.2024): 1-Lat: 45.05928, Long: 36.53598; 2-Lat: 45.07207, Long: 36.53134; 3-Lat: 45.08449, Long: 36.53701*

Table 1. Coordinates of submarine spill sources

Sentinel-1 AWS-IW-VV+VH (coordinate system: WGS-84)			
	Spill source ID	**Latitude, B**	**Longitude, L**
As of 18.12.2024:	1.	45.05916	36.53761
	2.	45.07224	36.53143
As of 23.12.2024:	1.	45.05928	36.53598
	2.	45.07207	36.53134
	3.	45.08449	36.53701
As of 31.12.2024:	2.	45.07200	36.53139
	3.	45.08459	36.53751

The evaluation of the effectiveness of backward slick tracing confirms the reliability of SAR-based identification of dark cores as stable markers of submarine spills, even under complex hydrodynamic conditions [1]. The modeling results and observations are consistent with the findings described in the works of Fingas [5], which emphasize the importance of accounting for the vertical ascent of emulsified particles and the influence of weather conditions on the formation of surface oil slicks.

Conclusions

The proposed methodology for backward tracing of fuel oil slicks based on Sentinel-1 and Sentinel-2 satellite imagery enabled the identification of underwater spill source coordinates with high accuracy—within 40–150 meters, depending on the quality of input data and meteorological conditions. The algorithm is based on SAR analysis of the spatial morphology of the dark core, drift direction correction using meteorological models, and optical verification of surface objects [2, 4].

The methodology proves effective in situations where physical access to the disaster site is limited or impossible. It enables stable retrospective monitoring, localization of environmental impact, and support for an evidence base in the context of military or technological conflict. The use of such approaches is recommended for monitoring underwater spills in crisis regions, including areas affected by armed conflict.

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ІНТЕГРОВАНА МЕТОДИКА ТРАСУВАННЯ НАФТОВИХ ШЛЕЙФІВ ЗА ДАНИМИ SENTINEL-1 ТА SENTINEL-2: ЗВОРОТНЕ МОДЕЛЮВАННЯ, МЕТЕОКОРЕКЦІЯ ТА ВІЗУАЛІЗАЦІЙНИЙ АНАЛІЗ

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Анотація

Сучасні супутникові системи, такі як Sentinel-1 (радар з синтезованою апертурою, SAR) і Sentinel-2 (оптичний спектр), надають цінні інструменти для виявлення просторової морфології морських забруднень, зокрема темних зон на зображеннях SAR, що вказують на тонкі поверхневі плівки або емульговані шари нафтопродуктів. На відміну від традиційного виявлення розливів, локалізація підводного джерела забруднення вимагає зворотного аналізу траєкторій з урахуванням вітрових та гідродинамічних умов. У цьому дослідженні представлено інтегровану методику зворотного трасування нафтових шлейфів, що поєднує аналіз супутникових знімків, моделювання вертикального підйому частинок та корекцію вектора дрейфу на основі даних Meteoblue. Особливу увагу приділено порівняльній оцінці скриптів візуалізації EO Browser, які використовуються для покращення виявлення поверхневих плівок і підвищення співвідношення сигнал/шум на знімках Sentinel-1 та Sentinel-2. Методика була протестована на прикладі інциденту з танкером «Волгонєфть» у північно-західній частині Чорного моря (грудень 2024 року). Результати демонструють придатність цього підходу для оперативної локалізації джерел забруднення в умовах обмеженої видимості, складної геополітичної ситуації або воєнного конфлікту.

Ключові слова: розлив нафти, морська акваторія, екологічний моніторинг, Sentinel-1, Sentinel-2, зображення з радаром синтезованої апертури (SAR), темна зона, моделювання дрейфу, метеокорекція, дистанційне зондування Землі.