Enhancing Oil Spill Interpretation Through Multisensor Fusion and Temporal Reconstruction: A Case Study Near the Strait of Gibraltar

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Abstract

Oil spills in confined maritime corridors often evolve faster than any single satellite mission can observe. Their surface expression breaks apart, shifts direction, and reorganizes as winds, currents, and ship traffic interact with the drifting material. This often complicates the interpretation of individual images and create gaps in understanding how a spill progresses between satellite overpasses. This study examines whether combining Sentinel-1 and Sentinel-2 observations can provide a more coherent picture of its development of a spill event, using the case of an oil spill occurred near the Strait of Gibraltar in late August 2022 after a collision between the OS35 and the Adam LNG.

The preliminary analysis evaluated each sensor separately. Sentinel-1 highlighted changes in surface roughness, while Sentinel-2 revealed reflectance anomalies linked to modified optical properties of the water. Since neither dataset on its own offered a complete account of the surface conditions, a fusion procedure was applied to the closest pair of post-event images. The fused map displayed sharper boundaries and more spatial detail than the radar scene alone, offering a clearer outline of the affected area. To address the temporal mismatch between acquisitions, intermediate surfaces were also reconstructed for both sensors, producing estimated representations of the marine conditions at dates not directly observed.

Taken together, the fused and reconstructed products formed a more continuous sequence of the spill’s evolution, capturing both its fragmentation and its short-term reorganisation. Although the approach does not replace dedicated operational monitoring, it demonstrates that combining complementary satellite data can reduce ambiguity in single-sensor interpretation and strengthen situational awareness in regions where surface conditions change quickly and unpredictably.

1. Introduction

Marine oil spills have long been known as one of the most disruptive hazards affecting coastal and offshore environments, when even relatively small releases can cause ecological damages that unfold over weeks or months. This problem troubles different sectors: fisheries, tourism, and the broader coastal economy are all . What makes these events particularly challenging is that their behaviour at sea rarely follows a simple or predictable pattern. Once oil reaches the water, physical processes begin reshaping it almost immediately. The slick often scattered in the clean water, and blends unevenly with the surface layer. Weathering processes change its optical and mechanical properties over time, while winds, tides, and waves push it in competing directions. Furthermore, the long-term social and economic implications of these events often persist long after the visible remnants have dispersed from the surface (de Oliveira Estevo et al., 2021).

Traditional monitoring methods rely on aircraft-based or ship-based patrols, along with aerial surveys. And while approaches provide valuable situational awareness, particularly in the early hours after a spill, they are inherently limited by range, cost, and logistics, due to the the fact they offer only snapshots in time, missing many intermediate stages in which the slick "reorganises" itself or expands into new areas. In narrow maritime corridors - as the Strait of Gibraltar - this problem is magnified. This area is an example of a confined channel, where Atlantic and Mediterranean water masses meet, and where commercial shipping forms a dense, continuous stream. Under such conditions, the trajectory of a spill event becomes highly sensitive to vessel wakes, currents, and rapid meteorological changes. What appears as a single and consistent feature during one overpass, may be entirely scattered a few hours later.

The limitations of conventional observation platforms have brought out the need for large-scale, repeatable monitoring tools. Satellite remote sensing has become central to this shift, offering broader spatial coverage and an archived historical record that can be revisited retrospectively. The traditional remote sensing option for oil spill detection is using synthetic aperture radar (SAR) instruments like Sentinel-1, operating independently of cloud cover or daylight, detect changes in surface roughness caused by the damping of short waves, allowing slicks to appear as darker-than-usual regions (Fingas and Brown, 2014; Naz et al., 2021). However, different satellite missions can contribute different types of information. For example, multispectral optical sensors, such as those on Sentinel-2, register variations in water colour and reflectance associated with emulsification, suspended matter, or changes induced by oil films (Hu et al., 2021).

Since each system has shortcomings - optical imagery is highly vulnerable to cloud cover, haze, sun glint, and natural variability in turbidity or biological activity (Bradford and Sanchez-Reyes, 2011), and SAR imagery, although robust under challenging atmospheric conditions, suffers from speckle noise and can easily confuse calm-water zones or natural surfactants with true oil slicks (Akkartal and Sunar, 2008) - a broader solution must be offerred. In dynamic environments such as Gibraltar, these weaknesses become more pronounced: a single Sentinel-2 scene might miss key developments due to cloudiness, while the nearest Sentinel-1 pass may fall several days earlier or later, capturing only a portion of the changing event.

Recent years have therefore seen a growing interest in multisensor methods. Studies have explored the potential of combining optical and SAR features, employing machine learning and deep learning to refine discrimination between oil and look-alike phenomena (Seydi et al., 2021; Yekeen et al., 2020). At the same time, the international community – through frameworks like the UN Sustainable Development Goals – has emphasised the importance of early detection and continuous environmental monitoring, underscoring the need for tools that

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extend beyond single-image interpretation (UNEP, 2023; United Nations, 2023).

However, a persistent challenge remains: temporal gaps between satellite overpasses. Sentinel-1 and Sentinel-2 rarely observe the same location on the same day. When a spill evolves over hours rather than days, this mismatch leaves significant portions of its progression undocumented. The difficulty is not only in identifying the slick on a given date, but in understanding how it moves and transforms in the intervals between acquisitions.

The present study addresses this gap by examining an oil spill that occurred near Gibraltar in late August 2022. Using both Sentinel-1 and Sentinel-2 data, the analysis explores how multisensor fusion can enhance spatial detail and reduce ambiguities inherent to each sensor type. In parallel, the study investigates a temporal reconstruction approach that approximates surface conditions on dates falling between the actual satellite observations, effectively filling in the missing steps of the spill’s evolution. By integrating complementary datasets and generating intermediate representations, the goal is to provide a more coherent and continuous description of the spill, improving both detection and interpretation in a complex and rapidly changing marine environment.

2. Methodology

2.1 Study area

The analysis was conducted on a spill event that occurred in the Strait of Gibraltar and its surrounding waters around August 2022. This region is an intersection between Atlantic inflow and Mediterranean outflow, producing shifting surface patterns that influence how pollutants spread and scatter in the ocean water. The strait is also one of the busiest passages in the region, with continuous commercial traffic that generates additional turbulence and complicates the interpretation of surface anomalies. These characteristics make it a suitable testbed for evaluating detection methods under rapidly changing marine conditions.

The spatial domain used in this study included the main corridor of the strait. A binary water mask was applied across all stages of the workflow to exclude land pixels and prevent shoreline artefacts from affecting the anomaly calculations or the fused outputs. Fig. 1 presents both the study area, and the corresponding water-only domain used throughout the analysis.

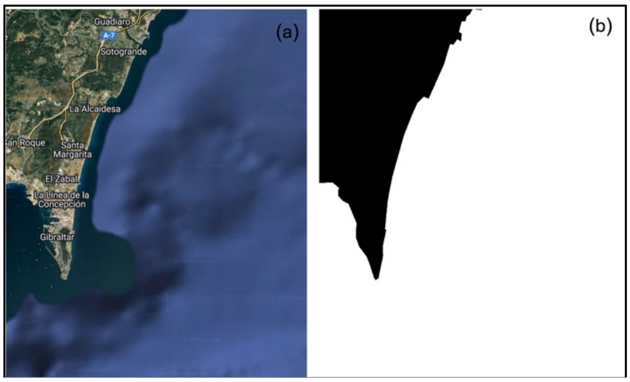

Figure 1. Study area and water mask: (a) Location of the spill site near the Strait of Gibraltar; (b) Binary land-water mask used to restrict all analysis to the marine area.

2.2 Satellite data and pre-processing

We The study relied on multi-sensor datasets, from both Sentinel-1 and Sentinel-2, as shown in Fig.2. Since the spill event took place in late August 2022, data was acquired from both sensors several days before the event (for baseline), during the event (or the closest), and a few days after the event. In terms of information - the two sensors offer complementery aspects: Sentinel-1 delivers C-band synthetic aperture radar measurements, sensitive to changes in surface roughness. Areas where short waves are dampened often appear darker than their surroundings and may indicate the presence of oil or surfactants; Sentinel-2 provides multispectral optical reflectance that is influenced by water colour, turbidity, and emulsification processes. Together, these datasets offer two independent perspectives on the evolving surface conditions.

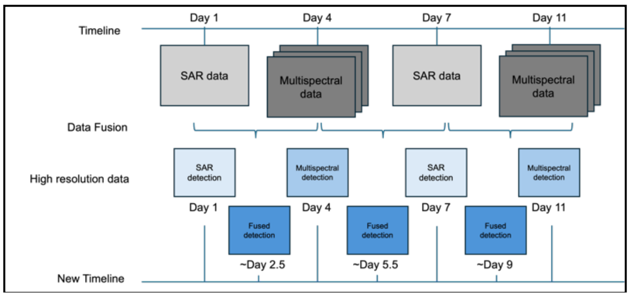

Figure 2. Processing workflow. Schematic overview of the multi-sensor fusion and temporal reconstruction steps applied to Sentinel-1 and Sentinel-2 data.

Two main temporal windows were selected. A Sentinel-1 scene from 27 August represented the pre-spill conditions, while the scene from 30 August captured the earliest SAR-visible anomalies. Sentinel-2 imagery from 1 September was used to examine optical anomalies that developed shortly after the incident. The mismatch between acquisition dates reflects a common limitation in operational monitoring but also motivated the reconstruction stage later in the workflow.

All images were corrected and standardised before the analysis. Sentinel-1 data were processed to remove thermal noise, apply radiometric calibration, and convert the VV channel to calibrated backscatter values. A conservative speckle-suppression filter was applied to reduce noise without eroding the fine-scale structures that are relevant for detection. Sentinel-2 scenes were atmospherically corrected and converted to surface reflectance. Cloud and shadow pixels were removed through a combination of the mission’s quality mask and additional threshold checks tailored to the local conditions.

Both datasets were resampled to a unified grid and clipped to the water mask shown in Fig. 1. This ensured that anomaly calculations, fusion operations, and reconstructions were applied only to open-water pixels, avoiding the contrast-driven artefacts that typically occur at coastline boundaries.

2.3 Single-sensor anomaly extraction

The first analytical stage focused on assessing what each sensor could reveal independently. This step served two purposes. It established a baseline that reflects the practical limitations of single-sensor monitoring, and it provided the reference surfaces required for the fusion and reconstruction processes.

For the SAR component, anomaly extraction was carried out using Sentinel-1 VV backscatter. The pre-spill scene from 27 August served as the clean-water reference, capturing the expected surface roughness patterns under prevailing wind conditions. The scene from 30 August was then normalised against this baseline. Areas where surface waves were dampened appeared as pronounced negative deviations, forming the darker patches that typically mark potential oil slicks or surfactant layers. The method is intentionally simple, mirroring common operational workflows that rely on relative differences between adjacent dates.

Optical anomalies were assessed from the 1 September Sentinel-2 acquisition. Because optical reflectance is influenced by several environmental factors, including suspended matter and biological activity, the extraction relied on spectral contrasts that emphasise abrupt changes in water colour rather than absolute values. A composite index was derived from the visible and near-infrared bands to highlight regions where the reflectance signature deviated from the local background. Cloud, haze, ship wakes, and atmospheric noise were masked to avoid false detections. Although this method identifies regions with spectral irregularities, it shares a key limitation with the SAR-only map: neither sensor, in isolation, provides a stable and unambiguous representation of the spill in a dynamic setting such as the Strait of Gibraltar.

2.4 Data fusion

The core of the methodology lies in combining the strengths of the two sensors to produce a spatially enriched surface that supports more reliable interpretation. The fusion step was designed to integrate the fine-scale structural information from Sentinel-1 with the spectral sensitivity of Sentinel-2. By aligning the two datasets on the common grid established in the pre-processing stage, the method generated a harmonised representation in which features linked to oil-induced anomalies are more clearly distinguished from natural variability.

The fused product was computed for the closest available pair of acquisitions, namely Sentinel-1 from 30 August and Sentinel-2 from 1 September. Since the spill was already dispersed into several streaks by this time, the fusion offered an opportunity to examine whether additional spatial detail could improve the separation between clean surface waters and suspected contamination. This separation was quantified through a boundary sharpness metric that compared local gradients around the anomaly boundaries in the SAR-only and fused surfaces. Higher values indicate a more distinct and spatially coherent transition between the background and the detected anomalies.

The fused anomaly field also enabled a more robust threshold-based classification. Because artefacts from calm-water zones and optical noise were partially suppressed during the integration process, a single global threshold was provided for a separation between high-confidence anomalies and the surrounding waters. Applying this threshold will then produce a binary mask that isolates the main cluster of suspected contamination. This output, while simple, was meant to reflect an operationally meaningful product that can support early response or targeted sampling.

2.5 Temporal reconstruction

While fusion might improves spatial detail, it does not resolve the temporal gaps between satellite overpasses. To address this, an intermediate reconstruction stage was introduced to approximate the surface conditions on dates that fall between the actual observations. The rationale behind this step is not to recreate a perfect optical or radar image, but rather to infer the likely pattern of surface anomalies during periods when no satellite data are available.

The reconstruction approach was based on a pixel-wise temporal interpolation applied between consecutive observations for each sensor. For each pixel, the signal was assumed to evolve gradually between acquisition dates, and intermediate values were estimated accordingly. The method was implemented independently for Sentinel-1 VV backscatter and Sentinel-2 reflectance bands. Prior to the interpolation, all images were co-registered and resampled to a common spatial grid to ensure consistency between observations.

This approach provides a simplified approximation of temporal evolution and does not explicitly model physical transport processes but rather aims to generate continuous intermediate representations between available satellite acquisitions. Although the reconstructed surfaces are not intended to match any real image with photographic accuracy, they provide a visual and analytical link between stages of the event that cannot be directly observed. These surfaces are designed to illustrate the potential added value of intermediate representations when evaluating rapidly changing marine conditions or preparing time-series analyses that depend on a more continuous view of the evolving slick.

3. Results

All results were generated exclusively within the marine mask defined in Fig. 1, allowing the analysis to focus on open-water conditions during and after the late-August 2022 spill event.

3.1 Single-sensor anomaly detection

The Sentinel-1 imagery provided the first indication of changes in surface roughness around the time of the event. The scene from 27 August 2022 showed a spatially uniform ocean background with no pronounced depressions in VV backscatter (Fig. 3a). In contrast, the acquisition from 30 August 2022 contained several elongated dark features, appearing as low-backscatter streaks distributed across the marine surface (Fig. 3b). These variations formed the earliest distinct patterns observed after the spill.

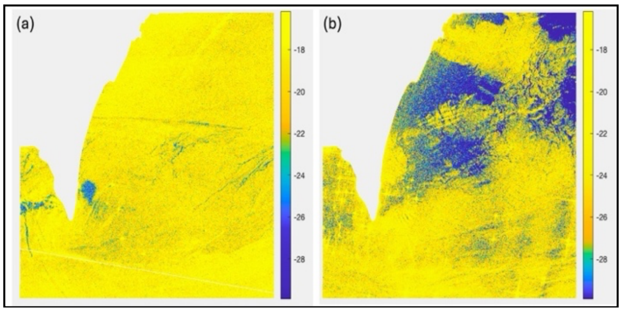

Figure 3. Sentinel-1 anomaly maps for 27 August (a) and 30 August 2022 (b), showing changes in VV backscatter within the marine mask.

Sentinel-2 data were examined using September 1st, 2022, image, which was closest to the spill event, to produce an anomaly field in which cloud artefacts and vessel signatures were masked (as shown in yellow in Fig. 4). The resulting map displayed a mixture of darker regions, which stood out against the surrounding water, and brighter areas that corresponded to clearer or more reflective surface patches. Together, the two sensors provided complementary spatial perspectives on the evolving conditions of the sea surface. It should be noted that the anomaly values shown in Figures 3 and 4 are sensor-specific and expressed in relative, unitless terms derived from internal normalization procedures. As a result, the value ranges are not directly comparable between Sentinel-1 and Sentinel-2, but rather reflect deviations from the respective background conditions within each sensor.

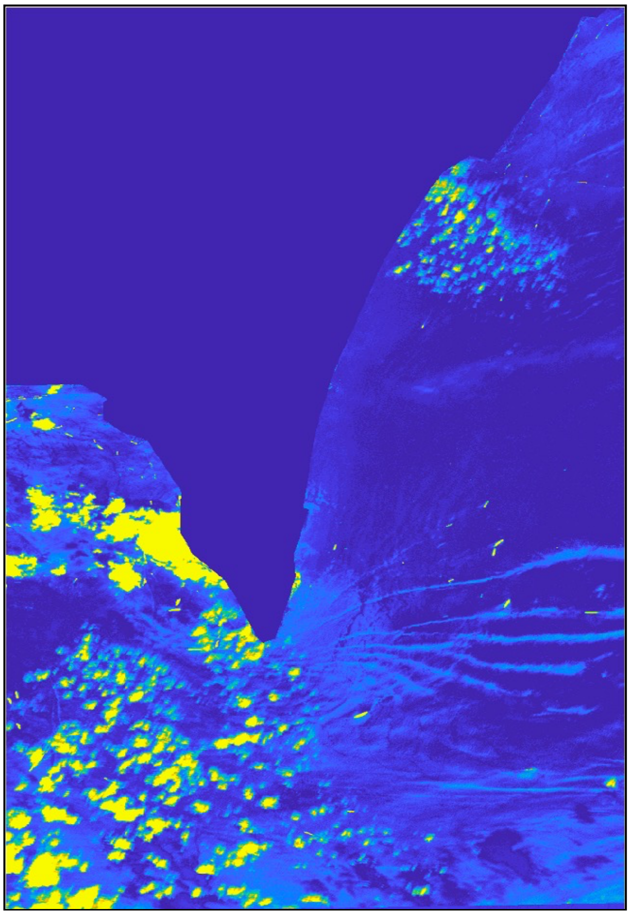

Figure 4. Sentinel-2 anomaly field for 1 September 2022 after masking cloud and vessel artefacts.

3.2 Spatial fusion of Sentinel-1 and Sentinel-2

A multisensor fusion product was then conducted using the closest pair of post-event acquisitions, combining the Sentinel-1 pass from 30 August with the Sentinel-2 image from 1 September. When visually compared, the map produced from Sentinel-1 alone (Fig. 5a) preserved the broad low-backscatter structures expected for this type of event, whereas the fused map (Fig. 5b) presented a more articulated spatial pattern, revealing additional detail within the same regions.

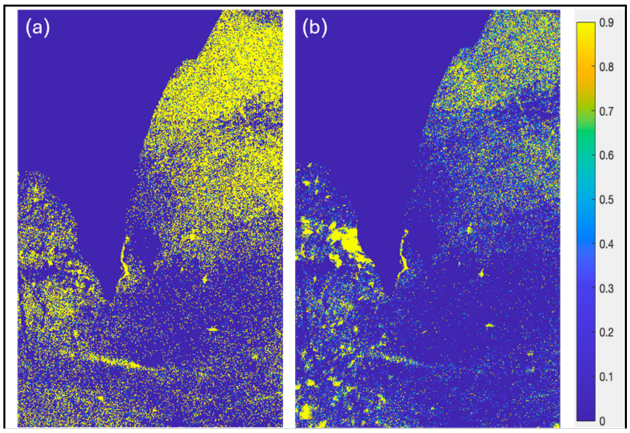

Figure 5. Comparison between Sentinel-1 anomaly map from 30 August 2022 (a) and the fused Sentinel-1/Sentinel-2 representation (b).

This improvement was also reflected numerically. A boundary-sharpness index, calculated as a measure of edge contrast, yielded a score of 0.120 for the Sentinel-1-only anomaly map and 0.210 for the fused product, indicating a notable increase in spatial definition. Based on this fused surface, a binary mask was derived using a consistent threshold, producing a continuous outline of the anomalous region (Fig. 6).

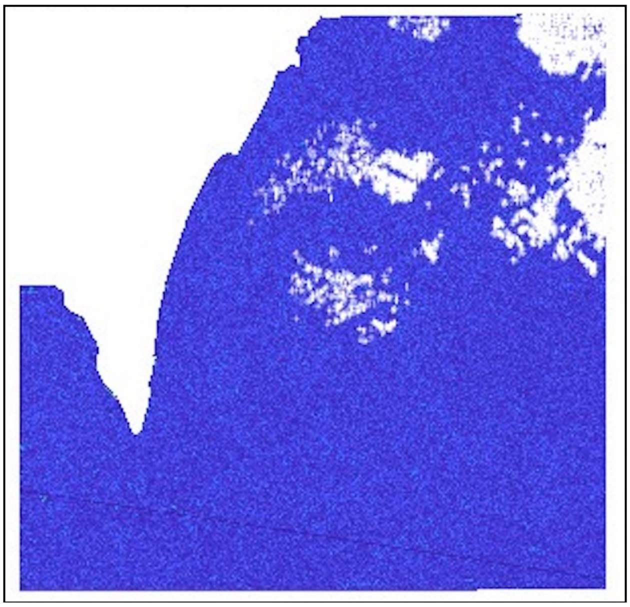

Figure 6. Binary spill mask derived from the fused anomaly surface for early September 2022

3.3 Temporal reconstruction between acquisition dates

To address the temporal gaps between overpasses, intermediate-date reconstructions were produced for both sensors. For Sentinel-2, the reconstruction targeted the mid-date between the two nearest optical images, corresponding to 1 September 2022. The generated Red-band and NIR-band surfaces showed close agreement with their neighbouring observations, with the Red band achieving a PSNR of 27.87 dB and an SSIM of 0.963, and the NIR band achieving a PSNR of 27.32 dB and an SSIM of 0.962.

A similar approach was applied to Sentinel-1, reconstructing the VV-band surface for the intermediate date of 30 August 2022. The resulting field produced a PSNR of 20.06 dB and an SSIM of 0.621 relative to its neighbouring scenes. The reconstructed surfaces for both sensors, shown in Fig. 7, provided continuous representations of the marine conditions at dates not directly observed by either mission.

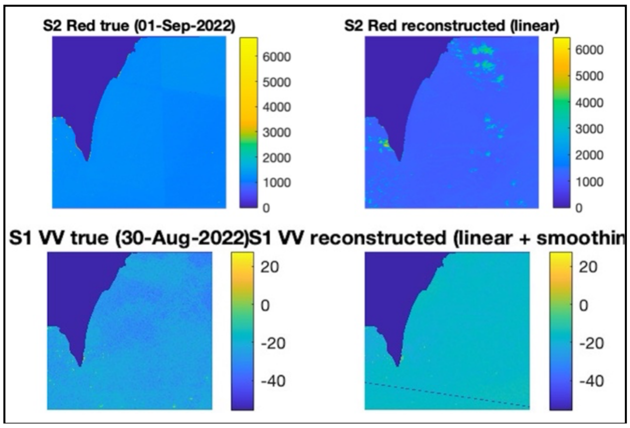

Figure 7. Temporal reconstructions of Sentinel-2 reflectance and Sentinel-1 backscatter for intermediate dates between adjacent acquisitions.

4. Discussion

An integrated view of spill behaviour in narrow, fast-changing marine corridors requires methods that can overcome the individual weaknesses of single-sensor observations. The purpose of this study was to examine whether combining complementary satellite datasets and reconstructing intermediate conditions could provide a more coherent description of an oil spill's evolution than either sensor could offer on its own. The discussion below places the results within this broader context, drawing connections between the characteristics of the study area, the behaviour documented in the imagery, and the advantages gained by applying fusion and temporal reconstruction techniques.

Spill events in constricted maritime passages, such as the Strait of Gibraltar, often display fragmented and rapidly evolving surface patterns shaped by water-mass exchanges, vessel wakes, and rapidly shifting meteorological conditions. These factors complicate the interpretation of single-acquisition images, a challenge frequently noted in previous work dealing with dynamic spill behaviour and heterogeneous water properties (Fingas and Brown, 2014; Hu et al., 2021; Naz et al., 2021). Within such environments, a single Sentinel-1 or Sentinel-2 scene tends to capture only part of the event: SAR imagery emphasises surface roughness anomalies but offers limited optical context, while multispectral images capture reflectance-driven patterns but suffer from cloud cover and glint. The single-sensor anomaly maps in this study reflected these known constraints, each highlighting different aspects of the surface response but not providing a fully coherent spatial picture when examined independently.

The multisensor fusion product addressed this gap by combining the structural information from SAR with the higher spatial detail available in the optical data. The fused anomaly field retained the core streak-like structures present in the Sentinel-1 scene while revealing additional textural variations associated with the optical signal. This improvement was also captured numerically through the increase in boundary sharpness, consistent with earlier reports on the benefits of hybrid approaches for discriminating oil from look-alike phenomena (Seydi et al., 2021; Yekeen et al., 2020). This is particularly relevant in dynamic environments such as the Strait of Gibraltar, where fragmented and rapidly evolving slick patterns require clear spatial delineation for reliable interpretation. The ability to derive a stable binary spill mask from the fused surface further demonstrates how multisensor approaches can support operational interpretation when individual datasets remain ambiguous.

Temporal reconstruction contributed a different, but complementary, advantage. Instead of providing sharper spatial features, it offered continuity across the temporal gaps inherent to the revisit cycles of Sentinel-1 and Sentinel-2. The reconstructed intermediate-date surfaces reproduced the broad spatial organisation of anomalies at their respective mid-dates and helped form a clearer sequence of how the spill evolved between acquisitions. This aligns with growing efforts in remote sensing to mitigate the effects of sparse temporal sampling through interpolation and data-driven modelling (Ienco et al., 2017; Jiang et al., 2023). While not intended to replicate the full physical complexity of slick movement, the reconstructions demonstrated that meaningful temporal "bridges" can be created between observations, offering a more complete view of spill progression in settings where hydrodynamic forcing and anthropogenic activity constantly reshape the surface.

Taken together, the combined observations, fused surfaces, and reconstructed intermediates form a more integrated understanding of the late-August 2022 spill near Gibraltar. They show how individual fragments visible in separate images relate to one another spatially, and how their shapes and distribution change over short intervals that no single satellite can monitor continuously. At the same time, the results highlight familiar limitations: optical data remain sensitive to atmospheric interference and spatial heterogeneity in water properties, whereas SAR continues to suffer from speckle and confusion with naturally smooth water surfaces. These challenges suggest that future extensions could employ advanced denoising approaches, adaptive thresholds, or physically informed modelling of wave–slick interactions to strengthen interpretation further. Additional gains may come from incorporating ancillary information such as surface-current fields from HF radar or numerical models, which could clarify short-term dispersal trends that satellites alone cannot resolve.

5. Conclusions

This study demonstrates that integrating Sentinel-1 and Sentinel-2 datasets can enhance the spatial and temporal interpretation of oil spill behaviour in narrow and dynamic maritime regions. Spatial fusion improved boundary definition and provided a more coherent anomaly field than either sensor alone, while temporal reconstruction supplied intermediate views that filled otherwise unobserved stages of the event. Applied to the August 2022 spill near Gibraltar, this combined approach captured both the fragmentation of the slick and its short-term reorganisation, offering a more continuous and interpretable representation of its evolution. Although these methods do not replace operational monitoring systems, they present a practical route toward reducing ambiguities associated with single-sensor imagery and improving situational awareness in environments where surface conditions evolve faster than satellite revisit cycles allow.

References

Akkartal, A., & Sunar, F. (2008). The usage of radar images in oil spill detection. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 37(B8), 271–276.

Bradford, B. N., & Sanchez-Reyes, P. J. (2011). Automated oil spill detection with multispectral imagery. *SPIE Ocean Sensing and Monitoring III*, 8030, 213–223.

de Oliveira Estevo, M., Lopes, P. F., de Oliveira Júnior, J. G. C., Junqueira, A. B., de Oliveira Santos, A. P., da Silva Lima, J. A., & Campos-Silva, J. V. (2021). Immediate social and economic impacts of a major oil spill on Brazilian coastal fishing communities. *Marine Pollution Bulletin*, 164, 111984.

Fingas, M., & Brown, C. (2014). Review of oil spill remote sensing. *Marine Pollution Bulletin*, 83(1), 9–23.

Hu, C., Lu, Y., Sun, S., & Liu, Y. (2021). Optical remote sensing of oil spills in the ocean: what is really possible? *Journal of Remote Sensing*.

Ienco, D., Gaetano, R., Dupaquier, C., & Maurel, P. (2017). Land cover classification via multitemporal spatial data by deep recurrent neural networks. IEEE Geoscience and Remote Sensing Letters, 14(10), 1685–1689.

Jafarzadeh, H., Mahdianpari, M., Homayouni, S., Mohammadimanesh, F., & Dabboor, M. (2021). Oil spill detection from synthetic aperture radar Earth observations: A meta-analysis and comprehensive review. *GIScience & Remote Sensing*, 58(7), 1022–1051.

Jiang, Y., Gao, K., Xu, X., Zhao, K., & Qin, T. (2023). STA-GAN: A spatio-temporal attention generative adversarial network for missing value imputation in satellite data. *Remote Sensing*, 15(1), 88.

Naz, S., Iqbal, M. F., Mahmood, I., & Allam, M. (2021). Marine oil spill detection using synthetic aperture radar over the Indian Ocean. *Marine Pollution Bulletin*, 162, 111921.

Seydi, S. T., Hasanlou, M., Amani, M., & Huang, W. (2021). Oil spill detection based on multiscale multidimensional residual CNN for optical remote sensing imagery. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 14, 10941–10952.

Setiani, P., & Ramdani, F. (2018). Oil spill mapping using multi-sensor Sentinel data in Balikpapan Bay, Indonesia. *4th International Symposium on Geoinformatics (ISyG)*, 1–4.

UNEP. (2023). *Goal 14: Life Below Water*. United Nations Environment Programme.

United Nations. (2023). *Sustainable Development Goal 13: Climate Action*.

Yekeen, S. T., Balogun, A. L., & Yusof, K. B. W. (2020). A novel deep learning instance segmentation model for automated marine oil spill detection. *ISPRS Journal of Photogrammetry and Remote Sensing*, 167, 190–200.

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