



Remote sensing of the oil spills caused by ships: A review[☆]

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ARTICLE INFO

Keywords:

Oil spill monitoring
Remote sensing
Oil spill
Ship accidents
Illegal oil discharge from ships

ABSTRACT

Oil spills caused by ships can be categorized as accidental and operational oil spills. For operational oil spills caused by illegal discharge, an efficient remote sensing system for routine surveillance on oil spills needs to be established. For the oil spills caused by ship accidents, the quantitative inversion on some key properties provides useful information for treatment and assessment. The spaceborne synthetic aperture radar is mostly used for both operational and the accidental oil spills due to its effectiveness of oil spill detection under various environments. Optical remote sensing is applied in the cases where the detailed information about oil spills needs to be identified. Some other sensing techniques that may be useful to monitor oil spills caused by ships are also discussed. By jointly utilizing various remote sensing techniques, it is expected to form a comprehensive sensing network and prevent the negative consequences caused by oil pollution from ships.

1. Introduction

As one of the major types of marine pollution, petroleum hydrocarbon (PHC) poses direct threats on the marine ecological system by blocking the substance exchange on the sea surface (Kingston, 2002), resulting in the massive death of marine organisms including plankton, fish, coral reefs, sea bird, etc. Some categories of marine industries that are vulnerable to oil spills including fishery, maritime transportation, tourism, etc. Oil spills could come from a variety of sources including natural seepage, oil drilling platforms, underwater pipeline, coastal facilities, ships, etc. Due to the imbalanced distribution of oil producers, PHC pollution is commonly caused by the leakage and accidents during the maritime transportation from oil producing areas to refineries and oil consuming areas (Hennig et al., 2012). With the development of maritime transportation and the increase of the tonnage and quantity of oil tankers, ships have become a major source of oil spills (Eckle et al., 2012). The heavy diesel used by ships contains high contents of polycyclic aromatic hydrocarbon (PAH), which can form oil emulsions with seawater and are difficult to degrade (Kvenvolden and Cooper, 2003; Leifer et al., 2010). As a result, the oil spills caused by ships may bring greater harms to the marine environment than other types of oil spills.

In response to the environmental issues caused by ships, the International Maritime Organization (IMO) formulated the International Convention for the Prevention of Pollution from Ships (also known as

MARPOL Convention). Preventing oil pollution from ships is listed as the major mission in the Annex 1 of MARPOL Convention. Oil spills caused by ships can be further categorized as accidental and operational oil spills. Accidental oil spills refer to the fuel and oil leakage caused by accidents such as running aground or collision of ships. Accompanied by several ship accidents, accidental oil spills usually result in large volume of oil leakage and attract the attentions all over the world. Operational oil spills refer to the oil leakage caused by crew members not complying with relevant regulations and indiscriminately discharging oily wastewater or tank cleaning water, or by the damages of oil pipeline or storage facilities on ships. Compared with the accidental oil spills, operational oil spills tend to be more concealed because the crew members could hide the oil spills to avoid potential punishment. We usually don't know about the happening of operational oil spills until they are found on sea surface long after the pollution.

As an important part of oil spill emergency responses, oil spill monitoring provides the spatial distributions and some detailed information (e.g., oil types, oil thickness, etc.) of the oil pollutants, which help formulate the plans for oil spill treatment. Remote sensing technology has gradually become an important means of monitoring oil spill targets on the sea surface due to its ability of rapid and large-scale monitoring (Fingas and Brown, 2013, 2014, 2018). Especially after the Deepwater Horizon (DWH) oil spill in 2010, the effectiveness of various remote sensing techniques was tested using the observation data

[☆] This article is part of a special issue entitled: Marine Pollution Caused by Ships - MPB published in Marine Pollution Bulletin.

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derived at that time (Leifer et al., 2012). Among the various techniques that have been developed for oil spill remote sensing, spaceborne synthetic aperture radar (SAR) and optical (including multi-spectral and hyperspectral) sensors are the two major approaches that are capable for oil spill monitoring in large spatial-scale. Oil spills are represented as dark areas in the SAR images due to the suppression on capillary waves by the presence of floating oil slicks (Alpers and Hühnerfuss, 1989), while the optical remote sensing technique distinguishes the oil spills from clean seawater based on their different optical properties (e.g., reflectance, absorption, etc.) in various optical bands (Hu et al., 2021). Despite the continuous studies on oil spill remote sensing in the past decades (Temitope Yekeen and Balogun, 2020; Al-Ruzouq et al., 2020), the oil spills caused by ships were not well documented. This is partly related to the current research patterns of oil spill remote sensing: new sensing technologies or detection methods were proposed and tested using simulated oil spill experiments or the remote observations on the areas where we have already known there are oil spills. The latter may work for the accidental oil spills. For the operational oil spills, however, many remote sensing techniques still suffer from distinguishing oil spills from look-alikes (Alpers et al., 2017) and are unable to determine if the detected target is an oil spill.

This article is intended to illustrate a comprehensive picture on the status and challenges on the remote sensing of oil spills caused by ships, and thus provide some guidance on the future studies by discussing the objectives of the remote sensing on the accidental and operational oil spills. This article mainly focuses on the researches and applications of spaceborne synthetic aperture radar (SAR) and optical remote sensing in detecting and identifying operational and accidental oil spills in Sections 2 and 3, respectively. Some other sensing technologies that could potentially be applied to monitor oil spills caused by ships are discussed in Section 4. The current challenges and potential trends of the related studies are also discussed for operational and accidental oil spills in Section 5. It should be noted that the topic of this review focuses on the oil spills caused by ships. Thus, the remote sensing on the oil spills from other sources, such as drilling platform accidents or natural seepage, are generally not considered as the scope of this article.

2. Remote sensing of operational oil spills

2.1. Characteristics of operational oil spills

Operational oil spills include the conscious discharge of oil pollutants from ships into the sea, and the unintentional oil leakage caused by mis-operation of the crew members or the damage of facilities. A large amount of pollution in the operational oil spills is caused by the discharge of ballast water, cleaning water, and oily wastewater from ships. Although the illegal discharge of oil pollutants is strictly prohibited by the MARPOL convention, the operational oil spills happen much more frequently than we expected. Dong et al. (2022) mapped the global oil spills using satellite-based remote sensing and found that a large portion of the detected oil spills distributed along the navigation routes, many of which had not been documented before. This is because the time and locations of the oil emissions from ships are extremely dispersed and the current remote sensing technology can barely meet the need of the law enforcement on illegal oil discharge. Considering the high cost of wastewater treatment at port and the low risk of being caught at sea, it is very difficult to stop the illegal oil discharge from ships despite the prohibition.

It can be inferred from the characteristics discussed above that the key to the responses of operational oil spills is the routine surveillance on oil spills with high accuracy. The false negative results lead to the ineffective detection of operational oil spills, while the false positive results bring unnecessary works on the confirmation of potential oil spills to maritime regulatory authorities. The identification on oil types and source tracing technologies may also help determine the ship involved in the illegal oil discharge. Nevertheless, since the accurate

detection on operational oil spills has not been achieved in current practice, further exploration is needed for identifying oil spill information.

2.2. Detection methods for operational oil spills

As analysed above, the detection of operational oil spills requires the capability of routine surveillance in large spatial-scale under various environmental conditions. The appearances of oil spills in optical images are affected by many environmental factors including sun glint (Sun and Hu, 2016; Zhu et al., 2022), water quality (Sun et al., 2022), wind conditions (Dong et al., 2024), etc. The optical features of oil spills have not been comprehensively characterized under different environmental conditions, and there hasn't been a robust procedure to detect oil spills in various optical remote sensing images, making it difficult to monitor operational oil spills in practice. Therefore, spaceborne SAR is still the most commonly-used approach to detect operational oil spills despite its limitation in distinguishing oil spills from look-alikes. This fact can also be inferred from a summary of current studies on the remote sensing of operational oil spill in the following contents (Table 1).

Because spaceborne SAR is more capable to detect the existence of oil spills rather than identify their detailed information, it is difficult to determine if the detected oil spills are caused by ships, or more importantly, which ship is responsible for the pollution. Instead of discussing the oil pollution discharged from a specific ship, the current studies on the remote sensing of operational oil spills caused by ships mostly examine the remote sensing images of some areas with intensive

Table 1
Sea areas with intensive shipping traffic and their relations with operational oil spills caused by ship emissions.

Research areas	Sensing Techniques	Major findings	Related literature
Black Sea	Spaceborne SAR and AIS	Strong correlations in the spatial distribution between the detected oil spills and the shipping traffic density	Mityagina and Lavrova, 2016; Ivanov and Kucheiko, 2016
Baltic Sea	Spaceborne SAR and AIS	Oil spills distribute along the shipping route	Krek et al., 2021
Mediterranean Sea	Spaceborne SAR	Oil spills locate near the entrance of the Suez Canal	Abou El-Magd et al., 2020
Barents Sea	Spaceborne SAR	Oil spills locate in the southern part of the sea where maritime shipping is busy	Ivanov et al., 2022
Eastern Arabian Sea	Spaceborne SAR	Illegal discharge from ships is the second largest source of oil spill after drilling platform leaks	Suneel et al., 2019; Dhavalikar and Choudhari, 2022; Swapna et al., 2024
Bohai Bay	Spaceborne SAR	Oil spills distribute along main ship routes rather than ports or drilling platforms	Ding et al., 2016
	Multi-spectral images	Strip-shape oil spills found in narrow ship channel	Jiang et al., 2023
South China Sea	Optical remote sensing	Most of the detected oil spills are caused by ships	Hong et al., 2022
Andaman Sea Karimata Strait	Optical remote sensing and deep learning	Strip-shape oil spills that are highly likely to be caused by ships	Jiang et al., 2023
South African Ocean	Spaceborne SAR		Mdakane and Kleynhans, 2017, 2022

maritime transportation and determine whether the detected oil spills are caused by ships (Ferraro et al., 2009; Bayramov et al., 2018). Some sea areas, where the oil spills detected through remote sensing technologies are related to ship emissions, are listed as Table 1.

For instances, Mdakane and Kleynhans (2017, 2022) detected long-strip-shaped oil spills in the South African Oceans in the Sentinel-1 A image and claimed that they are caused by the illegal discharge of moving vessels based on several geometric features. Mityagina and Lavrova (2016) examined about 4500 SAR images in the Black and Caspian Seas from Envisat and Sentinel-1 satellites and found strong correlations in the spatial distribution between the detected oil spills and the shipping traffic density in the Black Sea (Fig. 1a & b). They also attempted to distinguish the oil spills caused by ships from those caused by natural seepage based on their shapes in SAR images. Ivanov and Kucheiko (2016) studied the same sea areas using the SAR images from Radarsat and concluded that “the most important source of oil pollution is tank washing in the open sea and illegal discharges”. Similar pattern was found in the Baltic Sea by Krek et al. (2021) that the oil spills detected from SAR images distribute along the route with dense automatic identification system (AIS) record (Fig. 1c). Using the remote sensing data as input and validation, Lebedev (2018) numerically simulated the oil concentration in the Baltic Sea introduced by illegal ship discharge. Ding et al. (2016) analysed the origins of oil spills in the Bohai Bay using remote sensing images obtained from multiple SAR satellites and found that most detected oil slicks distributed along main ship routes rather than ports or drilling platforms. Abou El-Magd et al. (2020) mapped the oil spills in the Mediterranean Sea on over 800 Sentinel-1 SAR images collected during 2014–2019. They found that oil spills are frequently detected near the entrance of the Suez Canal and

their coverage areas are relatively small, which is most probably indicative of illegal ship discharges. Ivanov et al. (2022) analysed the oil spills in the Barents Sea using over 26,000 SAR images collected by Sentinel-1 satellite and found that most oil spills occurred in the southern part of the sea, where maritime traffic is busy. Suneel et al. (2019) tracked the source of oil spills in Eastern Arabian Sea using multiple techniques including SAR images, chemical fingerprinting, and numerical modelling. They found that the illegal discharge from ships is the second largest source of oil spill after drilling platform leaks. This conclusion was also conformed with some latter studies (Dhavalikar and Choudhari, 2022; Swapna et al., 2024) on the remote observations of the same sea area based on spaceborne SAR.

Some recent studies also report the feasibility of monitoring operational oil spills using optical remote sensing method. Jiang et al. (2023) analysed the Sentinel-2 multi-spectral images (MSI) of a narrow ship channel in the Bohai Strait and detected strip-shape oil spills that are highly likely to be caused by ships. Du et al. (2022) detected two strip-shaped oil spills in the Andaman Sea and the Karimata Strait using the optical remote sensing image obtained from HY-1C Coastal Zone Imager (CZI). Hong et al. (2022) conducted a survey with longer temporal coverage by using the optical images of the South China Sea obtained from Landsat-8 Ocean and Land Imager (OLI) during 2015–2019. Out of the 632 oil spills detected from the optical images, at least 490 were from ships. Compared with the studies on operational oil spill monitoring using SAR images, those using optical images involved much less regions and shorter temporal coverages. This is probably due to the lack of a robust method of oil spill detection in different conditions using optical remote sensing.

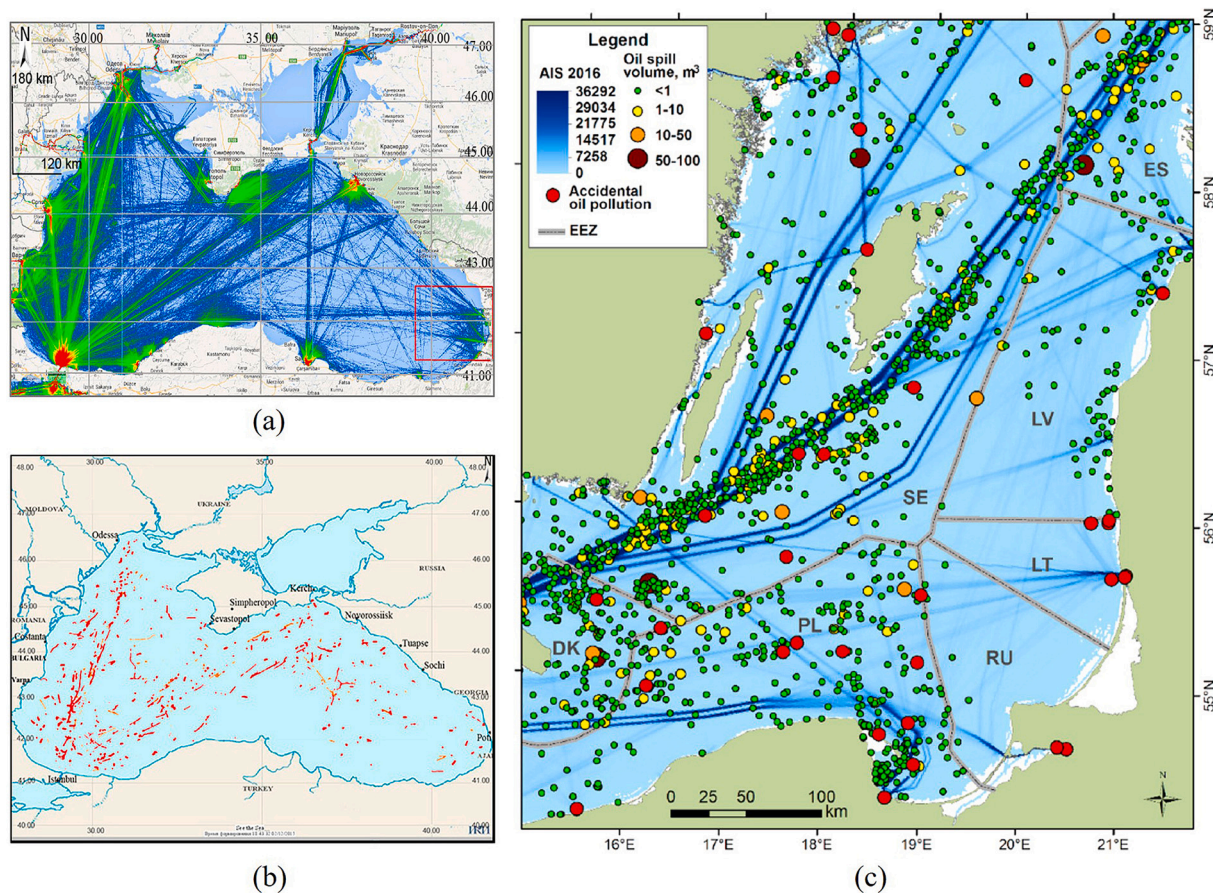


Fig. 1. Oil spills detected from remote sensing and the shipping traffic density derived from automatic identification system (AIS): (a) shipping traffic density map in the Black Sea (Mityagina and Lavrova, 2016); (b) oil spills detected from SAR images in the Black Sea (Mityagina and Lavrova, 2016); (c) shipping traffic and oil spills in the Southeastern Baltic Sea (Krek et al., 2021). Figures are reused under CC-BY 4.0 license.

2.3. Linking detected oil spills with ships

Despite the various studies that aim at eliminating the look-alike targets and improving the accuracy of the oil spill detection using SAR images, it is still a challenge to link the detected oil spills with the ship that is responsible for the pollution. Some studies attempted to solve this problem by simultaneously detecting ships and oil spills in the same SAR image (Staglianò et al., 2012; Lupidi et al., 2017; Basit et al., 2024). Since ships are characterized as bright dots in SAR images, a moving vessel emitting oil pollutants would show as a bright dot followed by a dark strip (Fig. 2). Of course, this method requires that the ship has not left too far away from the emitted oil pollutants when it is observed, which is not always the case considering the revisiting period of the satellite. Moreover, it is still difficult to obtain the name or the owner of the ship only using the remote sensing technology. Some additional information is required to determine the sources of the oil pollutants.

Since the operational oil spills are usually emitted during the ship navigation, they are characterized as long strips along the navigation routes. Thus, a practical way to determine the sources of operational oil spills would be a match between the location of oil spill detected in remote sensing images and the navigation records. Ivanov and Kucheiko (2014) presented a framework for monitoring illegal oil discharge from ship using remote sensing technology and AIS: The oil spills was detected from spaceborne SAR images, confirmed using optical images, and then compared with AIS records. Several suspected vessels were identified and the one that committed the illegal discharge was confirmed by boarding inspection. Another successful case was reported by Chinese Maritime Safety Agency (Liu et al., 2021), where spaceborne SAR was combined with shipborne AIS to trace illegal oil discharge from ships. The oil spill target was detected in the polarized SAR image obtained from Radarsat-2 satellite. After eliminating the possibility of false target, the spatial distribution of suspected oil spill target was analysed based on drifting and diffusion model with wind field and ocean current data. The results were then compared with the ships' routes data in AIS to locate the ship that committed the illegal discharge (Fig. 3). A similar case was reported in the Juan de Fuca Strait and the Strait of Georgia, British Colombia, Canada, where the SAR images acquired from Radarsat-2 mission were combined with AIS to determine the source of operational oil spills (Staples, 2022). Two ships were identified to be responsible for illegally discharging wastewater with oily contamination. These cases indicated that spaceborne remote sensing technology may be able to assist the maritime law enforcement in the similar way as traffic cameras.

3. Remote sensing of accidental oil spills

3.1. Characteristics of accidental oil spills

Accidental oil spills refer to the oil leakage into the ocean during navigation due to negligence, force majeure, accidents, or other maritime hazards such as grounding, collision, stranding, explosion, and fire. Accidental oil spills, especially those caused by oil tankers, result in large volume of oil pollution and pose a significant threat to the marine environment, especially when the accidents occur in the coastal areas

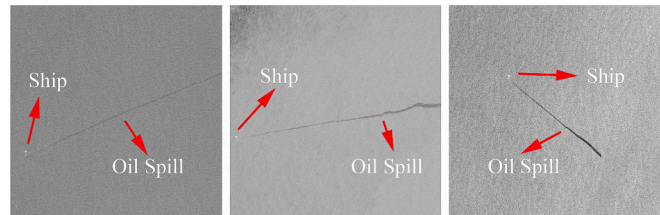


Fig. 2. SAR images of oil spills following ship targets obtained from Sentinel-1. Figures are reused from Basit et al. (2024) under CC-BY 4.0 license.

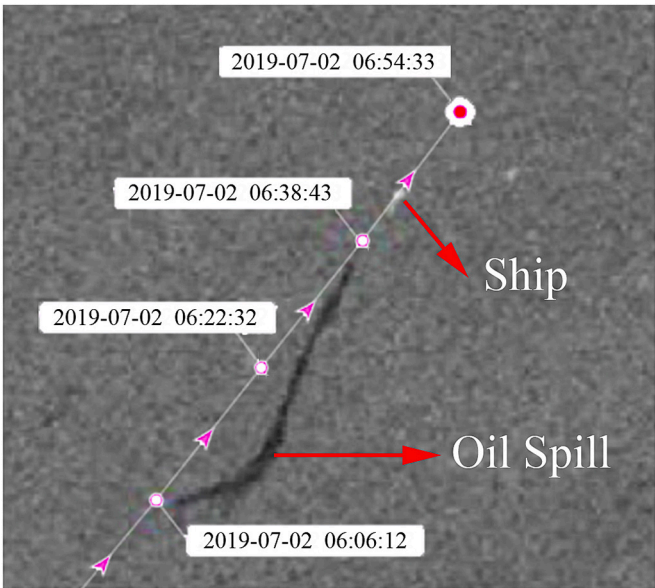


Fig. 3. Matching an operational oil spill detected in the Bohai Bay using Radarsat-2 images with AIS records. Pink arrows indicate the ship trajectory derived from AIS record. This figure is provided by Dr. Bingxin Liu from Dalian Maritime University and used with permission. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Rajendran et al., 2022).

Despite the destructive consequences of the oil spills caused by maritime accidents, not enough attentions have been paid on the remote sensing of accidental oil spills until the last decade, and many early oil spills caused by ship accidents were not well documented through remote sensing methods. This is due to fact that the spatial distribution of the oil spills roughly locates around the known cite of the ship in accident, which attenuates the need of detecting accidental oil spills. After the extensive studies on the remote sensing of DWH oil spill accidents, researchers started to realize that some remote sensing techniques can be used to identify certain information about the oil spills, which helps us quantitatively evaluate the influence of oil spills. As the

Table 2
Oil spills caused by major ship accidents that have been documented.

Ship accidents and locations	Research topics	Sensing techniques	Related literature
Oil tanker <i>Sanchi</i> in the East China Sea	Mapping oil distribution with thickness estimation	Spaceborne optical remote sensing	Sun et al., 2018
<i>MV Wakashio</i> in the Indian Ocean	Predicting oil drift	Spaceborne SAR	Yang et al., 2021a
	Assessing oil spill impact	Spaceborne SAR	Rao et al., 2022
	Mapping oil spill drift	Spaceborne SAR	Pelich et al., 2022
	Predicting oil drift	Spaceborne SAR	Gurumoorthi et al., 2021; Prasad et al., 2022
Oil tanker <i>Volganeft-139</i> in the Kerch Strait	Developing oil spill detection method	Spaceborne SAR	Kim and Jung, 2018
<i>Fun Shai Hai</i> in the Baltic Sea	Predicting oil drift	Spaceborne optical remote sensing	De Carolis et al., 2013 De Padova et al., 2017
<i>X-Press Pearl</i> in the Indian Ocean	Developing oil spill detection method	Spaceborne SAR	Welikanna and Jin, 2024

results, the recent oil spills caused by major ship accidents were studied using different remote sensing techniques, some of which are listed in Table 2 as follow:

3.2. Mapping oil spills caused by ship accidents

As shown above in Table 2, spaceborne SAR is also the major approach in the previous studies on the remote sensing of accidental oil spills. Compared with the moving vessels discharging oil pollutants, the accident ships usually lose their momentum and have little changes in their locations. As the result, the accidental oil spills are shown as dark areas around the ships in accident, which may smoothly bend and diffuse into sectors or circles under the influence of wind or ocean current (Li, 2024). Because oil spills are viscous, their boundary contours in SAR images obtained right after the ship accidents are relatively smooth, and then gradually blur with the increase of drifting time.

Since the spatial distribution of oil spills are sometimes roughly available after a ship accident, it is possible to produce a dataset with ground truth using the SAR images of accidental oil spills. Thus, new methods for oil spill mapping can be developed and quantitatively evaluated based on the remote sensing images with the known ground truth. For instances, Kim and Jung (2018) proposed an artificial neural network (ANN) for oil spill mapping and tested it with the TerraSAR-X images of an oil spill caused by oil tanker *Volganefti-139* in the Kerch Strait. They came to the conclusion that the ANN model reduced the false detection on look-alikes, which cannot be reached without the SAR images constructed from the accidental oil spills with labelled ground truth. Welikanna and Jin (2024) studied the damping ratio of oil spills caused by *X-Press Pearl* ship accident in the Indian Ocean and proposed an oil spill mapping algorithm based on the Gaussian Mixture Model using the SAR images obtained from Sentinel-1 satellite. This methodology is not unique to the oil spills caused by ship accidents, as they can also be applied for the accidental oil spills from offshore drilling platforms, oil tank in port, pipeline leakage, etc. (La et al., 2024).

In some cases, the accidental oil spills were too serious to fully capture their spatial distribution using conventional methods, or got overlooked for some reasons. And spaceborne SAR images can help assess the actual impacts of the accidental oil spills by mapping their coverages. For instances, Gade (2019) examined the long-term oil release from the ship wreck of *SS Mopang* that had sunk and left in the Black Sea since World War I. Thanks to the modern remote sensing technology, we can evaluate the impacts of oil spills from this forgotten ship wreck that has been lay over one century. Pelich et al. (2022) mapped the drift of oil spills after the accident of *MV Wakashio* along the coast the Southeastern Mauritius using time-series SAR images obtained from Radarsat-2 and Sentinel-1. Based on the similar sets of time-series SAR images, the impact of this oil spills accident was assessed by Rao et al. (2022). These studies revealed the transportation of oil spills and their persistent impacts along the coastal regions of the Southeastern Mauritius.

Although SAR remote sensing technology is excellent at remotely mapping oil spills on the sea surface, the treatment and evaluation of oil spills caused by ship accidents usually require additional information about the oil spills other than its distribution, such as oil thickness, emulsify rate, etc., which are difficult to be derived from SAR images. Built on the quantitative relations between oil spill properties and the optical reflectance, optical remote sensing has the potential of quantifying oil concentrations or oil thickness (Hu et al., 2021), and could be applied for the fine-grained oil spill identification based on the optical features embedded in multiple spectral bands (Xie et al., 2022). Therefore, optical remote sensing has been applied to quantify oil spills caused by ship accidents. A successful attempt was made by Sun et al. (2018), who tracked the oil spills caused by the oil tanker *Sanchi* and estimated the oil spill volume based on multiple spaceborne optical sensors. Not only did this study demonstrate the feasibility of estimating oil spill volume using optical remote sensing method, which is currently not

applicable on SAR images, but also implied the defects of optical remote sensing that its availability may be affected by the clouds and the smoke if the spilled oil was caught on fire.

3.3. Predicting oil drift using hydrodynamic models and remote sensing

Another meaningful yet challenging task during the emergence responses of the accidental oil spills caused ships is the prediction on oil drifting, which provides timely guidance on the spatial configuration of cleaning forces. The prediction on the trajectories of oil spills on the water surface mainly relies on the two-dimensional hydrodynamic models. In such studies, the oil spill coverages extracted from the remote sensing images are typically used as the input or validation data of the hydrodynamic models. The typical workflow of oil spill drifting prediction by jointly using hydrodynamic models and remote sensing technologies is shown as Fig. 4.

Taking spaceborne SAR images as the examples, Prasad et al. (2022) simulated the spatial and temporal distribution of oil spill caused by the accident of *MV Wakashio* over the coral reef regions along the coast of Mauritius and examined the results using the Sentinel-1 A images. Based on the same set of data, Gurumoorthi et al. (2021) tracked the fate of this oil spill accident under the influence of current and wind using GNOME simulation. Similar study was conducted on the oil spill accident of *Sanchi* ship by Yang et al. (2021a), who claimed that the integration of “numerical simulation and SAR remote sensing is a promising technique for real-time oil spill monitoring and the prediction of oil spreading”.

Optical remote sensing images are also used to develop the integration models for the oil spill drifting after ship accidents. Due to its potential ability of fine-grained identification on oil spill information, more input parameters, such as oil volume, could be provided to the hydrodynamic models. Taking the ship accident of *Fun Shai Hai* in the Baltic Sea as the example, De Carolis et al. (2013) quantitatively characterized the oil slick thickness in the near-infrared images obtained by MODIS, and numerally simulated the oil drifting using MIKE21 model. This method is further optimized by De Padova et al. (2017), who synergistically used the temporal observations on the spilled oil from *Fun Shai Hai* accident and the MIKE3 flow model to predict oil drifting. Since the optimal condition for optical remote sensing was not always available during the observation period, some SAR images were also supplemented in this study.

4. Other potential sensing technologies for oil spills caused by ships

4.1. Ultraviolet (UV) -induced fluorescence

Oil spill detection and identification using ultraviolet (UV) -induced fluorescence is built on the theoretical basis that the PAHs with large conjugated π bonds in oil spills can emit fluorescence under the exposure to UV light. Besides the detection of tracing oil spills, UV-induced fluorescence technology is especially useful to identify oil types based on the fluorometric features of different types of PAHs (Hou et al., 2021; Li et al., 2022; Xie et al., 2023a). In practice, UV-induced fluorescence is usually developed as a fluorometric sensor looking at a fixed point rather than an imager. Thus, it is particularly useful to the oil spill surveillance at stationary locations, but not the oil spill mapping in large spatial scales.

An early attempt of the development of fluorometric sensor is the airborne device invented by Brown et al. (1996), which were applied to monitor the oil seepages on the Santa Barbara coast. Owing to the development of laser technology and portable spectrometers, small and portable UV-induced fluorescence devices for oil spill monitoring have been developed and applied for practical applications. InterOcean Systems Inc. developed an integrated oil spill monitoring system called “Slick Sleuth” based on UV-induced fluorescence (Chase et al., 2005), which can provide fast detection of refined oil such as diesel and

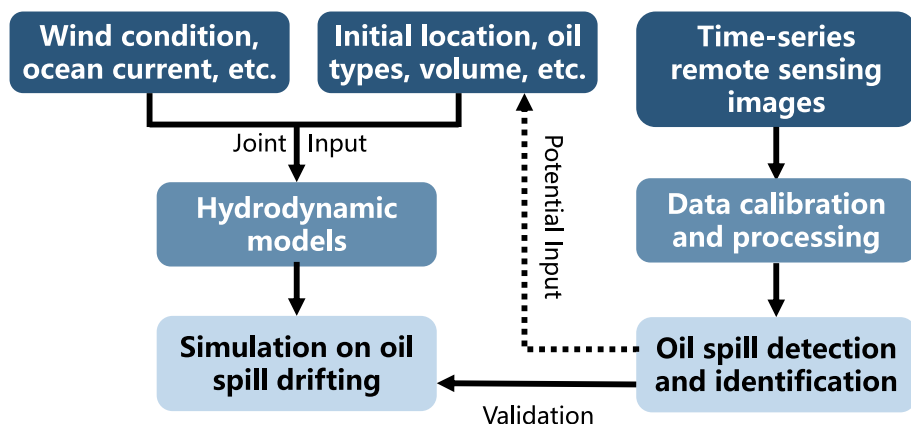


Fig. 4. The typical workflow of oil spill drifting prediction by jointly using hydrodynamic models and remote sensing technologies. This figure is modified and redrawn based on Prasad et al. (2022).

lubricant. Hou et al. (2017) developed a port-based oil spill detection device called “POSAS” (Fig. 5). Fluorescence is excited using an impulse xenon lamp and receives using a photomultiplier tube. This equipment can detect thin oil films formed in the early stage of oil spills and has been applied for the early warning of oil spills in ports and oil drilling platforms (Hou et al., 2022).

Limited by its detection range, however, the UV-induced fluorescence has not been widely applied to monitor the oil spills caused by ships. It may be useful to mount the fluorometric sensors on the fixed buoys along some key navigation routes to detect potential oil spills from ships, or even on the ships to provide early alarms on the oil

leakage. An application case was reported by Pärt et al. (2021), who implemented the fluorometric sensors on a ferry ship and a moored buoy for oil spill detection. Although there were some uncertainties with the calibration and measurement range, the fluorometric sensors extracted continuous fluorescence data, which were useful to characterize oil spills on sea surface.

4.2. Thermal infrared imaging

The existence of oil spills leads to the differences between the surface emissivity and temperature of oil-polluted and clean seawater (Grierson,

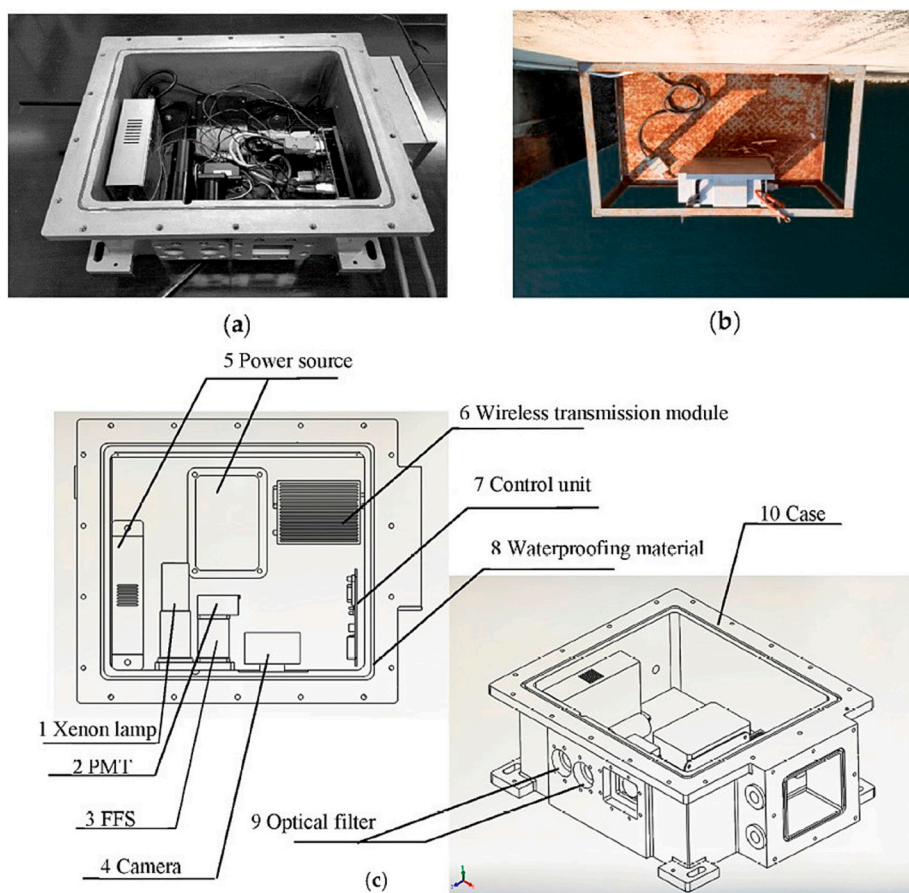


Fig. 5. Schematic diagram of the POSAS sensor for oil spill monitoring: (a) the internal structure; (b) photograph of the installation; and (c) structural sketch. Figures are reused from Hou et al. (2017) under CC-BY 4.0 license.

1998). Compared with clean seawater, oil is an optically thick substance in terms of heat capacity, heat flux, and thermal inertia (Shih and Andrews, 2008). As a result, the emissivity of oil slick in thermal infrared (IR) band is higher than the surrounding water in the afternoon after absorbing solar radiance, but could be lower in the late night if the air temperature drops lower than the water temperature (Lu et al., 2016). The differences in the emissivity of oil slick and seawater are the theoretical basis for oil spill detection using thermal IR imaging. As a passive remote sensing method built on the emissivity of the targets, thermal IR imaging can work without active radiation sources at all-day and all-weather. Nevertheless, it has not been widely-used to monitoring oil spills for several reasons: (1) The thermal IR emission can only be captured in close range. Thus, the thermal infrared imaging cannot be applied for the large-scale monitoring; (2) The temperature characteristics of oil spills changes at different times of a day (Lu et al., 2016; Jiao et al., 2021), making it difficult to develop a uniform algorithm for oil spill extraction on thermal IR images; (3) The cost of thermal IR imager increases exponentially with its resolution, making it too expensive to be applied for accurate oil spill detection in practice.

The disadvantages listed above limit the potential application of thermal IR imaging for monitoring oil spills caused by ships. However, since it has been mounted on some search-and-rescue helicopters to find drowning personnel during ship accidents, thermal IR imager may also be used to monitor the oil spills simultaneously.

4.3. Passive UV imaging

Oil films typically have a higher reflectivity than surrounding seawater. This contrast is more significant for the thin oil films (<300 μm) within the UV bands. Studies have shown that the UV reflectivity of thin oil sheens is much higher than that of clean seawater (Xie and Li, 2022). Comparing the contrast between the oil film and clean water in the VIS and UV images (Fig. 6a and b), the oil film is markedly clearer in the UV image. Therefore, passive UV imaging is a potential method for monitoring thin oil films on aqueous surfaces.

Based on the strong contrast between oil and water in UV images, airborne UV cameras have been developed for oil spill surveillance (Yin et al., 2010). Various algorithms have also been proposed to automatically detect thin oil films in passive UV images (Xie et al., 2023b). Nevertheless, due to the strong attenuation of UV light in the atmosphere, the signal-to-noise ratio of UV imager is relatively low (Shi et al., 2015), meaning that the passive UV remote sensing only works in close range. Most satellites with optical sensors are not equipped with UV bands for the same reason. Suo et al. (2021, 2023) examined the remote sensing images obtained from the UV imager mounted on HY-1C satellite, which include two UV bands with the central wavelengths at 355 nm and 385 nm. The results indicated that the oil spills were not shown as bright areas as they were shown in the UV images obtained at close range (Fig. 6b and c). Therefore, it is still a challenge to monitor oil spill based on spaceborne UV imager.

Despite the uncertainties of oil spill detection using passive UV imaging techniques from spaceborne sensors, it is still promising to utilize

the high contrast of thin oil films in the UV bands for oil spill monitoring in close range. Since many insoluble hazardous and noxious substances (HNSs) would form thin films on water surface, which also shown as bright areas in the UV images (Mehdi et al., 2022), it may be helpful to deploy UV imagers on HNS transport vessels to simultaneously detect the thin films generated by the leakage of HNS and oil. Compared with the fluoresensors discussed in Section 4.1, passive UV imagers cost much less as it requires no active radiation source, but cannot work during night-time as they require solar radiation.

4.4. Marine radar

Marine radar detects oil spills based on the same theoretical basis as SAR that the smoothing effect of oil spills reduces the sea surface tension and lowers the roughness of the oil-polluted sea surface compared to those of the clean sea surface. Therefore, oil spills are characterized as isolated dark areas on radar images. Oil spill areas are extracted mainly by delineating the abnormal shadowed areas in marine radar images (Liu et al., 2017, 2019). The detection accuracy depends on the signal differences between the oil spills and background sea surface. However, the studies and applications of oil spill detection based on marine radar are much less than those using SAR, partly due to the limited availability of marine radar images of oil spills. Moreover, the effective detection range of marine radar is much smaller than spaceborne SAR, and the cost of sending ships with marine radar specifically for the task of oil spill detection is very high.

Some applications indicated that it is possible to detect oil spills without affecting the regular function of the marine radar by using an extra signal acquisition card (Xu et al., 2018, 2019). Because ships above a certain tonnage must be equipped with marine radar according to regulations, they could form an intensive observation network on the operational oil spills along navigation routes if the oil spill detection system based on marine radar is promoted. This system can also be mounted on the emergency response vessels for oil spill treatment to obtain the spatial distribution of oil spills on-site. Thus, the application prospect of oil spill monitoring based on marine radar is probably more promising than it is indicated in current studies.

5. Challenges and future trends

5.1. Operational oil spills

For the operational oil spills caused by illegal ship discharges, the main challenge at present is still how to accurately detect oil spills and determine whether they are caused by ships. This is because that the monitoring on operational oil spills mainly relies on spaceborne SAR, of which the detection results are easily affected by look-alikes. The methodology of oil spill detection using multi-source remote sensing techniques is a promising approach. For example, some studies introduced the optical images as a validation of the suspected oil spills emitted from ships and detected from SAR images to eliminate the false targets in the detection results (Abou Samra and Ali, 2022).

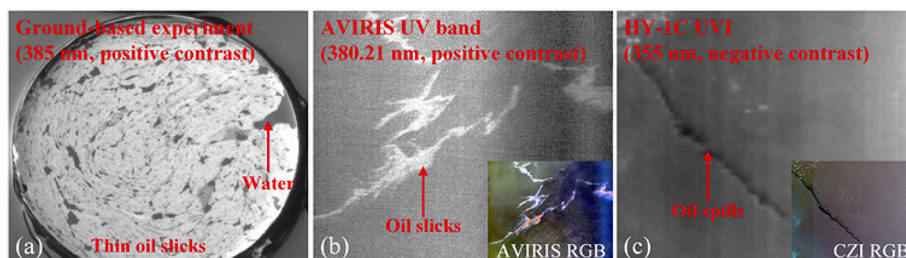


Fig. 6. Passive UV observations on thin oil films at different observation range: (a) ground-based experiment; (b) airborne imager; (c) spaceborne imager. Figures are reused from Suo et al. (2023) with permission from © The Optical Society.

Another challenge is to determine exactly which ship committed the oil discharge. This task is of great significance to form the evidence for the maritime law enforcement, but very difficult to directly accomplished through remote sensing methods. The joint use of remote sensing and AIS is a potential solution, but may not always work for a busy navigation route where multiple ships sail through the same oil spill region in a short period. Moreover, AIS data could be unavailable in many cases, because they may require strict permissions to access or the ships that commit the illegal discharge may purposely turn the AIS device off. The identification of oil types, which is mostly done through chemical methods such as mass spectroscopy (Teixeira et al., 2014) or isotope fingerprinting (Bayona et al., 2015), may help determine the source of the spilled oil. Although some recent studies have reported that the oil types may be identified through hyperspectral remote sensing (Yang et al., 2021b; Li et al., 2021; Jiang et al., 2024), the results were mostly obtained from the experiments on simulated oil spills. The feasibility of this method requires further tests and validation on actual oil spills.

In response to the operational oil spills caused by the damage of oil storage or transport facilities, a potential solution is the development of shipborne remote sensors that are capable to detect the trace oil pollutants or thin oil films formed at the beginning stage of the leakage. Such sensors provide early alarms on the potential leakage and avoid further damage. The UV-induced fluorescence or the passive UV imager discussed in Section 4 could be the candidates for this purpose.

5.2. Accidental oil spills

The quantitative inversion on some key properties of oil spills, especially the oil thickness (or concentration for oil emulsions), provides useful information for the treatment and assessment of accidental oil spills (Fingas, 2018). However, the quantitative inversion on oil thickness has always been a main challenge in the field of oil spill remote sensing (Fingas, 2018; Sun and Hu, 2019). Thermal IR is found to be sensitive to oil thickness for relatively thick oil, and several detailed approaches have been proposed to estimate oil thickness based on thermal IR images (Lu et al., 2016; Guo et al., 2020; Jiao et al., 2021; Leifer et al., 2022). Since the thermal IR characteristics of oil spills at sea changes over time, the robustness of these methods needs to be further examined. Some recent studies also reported that the hyperspectral remote sensing can be used to estimate the thickness of oil slicks (Kieu and Law, 2022; Wang et al., 2023) or concentration of oil emulsions (Jiao et al., 2023). These studies are also conducted using simulated oil spills in controlled conditions. The feasibility and inversion accuracies require the validation using the remote sensing observations of accidental oil spills.

6. Concluding remarks

Based on the characteristics and the practical needs of the operational oil spills and the accidental oil spills caused by ships, this article reviews the current studies and applications on the remote sensing approaches for monitoring these two types of oil spills. It is found that the spaceborne SAR is mostly used for both the operational and the accidental oil spills due to its effectiveness of oil spill detection under various environments. Optical remote sensing is also applied in the cases where the detailed information about oil spills needs to be identified.

For the operational oil spills caused by illegal oil discharge, an efficient remote sensing system for large-scale and routine surveillance on oil spills needs to be established. Further improvement on the elimination of look-alikes is required to reduce the workloads of maritime agencies. The determination of the ship that is responsible for the oil discharge is also a challenging task. For the operational oil spills caused by unintentional leakage, the development of the remote sensors that can provide early alarms on oil leakage is of great significance. For the oil spills caused by ship accidents, the main tasks include the tracking

(and even prediction) of the spatial distribution of spilled oils, and the assessment on their impacts. Optical remote sensing is a potential solution that has been examined through experimental analysis, but its feasibility needs further validation.

Besides the spaceborne SAR and optical remote sensing, several other sensing techniques may also be useful to monitor oil spills caused by ships. These techniques generally lack the ability of oil spill detection in large spatial scale, but may provide solutions to some specific problems. By jointly utilizing various remote sensing techniques built on multiple platforms, it is expected to form a comprehensive sensing network for the surveillance of both operational and accidental oil spills, which supports the implementation of MARPOL Convention and prevents the negative consequences caused by oil pollution from ships.

CRedit authorship contribution statement

Ming Xie: Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Ying Li:** Writing – review & editing, Project administration, Funding acquisition. **Zhaoyi Zhang:** Writing – review & editing, Resources, Investigation. **Qiang Fu:** Visualization, Validation. **Huolin Jiang:** Supervision, Resources.

Funding

This research was funded in part by the Key Technologies Research and Development Program [grant number 2023YFC3108300], the National Natural Science Foundation of China [grant number 52471375, 42406188], the Natural Science Foundation of Liaoning Province [grant number 2024-BS-022], the Asian Cooperation Fund Project, the Fundamental Research Funds for the Central Universities [grant number 3132023507], and the Dalian High-Level Talent Innovation Program [grant number 2022RG02].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded in part by the Key Technologies Research and Development Program [grant number 2023YFC3108300], the National Natural Science Foundation of China [grant number 52471375, 42406188], the Natural Science Foundation of Liaoning Province [grant number 2024-BS-022], the Asian Cooperation Fund Project, the Fundamental Research Funds for the Central Universities [grant number 3132023507], and the Dalian High-Level Talent Innovation Program [grant number 2022RG02]. The authors are grateful to Dr. Bingxin Liu from Dalian Maritime University for providing the figures used in this article. The author would like to thank © The Optical Society for providing the free permission to reuse the figures in this article.

Data availability

No data was used for the research described in this article.

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