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Shaojie Sun
University of South Florida

Yingcheng Lu
University of South Florida

Mengqiu Wang
University of South Florida

Chuanmin Hu
University of South Florida, huc@usf.edu

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Key Points:

- VIIRS nighttime data and wind-adjusted model show unprecedented value in tracking an oil tanker over >350 km after a major collision
- Other satellite imagery capture smokes and spilled oils in the East China Sea
- A combination of all remote sensing and modeling efforts proves to be effective in monitoring the tragic accident

Correspondence to:

C. Hu,
huc@usf.edu

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Tracking an Oil Tanker Collision and Spilled Oils in the East China Sea Using Multisensor Day and Night Satellite Imagery

Shaojie Sun¹ , Yingcheng Lu^{1,2} , Yongxue Liu³ , Mengqiu Wang¹ , and Chuanmin Hu¹

¹College of Marine Science, University of South Florida, St. Petersburg, FL, USA, ²International Institute for Earth System Science, Nanjing University, Nanjing, China, ³Department of Geographic Information Science, Nanjing University, Nanjing, China

Abstract Satellite remote sensing is well known to play a critical role in monitoring marine accidents such as oil spills, yet the recent SANCHI oil tanker collision event in January 2018 in the East China Sea indicates that traditional techniques using synthetic aperture radar or daytime optical imagery could not provide timely and adequate coverage. In this study, we show the unprecedented value of Visible Infrared Imaging Radiometer Suite (VIIRS) Nightfire product and Day/Night Band data in tracking the oil tanker's drifting pathway and locations when all other means are not as effective for the same purpose. Such pathway and locations can also be reproduced with a numerical model, with root-mean-square error of <15 km. While high-resolution optical imagery after 4 days of the tanker's sinking reveals much larger oil spill area (>350 km²) than previous reports, the impact of the spilled condensate oil on the marine environment requires further research.

Plain Language Summary The Iranian oil tanker SANCHI collided with a grain freighter on 6 January 2018 in the East China Sea, causing major fires and oil spills. For event response, nighttime data collected by the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite instrument show unprecedented value in monitoring the fires and tracking the >350 km drifting pathway of the SANCHI tanker. A numerical model to combine surface currents and wind can also simulate the tanker's locations until it sank on 14 January. Satellite remote sensing during daytime shows smokes and spilled oil on the ocean surface, some of which appears to be oil emulsion. A combination of all available remote sensing and modeling techniques can provide effective means to monitor marine accidents and oil spills to assist event response.

1. Introduction

The Iranian oil tanker SANCHI (IMO: 9356608), carrying ~1 million U.S. barrels (136,000 metric tons) of condensate oil heading to South Korea from Iran with 32 crews on board, collided with the Chinese grain freighter CF Crystal (IMO: 9497050) in the East China Sea (ECS) at ~8 p.m. on 6 January 2018 [Beijing time = GMT + 8 hr; hereafter time used in this paper is all Beijing time; Ministry of Transport of the People's Republic of China (MOT), 2018a]. The accident caused SANCHI on fire and tilted, drifting ablaze for a week, until it exploded and sunk at ~3 p.m. on 14 January 2018. Three bodies of the 32 crew members were found, with the other 29 missing members presumed dead. During the drift, SANCHI leaked oil since 7 January, according to online reports (MOT, 2018a; State Oceanic Administration (SOA), People's Republic of China 2018a, 2018b). Oil slicks have been observed and reported around the tanker's sinking location since 14 January 2018 through airborne and shipborne surveys (SOA, 2018b).

Monitoring the tanker's drifting pathway and potential spills from a moving target represents a critical need for event response and mitigation. Unfortunately, for this specific event it has proven extremely difficult for two reasons: (1) persistent cloud cover during and after the collision prevented any effective use of optical remote sensing from satellites; (2) the use of synthetic aperture radar (SAR, immune to cloud cover) required a response time, which can vary between hours and days because it includes time for event reporting, image acquisition planning, and execution of image acquisition over the targeted area (IPIECA-IOPG, 2014). Airborne surveys, on the other hand, were limited in space and time. As a result, traditional means through satellite remote sensing and airborne surveys appeared inadequate for event response of this disaster.

Here we demonstrate the unprecedented value of nighttime data collected by the Visible Infrared Imaging Radiometer Suite (VIIRS) in monitoring such an event. Additionally, a numerical model is calibrated using

Table 1*Number of Days With Imagery or Data Product Coverage From Individual or Multiple Sensors Along the Tanker's Drifting Trajectory (7–14 January 2018) and Around the Tanker Sinking Site (15–18 January 2018)*

	Satellite sensor/products	7–14 January	15–18 January
Optical cloud-free coverage	MODIS	1	3
	OLCI	1	1
	VIIRS	1	1
	GOCI	2	3
	ETM+	0	0
	OLI	0	0
	MSI	1	1
SAR coverage	Sentinel-1	0	0
	Radarsat-2	2	1
	COSMO-SkyMed	0	4
	TerraSAR-X	0	0
Fire/Night-light anomalies	FIRMS	2	0
	VIIRS Nightfire	7	1
	VIIRS DNB	8	4

Note. As multiple images/products per day are possible from some sensor(s) (e.g., MODIS Terra and MODIS Aqua, and GOCI), the statistics is based on daily frequency (in Beijing time).

these data to track the tanker location, and high-resolution optical satellite imagery collected after 4 days of the tanker sinking shows the area of oil slicks much larger than those reported, which also shows signs of oil emulsions. The objective of this paper is to show the worth of combining all remote sensing imagery (day and night) and numerical modeling in event response, therefore possibly serving as a template when responding to other similar events.

2. Data and Methods

2.1. Satellite Data

Data from all civilian satellites, whenever available for public access, were downloaded from the corresponding agencies. These include Terra/Aqua Moderate Resolution Imaging Spectroradiometer (MODIS), Suomi-NPP VIIRS, Sentinel-3 Ocean and Land Color Instrument (OLCI), COMS Geostationary Ocean Color Imager (GOCI), Landsat ETM+/OLI, Sentinel-2 MultiSpectral Instrument (MSI), and Sentinel-1 SAR. Commercial Radarsat-2, COSMO-SkyMed and TerraSAR-X SAR data archives have also been checked. Detailed information of imagery coverage is provided in Table 1.

After the collision accident, all optical imagery collected during the daytime showed persistent cloud cover until 13 January when the images showed scattered clouds to allow for inspection of some of the pixels. During this period, oil spill detection was impossible but smoke from the burning tanker could be detected on 13 January (see below). Between 7 and 14 January, the above SAR data showed only 2 days of coverage over the tanker's drifting trajectory, while more frequent coverage after the tanker's sinking (on 14 January) was available from COSMO-SkyMed. The Chinese Gaofen-3 (GF-3) satellite launched in 2016 carries a C-band SAR sensor, which works in 12 imaging modes with spatial resolution ranging from 1 m to 500 m and swath ranging from 10 to 650 km (<https://chinaspacereport.com/spacecraft/gaofen/>). GF-3 was reported to have collected data over the SANCHI location since 8 January (CRESDA, 2018), yet the data were not open to research communities or the public.

Because of the limitations above, the only possibly useful data during the initial phase of the accident were VIIRS nighttime data. There are two types of nighttime data used in this study. The first is the VIIRS Nightfire (v3.0) data product (https://ngdc.noaa.gov/eog/viirs/download_viirs_fire.html), obtained from the National Oceanic and Atmospheric Administration Earth Observation Group every day. A multispectral algorithm was used to detect subpixel hot sources (Elvidge et al., 2013). Candidate hot pixels were first identified by the nighttime M10 (1,601 nm) band. Six other spectral bands including the Day/Night Band (DNB), M7 (862 nm), M8 (1,238.5 nm), M11 (2,250 nm), M12 (3,694.5 nm), and M13 (4,066 nm) were used to confirm the initial detection. A black-body emission curve fitting was then applied to the confirmed hot source

using these bands, from which the hot source temperature and area were determined (Elvidge et al., 2015). Similar fire products from both MODIS and VIIRS for both day and night were also explored from the Fire Information for Resource Management System (FIRMS, <https://firms.modaps.eosdis.nasa.gov/map/>). FIRMS uses reflectance and/or brightness temperature thresholds to first classify cloud pixels on both day and night imagery (Giglio et al., 2016; Schroeder et al., 2014) and then mask these pixels from fire detection (Schroeder et al., 2014). Because of the cloud masking before fire detection, FIRMS products showed no valid coverage before 12 January due to persistent cloud cover (Table 1). In contrast, the VIIRS Nightfire algorithm is applied to all pixels, with cloud cover conditions recorded in the final product (Elvidge et al., 2013).

The second type of nighttime data was collected by the low-light imaging DNB (500–900 nm), designed primarily to detect light sources such as city lights (Miller et al., 2013). In this study, VIIRS DNB SDR (Sensor Data Records) calibrated radiance data were obtained from National Oceanic and Atmospheric Administration/Comprehensive Large Array-data Stewardship System (NOAA/CLASS).

Lastly, after persistent cloud cover for many days, MSI images with some cloud-free spots were available on 13 January (1 day before the tanker's sinking) and 18 January (4 days after the tanker's sinking). The Level-1C data were processed using the ACOLITE software (<https://odnature.naturalsciences.be/remsem/software-and-data/acolite>) to produce spectral Rayleigh-corrected reflectance (R_{rc} , dimensionless), with all the spectral bands resampled to 10 m resolution. Red-Green-Blue (RGB) true color ($R = 664$ nm, $G = 560$ nm, $B = 497$ nm) images were generated for smoke detection while false-color RGB images ($R = 1614$ nm, $G = 835$ nm, $B = 664$ nm) were generated to detect spilled oils. Normalized sun glint reflectance (L_{GN} , sr^{-1}) was estimated using the Cox and Munk model and National Centers for Environmental Prediction (NCEP) wind data (Cox & Munk, 1954; Lu et al., 2016; Wang & Bailey, 2001). Oil slicks were manually delineated in the ArcMap software (version 10.3) using methods described in Sun et al. (2015).

2.2. Numerical Model to Track Tanker Locations

The tanker's drifting pathway was simulated using Global HYCOM daily surface currents and the NCEP Reanalysis daily wind data (10 m above sea level). HYCOM surface currents data were obtained from the Global Reanalysis (experiment 91.2). A Runge-Kutta fourth-order method was used to model the tanker trajectories with a time step of 15 min. In modeling oil spill trajectory, a factor of 3% was often applied to wind velocity (IPIECA-IOPG, 2015; Lehr & Simecek-Beatty, 2000). The large size of the tanker (overall length of 274 m, beam width of 50 m, and full-load draught of 17 m) enables a larger cross section (than surface oil) to the wind direction. Therefore, wind was expected to play a more important role than the usual assumption of 3%. A sensitivity test by varying the factor from 1% to 7% was conducted to determine the optimal wind factor that led to the least difference between modeled SANCHI locations and observed locations.

3. Results

3.1. SANCHI Locations From VIIRS Night Time Data and Numerical Modeling

Before 13 January 2018, optical remote sensing data collected by all sensors during daytime were useless due to persistent and complete cloud cover. In contrast, VIIRS nighttime data, specifically the Nightfire data product and DNB data, showed locations of the tanker as well as the size of the hot spot footprint every night starting 8 January (Figure 1). After the tanker's sinking on 14 January, VIIRS showed three separate fire sources in the following night (last panel of Figure 1), indicating surface drifting of floating oil.

The tanker's drifting trajectory could be reproduced by the numerical model (Figure 2). With a wind factor of 4.1%, the modeled tanker locations agreed well with those observed from the VIIRS nighttime data, with a root-mean-square difference of 14.3 km. When other wind factors between 1% and 7% were applied, root-mean-square difference was significantly higher (e.g., ~40 km at 3%).

3.2. The Value of Optical Remote Sensing Data During Daytime

On 13 January, after persistent and complete cloud cover since the collision, some optical remote sensing imagery covering the area of interest showed smoke around the tanker location. The example in Figure 3 from the MSI image clearly reveals the smoke, which appears brownish in the RGB image. Wind is about

Figure 1. (a) SANCHI oil tanker locations derived from VIIRS Nightfire product in the East China Sea, overlaid on the VIIRS Day/Night Band image captured at 2 a.m. on 11 January 2018. The initial collision was at 8 p.m. on 6 January 2018 (Beijing time = GMT + 8), while the first VIIRS capture was at 1:16 a.m. on 8 January. The last detection was at 12:45 a.m. on 15 January. SANCHI was reported to sink at 3 p.m. on 14 January (red circle), but fires on ocean surface did not stop until ~10 a.m. on 15 January (SOA, 2018b). The sinking location was reported to be ~280 km southeast of the initial collision location (MOT, 2018b). The VIIRS-based results agree well with both reports. (b) VIIRS Day/Night Band radiance shows local hot spots from 8 to 15 January, with temperature (T , in Kelvins) and location of the hotspot as well as the footprint area (A , in m^2) annotated. Three active fires (yellow dots in the last panel) were detected in the vicinity of the sinking location (red circle in the last panel).

Figure 2. Trajectory and locations of the SANCHI tanker movement determined from VIIRS Nightfire data product (except for the last point at 3 p.m. on 14 January, which is the reported sinking location) and a numerical model. In the model, a 4.1% factor was applied to wind, which resulted in a minimal root-mean-square difference between modeled and observed locations (~ 14.3 km). A 3% wind factor would lead to RMS difference of ~ 40 km. Average wind speed and direction for each day are plotted as green arrows, with wind speed (m/s) annotated to the left of the wind vector.

8.1 m/s blowing from the NNE to SSW. Correspondingly, the smoke is about 15 km SSW of the tanker's location 9 hr ago, and 14 hr later the tanker's location is to the SSW of the smoke. Other than the smoke, the images could not be used to detect spilled oils due to cloud cover surrounding the smoke area.

Four days after the tanker's sinking, on 18 January, the first high-resolution optical image that could be used to detect spilled oils was captured by MSI (Figure 4). One slick was detected 3 km north of the sinking location, with a slick size of ~ 86 km² elongated in the west to east direction (Figure 4b, Slick 2). The slick shows mostly negative contrast from water (i.e., darker than water) due to weak sun glint ($L_{GN} = 1.5E-4$ sr⁻¹) (Sun & Hu, 2016). Another larger slick was captured 30–40 km northeast of the sinking location, with a slick size of ~ 270 km² (Figure 4a, Slick 1). In the center of this slick, some oil stripes in the NNE-SSW direction show signs of oil emulsions as they appear reddish (elevated 1,614 nm reflectance) in the false-color RGB image (Figure 4a). The NNE-SSW stripes within both slicks in Figures 4a and 4b are apparently due to wind-driven Langmuir circulation, with the direction of the stripes aligned with the NNE-SSW wind direction. These slick size estimations, although biased low due to lack of MSI data coverage to the east of the slicks, are significantly higher than those reported online (SOA, 2018c).

4. Discussion

Massive oil spills and possible application of dispersant could cause severe and long-term impacts on the marine ecosystem and local economies (Joye, 2015; Michel et al., 2013; Peterson et al., 2003), thus calling

Figure 3. MSI RGB image ($R = 664$ nm, $G = 560$ nm, $B = 497$ nm) on 13 January 2018 (10:20 a.m.) shows smoke (outlined in red), where VIIRS-detected SANCHI locations on 13 January (1:22 a.m.) and 14 January (1:04 a.m.) are annotated. At the time of imaging, wind blew from northeast to southwest at a speed of 8.1 m/s.

for accurate and timely assessment during and after the spill. Unfortunately, due to persistent cloud cover and lack of coverage, none of the traditional remote sensing techniques (SAR, daytime optical imagery) proved to be fully effective for this particular event. Here nighttime imagery from VIIRS showed unprecedented value in tracking the tanker's location and fire footprint, thus providing first-hand timely knowledge every night to assist in event response. On the other hand, identifying the tanker's location through locating fires is not trivial, as active fires from gas flares of offshore platforms could confuse the findings. In this study, hot sources from gas flares in the East China Sea were ruled out using a global oil

Figure 4. MSI false-color RGB image ($R = 1614$ nm, $G = 835$ nm, $B = 664$ nm) at 10:20 a.m. on 18 January 2018 shows two major slicks (locations annotated in inset figure): (a) Slick 1 is 30–40 km northeast of the reported sinking site, with a slick size of ~ 270 km². This number is an underestimate, as the area east of the oil slick was not covered by the MSI image. The center of the slick shows signs of oil emulsion (enlarged area from the green rectangle) as they appear reddish in the false-color RGB image. Spectral analysis (inset reflectance spectrum) of a randomly selected point (black arrow) shows elevated reflectance at 1,614 nm, a clear indication of oil emulsion. (b) Slick 2 is 3 km north of the sinking site, with a slick size of ~ 86 km² (also underestimated due to lack of MSI coverage to the east). The total area ($270 + 86$ km²) is significantly higher than any reported numbers (SOA, 2018c) that ranged between ~ 160 km² from field observations and 20.7 km² from satellite interpretation. The slicks appear darker than water due to the presence of weak sun glint ($L_{GN} = 1.5E-4$ sr⁻¹).

platform database (Liu et al., 2016), making the detection of tanker location reliable. The ability of emissive radiation to penetrate thin clouds makes it possible to detect hot sources even under thin cloud cover, although the temperature of the hot source may contain large degree of uncertainties due to cloud absorption of the radiant emissions (Elvidge et al., 2013).

Oil released to the ocean from this accident was from two sources: the remaining condensate oil after combustion and evaporation, and the remaining bunker fuel or heavy fuel oil. The latter strongly absorbs blue light (Byfield, 1998), while the former is nearly transparent in the visible and near-infrared (NIR) wavelengths (470–1,000 nm) at a thickness of $<200\ \mu\text{m}$ (Wettle et al., 2009). Both will dampen the surface wave, thus detectable in SAR imagery (Alpers et al., 2017; Brekke & Solberg, 2005; Garcia-Pineda et al., 2013), and optical imagery (Adamo et al., 2009; Hu et al., 2009; Pisano et al., 2015; Sun & Hu, 2016) under optimal wind conditions. Because condensate oil is believed to evaporate fast, it was expected that oil emulsions could not be observed. However, a surprising result from this analysis is that oil emulsion patches appear to have formed on the sea surface after the tanker's sinking (Figure 4). Spectral analysis of selected pixels in the reddish patches of the oil slicks showed significantly elevated reflectance at 1,614 nm (Figure 4a inset), an indication of oil emulsion (Clark et al., 2010; Svejksky et al., 2016). Because condensate oil evaporates fast, it is speculated that the oil emulsion originated from the bunker oil released by the tanker after its sinking. Indeed, HYCOM surface currents showed NNE direction after the tanker's sinking, suggesting that the spilled oil could originate from the tanker after its sinking.

By no means does this work de-emphasize the value of SAR and other remote sensing techniques in oil spill response. Instead, the study here is to demonstrate how VIIRS nighttime data can provide critical location information on marine accidents through its unprecedented capacity in identifying fire sources and observing low light at night. Indeed, although due to data restriction policy the commercial SAR data could not be accessed, some quick-look images posted online did show oil slicks in the study region. Additionally, post-sinking MSI imagery showed more spilled oils than those determined from airborne and shipborne surveys, once again proving the value of optical remote sensing. On the other hand, the combination of surface currents and wind data provided a relatively accurate estimate on the tanker's drifting pathway, indicating that numerical modeling can also provide guidance on search and rescue, similar to the search of the Air France 447 in the Equatorial Atlantic (Chen et al., 2012).

Altogether, the multisensor observations from day and night provide way more complete information than any individual sensors alone. This is particularly important for event response during the initial phase as opposed to postevent assessment. For example, without satellite remote sensing providing approximate locations at the very beginning, it would be difficult to narrow down targeted regions to point high-resolution satellite sensors. The case study here demonstrates the value of VIIRS nighttime data in providing such critical information within 30 hr of the accident, therefore complementing other means for event response.

At the time of this writing, postspill assessments are still ongoing, for example, to evaluate the potential impact of the tragic event to the marine environment. Such assessments have proven to be difficult from the Deepwater Horizon oil spill event in the northern Gulf of Mexico in 2010, mainly due to the lack of "baseline" data before the event. Modern satellite remote sensing has provided continuous ocean measurements since 1997 when Sea-viewing Wide Field-of-view Sensor began collecting data, where surface ocean transparency and chlorophyll-a concentration data records may serve as baseline (mean conditions and natural variability) to evaluate the potential impact of the event on nearby ocean environment. Such an impact assessment may be an immediate follow-on study for this tragic event.

5. Conclusion

Although VIIRS nighttime data have been widely used to map city lights and fires, this study demonstrates its value in tracking a major collision and oil spill event. More importantly, during the initial days after the collision, VIIRS nighttime data were the only publically available satellite data proven to be effective in tracking the tanker's drifting pathway and daily locations, as all other satellite sensors suffer from lack of coverage or cloud cover. This capacity, along with the numerical tool to track the oil tanker and other sensors to map spilled oil, may serve as a template for similar events in the future.

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