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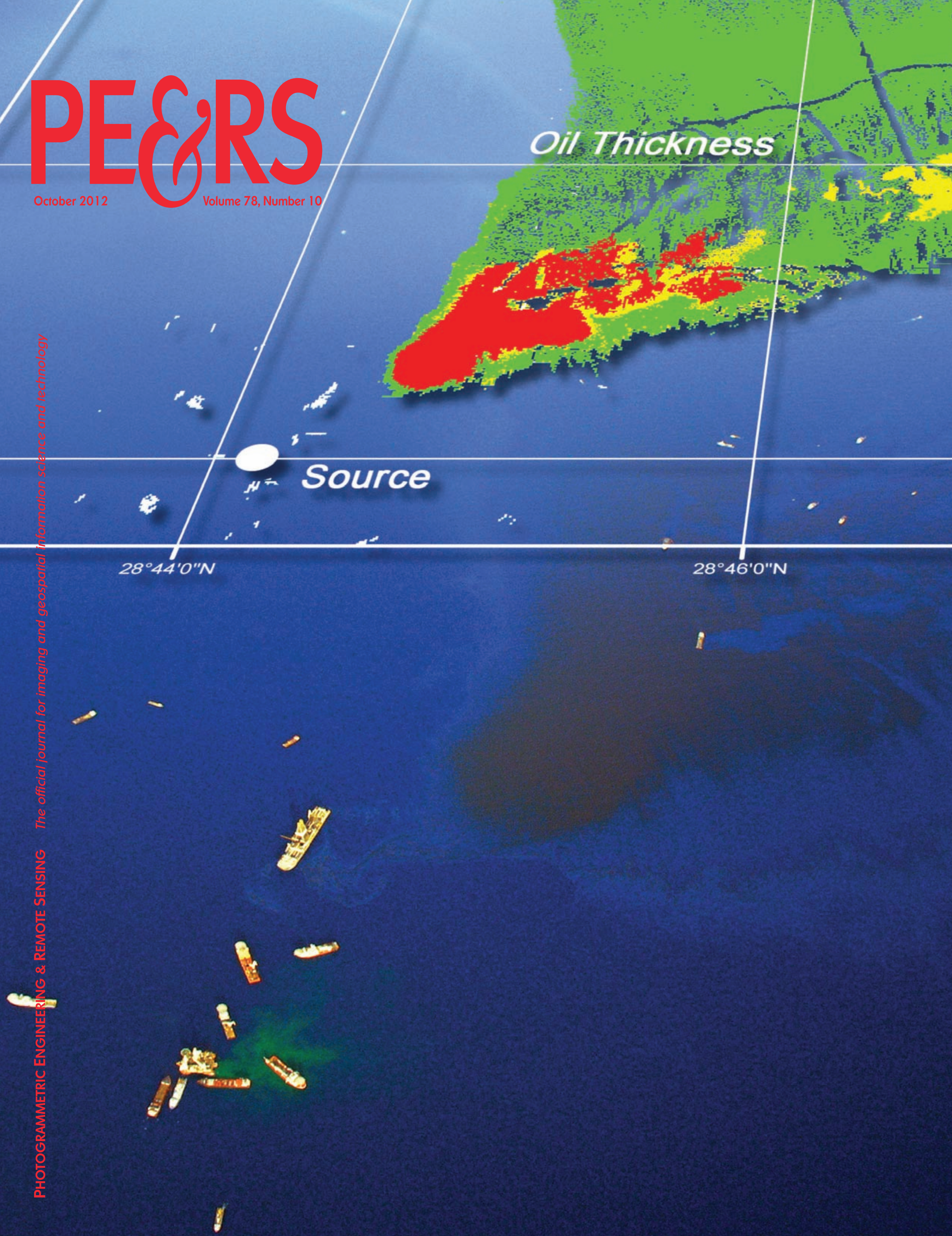

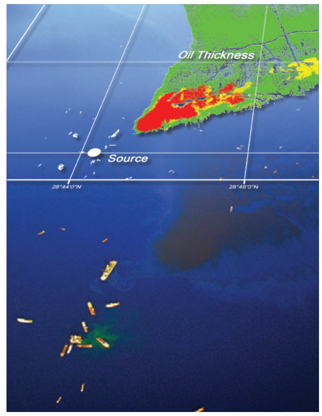

This image composite shows and aerial photo of the region around the source site of the Deepwater Horizon (MC-252) oil spill in the Gulf of Mexico on 5/26/2010. Overlaid is an oil thickness distribution map derived from Ocean Imaging Corp.'s aerial multi-spectral mapping system. The system's oil thickness derivation algorithm used three channels in the visible, one in the near-IR and one in the thermal-IR to assign the oil-containing pixels into several thickness classes. Such GIS-compatible maps of the source region and other regions of priority within the spill were generated once to twice daily and electronically disseminated to the response community. More details on the imaging and how it was utilized throughout the response can be found in a peer-reviewed article in this issue. The surface oil signature is displaced from the actual bottom source location due to currents that affected the oil as it took 4+ hours to rise from the 1500m depth. The greenish feature between the vessels in the lower left corresponds to residual drilling mud used during one of several different attempts to inject material into and plug the leaking well. For more information on the system and Ocean Imaging Corp. see www.oceani.com or call 858-792-8529. Cover image art by Paula Klein, Ocean Imaging.

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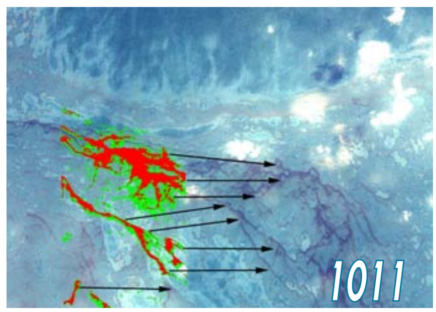
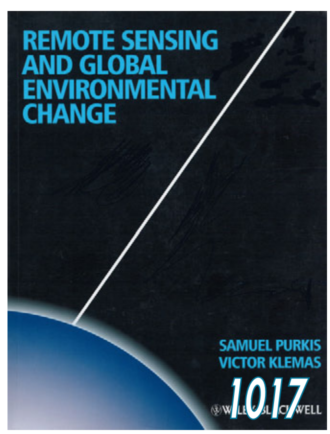
Highlight Article



Columns & Updates



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Expanding the Utility of Remote Sensing Data for Oil Spill Response

By Jan Svejkovsky and Mark Hess

Introduction

The operational utilization of satellite and aerial remote sensing data for oil spill reconnaissance and response has steadily increased with each event. A number of European nations have utilized various remote sensing technologies for over a decade to detect and monitor at-sea spills and illegal bilge dumps (Trieschmann *et al*. 2003, Zielinski 2003, Bonn Agreement 2007, Ferraro *et al*. 2009). Remote sensing has also been increasingly utilized during spill response around the American continent, most notably during the 2010 Deepwater Horizon (DWH) spill in the Gulf of Mexico, which represents to-date the most intense, multi-faceted utilization of remote sensing technology in a major oil spill. During that event, satellite and aerial imaging were heavily relied upon to monitor the extents of the spill, as well as helped guide daily response operations. A peer-reviewed article (Svejkovsky *et al*., this issue) details the various applications of aerial multispectral imaging done during the DWH response with a system developed by Ocean Imaging Corporation (OI).

The most common application of satellite and aerial imaging for oil spill response has up to now been focused on mapping the spatial extents of the oil slick on the ocean surface, and potentially its thickness and weathering properties. Research work and OI's operational involvement in the DWH and other spills have shown, however, that remote sensing technologies can provide useful information extending beyond the traditional oil slick extent mapping surveys. This article highlights three such emerging remote sensing applications.

Sensing Dispersant Effects with Thermal Imagery

Surface and, for the first time, subsurface chemical dispersants were used during the DWH response and proved to be highly effective for decreasing the amount of oil floating on the sea surface (and thus potentially reaching the shoreline). Traditional aerial dispersant spraying was utilized throughout the response. Additionally, dispersants were directly applied to the leaking wellhead at depth (~1500 m). To obtain permission from the Environmental Protection Agency (EPA) for the subsurface application, the usage required evaluation, which occurred in early May, 2010 as a series of time-dependent application tests. OI's aerial oil mapping system was one of the techniques used to evaluate the efficacy of the subsurface dispersant injections. Multispectral visible/near IR and thermal IR imagery was collected over the spill source site before, during and after the subsurface dispersant injection. Due to the depth of the DWH well, it took over four hours for the oil to reach the sea surface, resulting in a significant time lag between the initiation and termination of the dispersant injections and any changes in oil volume perceived on the surface. With these considerations in mind, several imaging survey missions were performed over the source site that quantified the surface oil density using multispectral-based oil thickness algorithms (Svejkovsky *et al*. 2008, Svejkovsky and Muskat 2009). Results are displayed in Figure 1. The imagery documented a significant decrease in surface oil as a result of the subsurface dispersant test injections. These remote sensing-based analyses were one of the data sets incorporated by the EPA and other

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agencies in assessing the continued use of subsurface dispersants, which subsequently permitted their continued utilization during the DWH spill response.

Perhaps the most interesting development stemming from OI's dispersant-related imaging during DWH was the documentation of aerial dispersant application effects. As is also discussed in Svejkovsky *et al*. (this issue), some of OI's aerial imaging over-flights were coordinated with aerial dispersant releases so that pre- and post-application imagery could be acquired. Since emittance in the thermal IR portion of the spectrum does not appreciably penetrate the water column, thermal imagery recorded by OI's multispectral aerial system represents thermal patterns at the sea surface only. During daytime, oil floating on the surface can appear either warmer or cooler than the surrounding sea water, depending on its thickness (Byfield 1998, Davies *et al*. 1999, Jha *et al*. 2008, Svejkovsky and Muskat 2009). Once submerged, the thermal contrast signature is lost. This effect was noted in imagery collected during the DWH incident over areas where aerial dispersants were successfully applied. The signal from the surface oil was quickly degraded as the aerial dispersants were successful in breaking down the oil components, which entered the water column as droplets.

Aerial dispersant applications presently mandate monitoring of their success using the Special Monitoring of Applied Response Technologies (SMART) protocol (NOAA 2012). The traditional SMART monitoring techniques rely on ship-based *in situ* sampling, which is time consuming and spatially limited. Aerial imaging can augment the traditional SMART methodology and extend its monitoring efficiency in both time and space. Based on initial observations during the DWH flights, additional tests of the concept were conducted at the U.S. Department of Interior's Bureau of Safety and Environmental Enforcement's (BSEE)'s Ohmsett test facility (a national oil spill response test facility, located in Leonardo, New Jersey) in late 2011. The initial test results support OI's DWH observations. As exemplified in Figure 2, within two minutes of being poured into the test tank, thick crude oil attains a warmer-than-surrounding-water thermal contrast of several degrees Centigrade (Figure 2A). If left untreated with dispersant, the oil maintained this thermal signature even when subjected to natural dispersion, through wave action induced in the test tank. If treated with the chemical dispersant Corexit 9500 (used during DWH), the positive thermal contrast rapidly began to disappear (Figure 2 B).This signature change corresponded to the oil's rapid dissolution into the water column, as was also corroborated by visual and *in situ* instrument assessments. Ultimately, only residual sheen signatures corresponding to a negative (i.e., cooler-than-water) thermal contrast were discernible in the imagery (Figure 2C). Further testing is planned to evaluate the dispersant application monitoring utility of thermal imaging under various sea states, and to determine if the technique could be additionally used to quantify the dispersion success rate in cases where complete dispersion was not achieved.

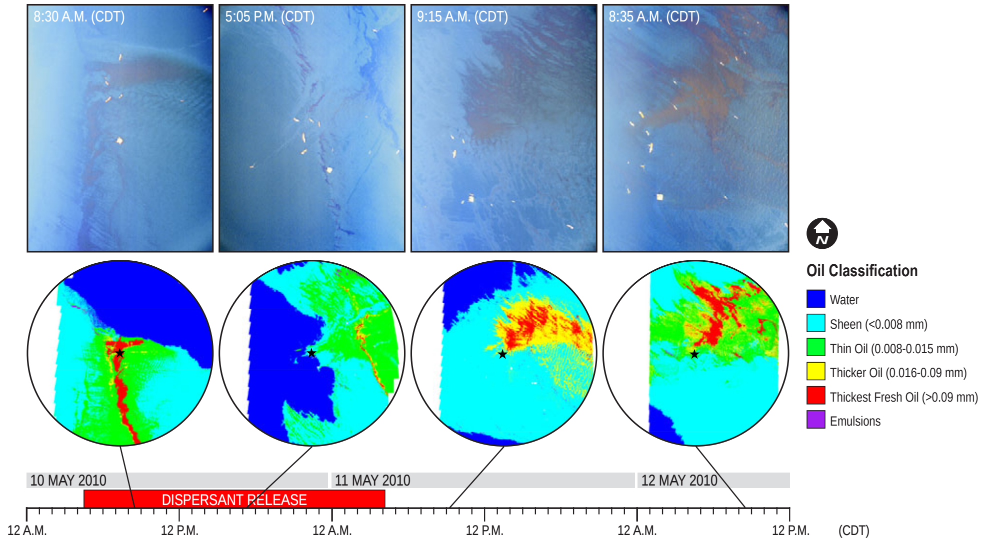

Figure 1. Color photos (top) and oil thickness distributions within a 10km radius of the DWH spill source site derived from aerial multispectral imagery (middle) during and after an experimental subsurface dispersant injection 10-11 May, 2010. The data document a marked decrease in surface areas covered by thick oil during the release, and a resumption of greater oil volume surfacing after the dispersant injection stopped.

Tracking Surface Oil Movement

Accurate estimation of surface oil drift trajectories is very important in all oil spill situations. During DWH, the National Oceanic and Atmospheric Administration (NOAA) provided daily 24-hour, 48-hour and 72-hour spill trajectories. These were based on a number of atmospheric and oceanographic parameters, including OI's aerial image-based oil thickness analyses. Not utilized, however, were direct observations of the oil drift itself, which were not readily available at the time but can be obtained from time series of aerial or satellite images. The determination of surface current velocity and direction by tracking thermal or visible features in time-sequential satellite imagery was pioneered in the 1980s (Vastano and Reid 1985, Emery *et al*. 1986, Svejkovsky 1988). The same technique can be applied to directly measure the drift of features within an oil slick using a pair of aerial or satellite images, or a combination of the two, separated by a known time interval. OI has begun investigating this capability using data obtained during the DWH spill. As an example, Figure 3 shows surface oil drift vectors derived from directly tracking the spatial displacement of distinct oil features identified in OI's aerial imagery acquired near the DWH spill source site on June 17, 2010 and a WorldView-2 satellite image of the same area acquired 1.8 hours later. The example underscores the relative complexity of the region's surface flow field, which could not be resolved in relatively sparse atmospheric and oceanic buoy data but can be extracted in high detail from the imagery. Figure 4 highlights meso-scale features identifiable through a time series of satellite Synthetic Aperture Radar (SAR) images that can be used to measure the overall movement pattern of the DWH slick. Unlike satellite imagery whose acquisition timing generally cannot be altered, aerial imaging provides the advantage of enabling the exact scheduling of the time interval between successive flights and data acquisitions, hence enabling adjustment of the feature tracking time interval to maximize the method's effectiveness under existing current and wind drift conditions.

Mapping Oil Slicks at Night

Up to the present (including the DWH incident), oil spill response activities, including visual aerial surveys, oil recovery, *in-situ* burning and dispersant applications have been generally limited to daylight hours. The primary reason for suspending response operations at night is safety. However, decreased ability to efficiently and accurately locate suitable oil targets at night also restricts direct response efficiency at nighttime. This limitation can become even more serious during a potential future wintertime spill at high latitudes where very short or no daily sunlight intervals occur. Experiments done at Ohmsett by OI in the past few years show that thermal IR imaging clearly reveals floating oil during nighttime, and actually enables useful estimations of its relative thickness distributions to be made. Similar observations were also made by Svejkovsky when examining thermal IR videos collected at night by the Spanish Coast Guard over areas affected by the M/V Prestige spill off Spain in 2002.

Thermal imaging of oil at night yields data that is actually easier to interpret than imagery from daytime. Unlike during the day when thin oil films appear cooler and thick films appear warmer than surrounding water, nighttime thermal signals from spilled oil appear consistently cooler-than-water, mostly due to the petroleum's lower-than-water emissivity. The negative contrast increases with increasing oil thickness up to at least 2 mm, as per OI's experiments, with thicker films exhibiting a similar maximum contrast. This effect can thus provide a quick, straightforward assessment of relative oil thickness and the location of the thickest oil accumulations. Even if no direct response operations take place at night, pre-dawn thermal imaging-based spill surveys could provide the most up-to-date oil distribution information for immediate use before daytime operations resume.

Thermal imaging could also provide a means for at-sea recovery vessels to increase their field of view during both day and night and enable them to better identify recoverable oil targets. By mounting a forward viewing thermal imaging camera on a ship's mast the recovery vessel's crew could gain a much more comprehensive view of upcoming oil patches (and their relative thickness) than is presently possible

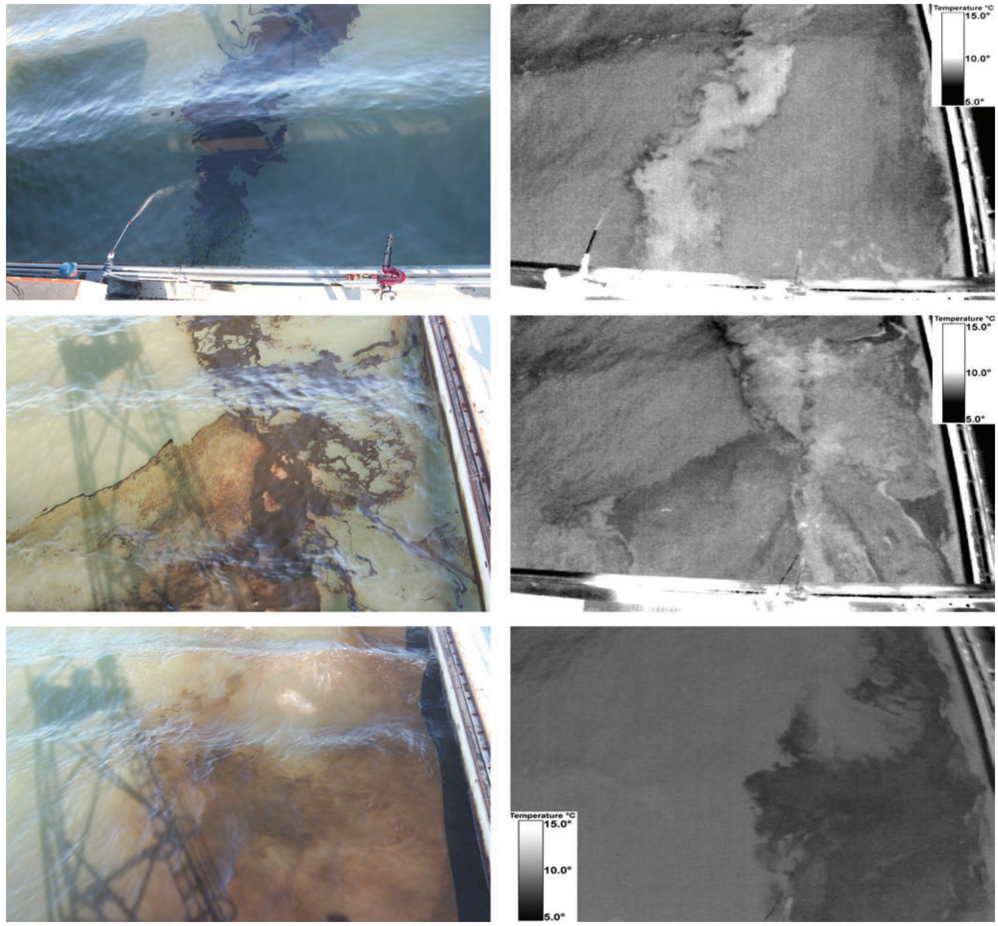

Figure 2. Sequence of color (left) and thermal IR (right) images from a crude oil slick experiment at Ohmsett during which dispersant was applied. **Top:** Oil slick approximately 2 minutes after laydown while dispersant is being applied (thick oil areas are 1-3°C warmer than water); **Middle:** Oil slick after dispersant had been applied and subjected to wave agitation. Thermal image shows a mixture of dispersed (invisible in IR) and undispersed (warm in IR) oil, and sheen (cool in IR); **Bottom:** Oil slick area 8 minutes after dispersant application showing only residual sheen (cool) as it aggregated on the right side of the tank.

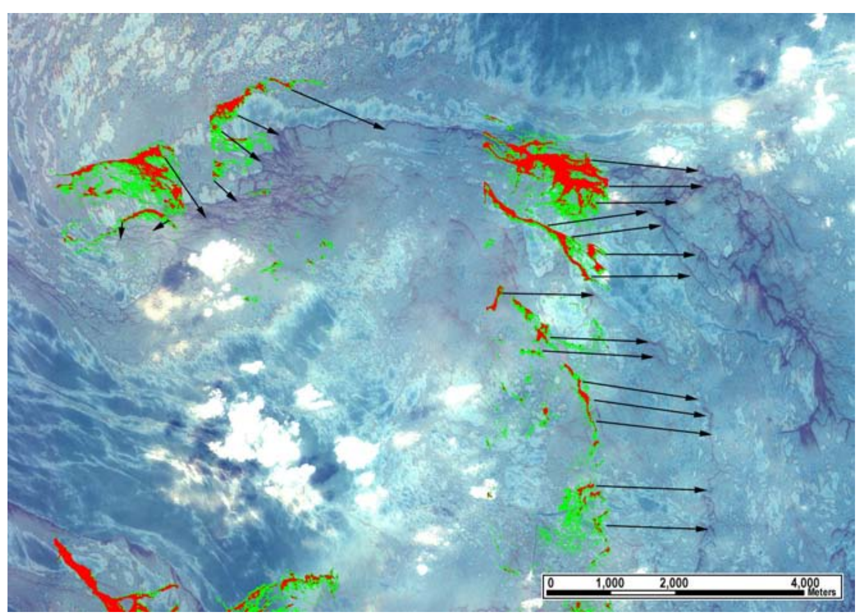

Figure 3. DigitalGlobe's WorldView-2 satellite multispectral image from near the DWH spill source site on 6/17/2010. Overlaid in color are two thickest oil classes from OI's aerial image-based analyses along two (non-overlapping) flight lines acquired 1.8 hours earlier over the same area on the same day. The vectors show drift distance and direction of individual thick oil features tracked through the two-image time interval. The fastest drift rates correspond to 27 cm/sec. (Satellite image courtesy and copyright of DigitalGlobe).

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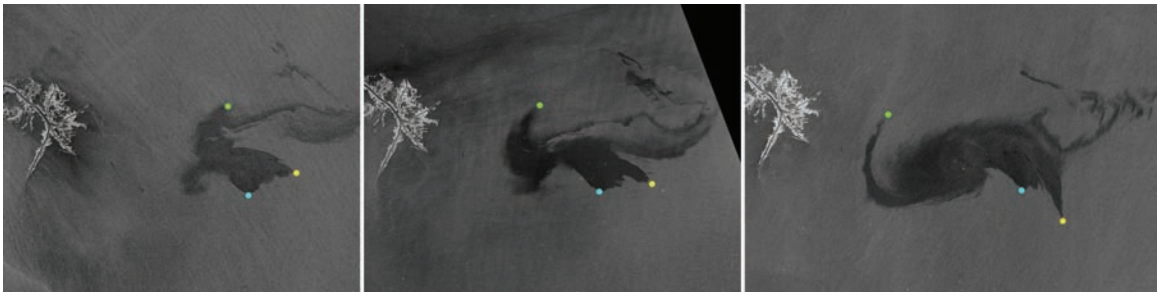

Figure 4. Radarsat SAR images of the DWH oil slick from 4/26, 4/27, and 4/28/2010. The dots identify three representative features within the slick that remained identifiable throughout the three-day period and can be used to compute the slick's overall surface drift field. (SAR data copyright Radarsat).

through visual means. Alternately, a thermal imaging camera could be mounted on an unmanned aerial vehicle (UAV) operated and retrievable from the recovery vessel, providing even broader field of view coverage.

Conclusions

As satellite and aerial remote sensing becomes a more generally accepted and routine part of oil spill response, its applications need not be limited to merely mapping the locations, extents and thickness of the existing oil slick for direction of operations. As this article shows, the imaging can be more application driven by aiding in dispersant effectiveness testing, deriving high spatial and temporal resolution oil drift information and offer the potential to extend monitoring and recovery guidance into nighttime. Although the limited tests and observations outlined here represent only initial proof-of-concept studies which need to be followed by additional research, they exemplify an expanded role of remote sensing technologies in responding to at-sea oil spills.

Acknowledgements

The initial spill mapping system development work was funded by research grants from California Department of Fish & Game's Office of Spill Prevention and Response (OSPR) and the Bureau of Safety and Environmental Enforcement (formerly the U.S. Minerals Management Service). The operational use of the system during the DWH spill was funded by BP, with aircraft and pilot crew generously made available to OI by NOAA. OI's follow-on work investigating the utility of thermal imaging for dispersant application monitoring is being sponsored by ExxonMobil.

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