

SMART Protocol Using Polarized Infrared Cameras

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ABSTRACT

Tier II/III SMART protocol for dispersant use requires placing fluorometers in the water and towing them under a slick by boat. To protect the health of SMART teams, boats typically remain at least 2 miles away from slicks during aerial dispersant treatment. After the spray completes, the SMART boats transit into oil slicks. The time between completion of spray and initiation of SMART monitoring can be > 30 minutes. In 30 minutes, dispersed oil plumes will significantly dilute making them difficult to detect based on fluorescence. Further, we identified a separate issue. That is, oil fluoresces primarily because of the aromatic constituents in the oil and many of the aromatics in oil are at least somewhat volatile and water soluble. Modeling found that these aromatics leach from the oil prior to the application of dispersant. So, even if fluorometers were immediately underneath dispersing oils slicks, the loss of aromatics from the oil challenges SMART. The combination of aromatic leaching and rapid plume dilution limits the ability of the Tier II/III SMART protocol to identify fluorescence signals above the recommended five times background. This means that effectively dispersed oil slicks might not be accurately characterized. What is needed is a monitoring technique that can be applied rapidly and targets some other characteristic of the oil.

Polarized infrared (IR) cameras can measure both the thermal differences between slicks and water and the difference in emissivity when IR energy is emitted by sheens / slicks relative to

water. These cameras can be easily flown on dispersant spray/support planes. They can be used to image oil slicks before, during, and after dispersant spray operations. Effectively dispersed oil slicks will have a significant change in their thermal signature and IR emissivity as the oil transfers from the water surface into the water column. Polarized infrared cameras can be an effective tool for monitoring dispersant operations. They can be deployed continually during slick dispersion providing a longitudinal and synoptic record of the dispersion process.

In this paper, we describe modeling to estimate the water-column concentrations of aromatic hydrocarbons (both mono and polycyclic) from plumes after applying dispersants to an oil slick. In addition, we describe testing of a polarized IR camera at the OHMSETT tank during dispersant testing. We use the modeling to identify the need for modifying SMART and the OHMSETT testing to show that polarized IR cameras can meet this need.

INTRODUCTION

Special Monitoring of Applied Response Technologies (SMART) is a cooperatively designed monitoring program for in situ burning and dispersants (NOAA, 2006). SMART relies on small, highly mobile teams that collect real-time data using portable, rugged, and easy-to-use instruments during dispersant and *in situ* burning operations.

To monitor the efficacy of dispersant application, SMART provides a monitoring protocol for rapid collection of real-time, scientifically based information, to assist the Unified Command with decision-making during dispersant applications. The SMART protocol has three tiers.

Tier I: A trained observer, flying over the oil slick and using photographic job aids or advanced remote sensing instruments, assesses dispersant efficacy and reports back to the Unified Command in charge of a spill response.

Tier II: Tier II is intended to provide real-time data on the effectiveness of dispersants on a treated slick, predominantly with fluorometry. A sampling team on a boat uses a fluorometer to

continuously monitor for dispersed oil one meter under the dispersant-treated slick. The team records and conveys the data to the Scientific Support Team, which forwards it, with recommendations, to the Unified Command. Water samples are also taken for later analysis at a laboratory.

Tier III: By expanding the monitoring efforts in several ways, SMART Tier III is intended to provide information on where the dispersed oil goes and what happens to it.

1. Two fluorometers are used on the same vessel to monitor fluorescence at the center of the treated slick at several water depths, from 1 to 10 meters.
2. A portable water laboratory provides data on water temperature, pH, conductivity, dissolved oxygen, and turbidity.

Tier I visual monitoring is relatively simple and readily done. However, there is concern that visual observations alone do not always provide confirmation that the oil dispersed. Tier II provides a near real-time method using water-column monitoring via a direct reading instrument and water sampling. Tier III follows the Tier II procedures, but collects additional information on the transport and dispersion of the oil in the water column. It is intended to help verify that the dispersed oil is diluting towards background levels. Tier III is simply an expanded monitoring role intended to further meet the needs of the Unified Command.

The SMART guideline recommends that the protocol alone should not be used as an action level for dispersant use and recommends further judgement of a Technical Specialist is required.

Goodman (2003) prepared a critical review of the SMART protocol, where he identified some challenges with implementing SMART Tier II/III to evaluate dispersant effectiveness. The first concern is simply finding the dispersed oil plume under a potentially large slick. This could be an issue, especially for a large slick, because the dispersant spray may have only treated a

small portion of the slick and by the time SMART monitoring vessels reach the slick, the personnel on-board may have no way to identify where the plume is.

In addition, Goodman was concerned that the surface slick motion, which is controlled by a vector sum of wind and currents, is somewhat disconnected from the motion of the plume, which is strictly controlled by the currents. In most open-ocean systems, the surface currents controlled by the wind can be offset 90° or more from currents just below the surface because of Eckman's Spiral.

Trudel et al. (2009) reviewed the SMART dispersant effectiveness protocol as well. They conducted a stakeholder workshop to recommend revisions to SMART based on field experience. They concluded that SMART monitoring using a fluorometer, even in the controlled OHMSETT test basin, resulted in high variability in fluorescence intensity between the dispersant-treated and control slicks and was a poor indicator of effectiveness and recommended that a combination of fluorometry and oil-droplet size measurement provided a better indicator.

The purpose of SMART monitoring is to assist the Unified Command with decision making regarding dispersant effectiveness and continued dispersant use during a response. As described, the current method of employing subsurface fluorometers to determine if dispersant application has been effective faces the practical realities and difficulties highlighted by Goodman (2003) and Trudel et al. (2009). In addition, we are concerned about the fluorometer itself.

Fluorometers work by passing UV light through water to elicit a fluorescence response from aromatics associated with the dispersed oil. The SMART protocol (NOAA, 2006) provides guidance stating that dispersants are considered effective if the fluorometers measure fluorescence intensities that are five times or greater compared to the readings at the untreated oil slick and the difference between the untreated slick and background (no oil). This approach

relies on the implicit assumption that aromatics are still sufficiently present in a slick when dispersant is applied and present under the slick after dispersion. There are several potential issues with these two assumptions.

If dispersants are an oil spill response option, it generally takes many hours after the spill to get spray equipment in place in addition to the time required to get stakeholder approvals. Thus, most oil slicks will spend 12-to-24 hours on the water surface before application of dispersants. During this time, soluble low-molecular weight aromatics, which are often the most predominant aromatic components in crude oil (Wang et al., 2014), will be preferentially lost from the oil slick through evaporation and dissolution within a few hours after spilling to the sea surface (Stiver and Mackay, 1984; Atlas, 1995; Gros et al., 2014). Oil resulting from a blowout in deep water may lose a significant fraction of the soluble aromatics even before they reach the surface. Brown et al., (2011) collected surface oil samples during the Deepwater Horizon incident in 2010 and found that the oil rapidly weathered with substantial loss of 2- and 3-ring aromatics.

Forth et al., (2015) characterized fresh Macondo crude oil, two surface slick oils collected during the Deepwater Horizon spill, and one artificially weathered oil. They found that the fresh oil had BTEX concentrations approaching 2%. The parent and alkylated naphthalenes made up about 0.5% of the fresh oil. The artificially weathered oil contained no BTEX but the naphthalenes were actually concentrated relative to the fresh oil. Further, many of the larger PAHs were concentrated in the artificially weathered oil. In contrast, the field collected samples (so called Slick A from the CTC barge and Slick B from the Juniper barge) had no BTEX and very little naphthalene. Further still, the larger PAHs in the field collected samples were all significantly reduced in concentration compared to the fresh Macondo oil. The differences between the artificially weathered oil and the field collected samples suggest that dissolution of

the PAHs (particularly the naphthalenes that had at least a 90% loss in both field slicks) is an important loss mechanism considering the artificially weathered oil only underwent evaporation on a hot plate. Photo-oxidation of the PAHs in the surface slicks could also account for at least a portion of their loss.

Whatever the mechanism, loss of the aromatics from oil spilled to the ocean surface and oil released from a blowout results in surface slicks losing a significant amount of the group of compounds that provide the fluorescence signal SMART needs to identify whether or not the slick is dispersing. Artificial weathering through evaporation does not appear to represent the real-world aromatics loss.

Further, surface oil and oil dispersed or dissolved below the surface are controlled by different dynamics. Surface oil is controlled predominantly by the wind. Once oil disperses below the surface into the water column, different dynamical processes dominate (French-McCay, 2004). This then results in surface and subsurface oil moving relative to each other independently. Because SMART field teams during the Deepwater Horizon spill were required remain up to 2 miles away from dispersant spray operations for safety (Parscal et al., 2014), there can be a delay of 30 or more minutes after dispersants are applied before subsurface fluorometry measurements begin, the dispersed subsurface oil is likely no longer underneath any residual surface slick while sampling occurs. In addition, due to turbulence and entrainment processes, the subsurface oil continues to be mixed and transported both horizontally and vertically resulting in a steady reduction in concentration through dilution. This combined with aromatic dissolution / evaporation suggests that the ability to locate and measure fluorescence intensity five times greater than an untreated slick even from an effectively dispersed oil slick is challenged.

The intent of the SMART protocol is clear. However, what is not as clear is the effectiveness of the water-column monitoring requirement. Our concern is that the very likely inability of SMART to ever find signal intensity five times background could confuse decision making. Numerical modeling work presented in the following section suggests that Tier II and III water-column monitoring with fluorometry is likely to not result in sufficiently high fluorescence signals. Thus, alternative monitoring techniques may be needed to fulfill the intent of the SMART Tier II and III monitoring. As will be discussed further, a long-wave infrared polarimetric camera can provide robust monitoring of dispersive effectiveness.

NUMERICAL MODELING MODEL SETUP

We used the 3-Dimensional SIMAP Model (Version 7.0.3.0) for this analysis. The model is developed, distributed, and supported by RPS, Inc. (French-McCay, 2004). We chose SIMAP because of its ability to predict water concentrations of aromatic hydrocarbons (both mono and polycyclic) resulting from oil spills. We assumed the spill occurred under conditions consistent with the Gulf of Mexico in summer. To simplify analysis, we used invariant winds and currents (5 knots to the north and 3 knots to the west, respectively) to force the model. The same release time and model forcing was utilized in all of the model runs.

The location of the release was arbitrarily selected in open water approximately 205 km south of the Mississippi River. We assumed the sea surface temperature was 75°C. The oil utilized in the analyses was high volatility Alaska North Slope (ANS) crude oil. The modeled oil contained approximately 60% aliphatics, 28% aromatics, and 12% polars (asphaltenes and resins). The aromatic content was 33% 1 ring, 27% 2 ring, and 40% 3+ ring (French et al., 1996). Figure 1 shows a graph with composition of the crude oil. We selected ANS to represent

an oil with a high potential to contribute aromatics to the water column. In comparison, the fresh Macondo oil spilled during the Deepwater Horizon incident was found to have much lower aromatic content (74% aliphatics, 16% aromatics, & 10% polars; Reddy et al., 2012).

Three slick thickness scenarios were modeled (0.2 mm, 0.5 mm, and 1.0 mm) and model runs lasted 2 days. To maximize the potential for aromatics in the water column, the dispersant was assumed to be 100% effective (i.e., any portion of the slick that was treated with dispersant was assumed to fully disperse). Further, we assumed a conservative 6-hour period between spill initiation and start of spray operations and spray operation lasted 1 hour. We modeled a second 1-hour spraying operation at hour 12. We compared predictions of aromatic concentrations emanating from dispersant-treated slicks to slicks we modeled with no dispersant application.

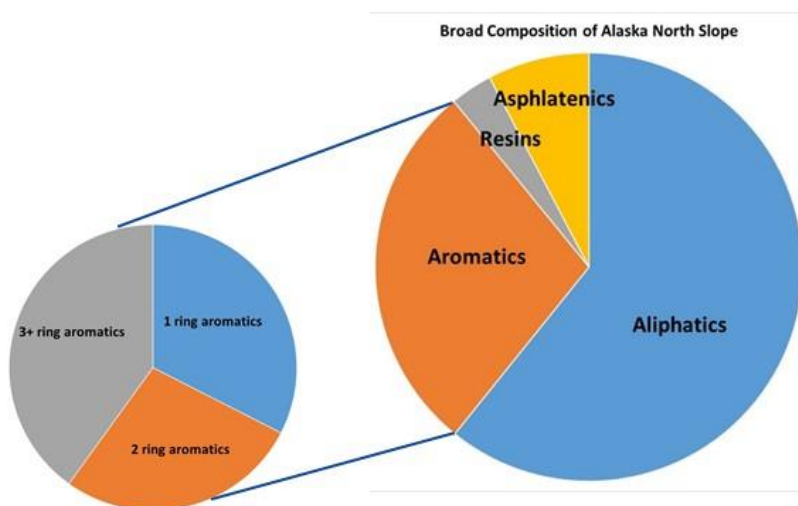


Figure 1: Composition of the Alaska North Slope crude oil used for this study.

SCENARIOS

The volumes released to produce the appropriate slick thickness was as follows:

1 mm slick thickness – 1000 m³ over 1 km²

0.5 mm slick thickness – 500 m³ over 1 km²

0.2 mm slick thickness - 200 m³ over 1 km²

The outputs provided by the SIMAP model include a trajectory and mass balance over time. SIMAP also produces information on water concentrations of aromatics and total hydrocarbons. The water concentrations can be determined at point locations over time and by maximum concentrations in a water layer over time. The data we report here were the model predicted highest total aromatic concentration at any location at each 1 hour model time step.

RESULTS

Figures 2 through 4 show plots of the maximum total water column aromatic concentration anywhere in the water column at each 1 hour model time step generated after spraying dispersant on the three slick scenarios for the duration of the 48-hour model runs. As can be seen, the model predicted an immediate spike in aromatic concentration for each slick thickness and the magnitude of the spike depended on the initial slick thickness, as expected. At ≥ 6 hours, when the first dispersant spray started, there is very little difference in aromatic concentration and certainly not five times difference. The 0.2 mm slick (Figure 2) shows a difference in aromatic concentration after 12 hours but this is likely due to the low concentrations in general and the random method that the model uses to simulate ocean turbulence. The randomness can be seen in Figure 4 (1.0 mm slick) where the untreated slick actually had a higher aromatic concentration than the treated slick after the dispersant spray at 6 hours. The consistent finding from the modeling is that the slicks rapidly lose aromatics (either through volatilization or dissolution) prior to the start of dispersant spray operations. This should not be unexpected because dispersion does happen regardless of whether or not dispersants are applied. The difference is that untreated slicks form unstable dispersions of relatively large droplets that rapidly resurface. This repetitive dispersion / resurfacing action provides conditions for semi / slightly soluble components to dissolve into the water. The droplets of oil provide greater surface area for

dissolution compared to the surface slick, and the motion of the surface slick relative to the currents avoids buildup of aromatics in the water that would reduce dissolution rates.

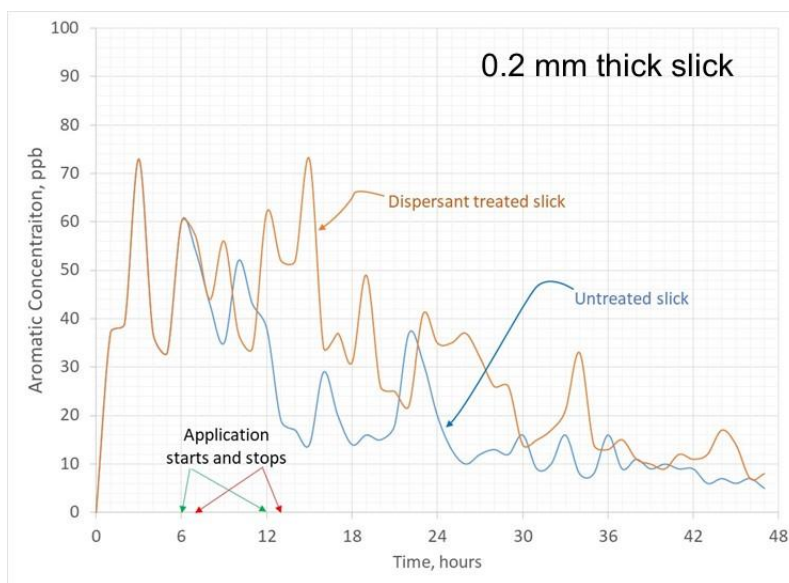


Figure 2: SIMAP predicted maximum total aromatic concentration at any location in the dispersed oil plume at each 1-hour model time step on the 0.2 mm slick both with and without dispersant treatment.

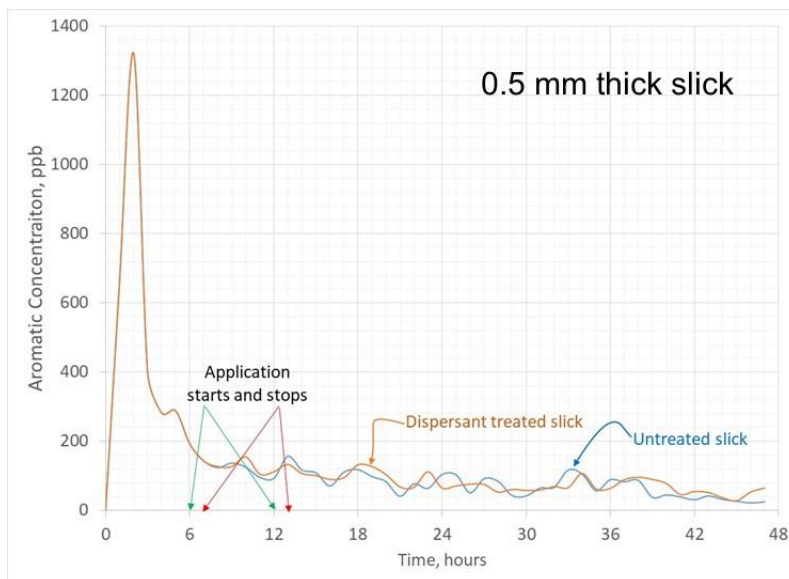


Figure 3: SIMAP predicted maximum total aromatic concentration at any location in the dispersed oil plume at each 1-hour model time step on the 0.5 mm slick both with and without dispersant treatment.

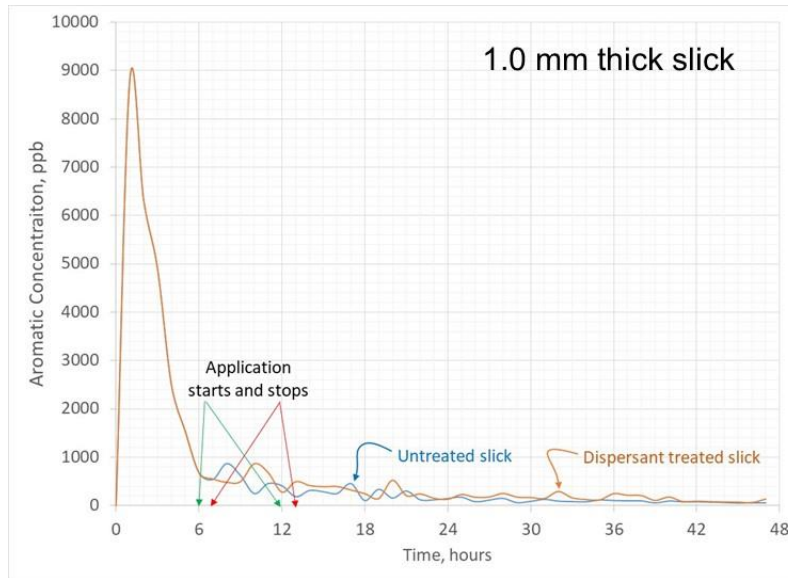


Figure 4: SIMAP predicted maximum total aromatic concentration at any location in the dispersed oil plume at each 1-hour model time step on the 1.0 mm slick both with and without dispersant treatment.

Figure 5 shows an example from the model where the surface oil has migrated almost completely off of the subsurface aromatic plume released by the oil. This demonstrates the challenge SMART teams will have of simply encountering the dispersed oil plume if they sample under residual surface oil.

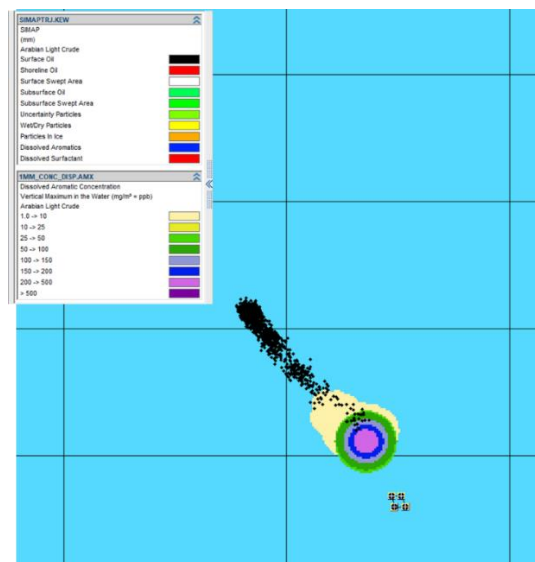


Figure 5: Model simulation showing where the surface oil (black dots) has migrated almost completely off of the subsurface aromatic plume released by the oil.

MONITORING DISPERSANT EFFECTIVENESS WITH A POLARIMETRIC SENSOR

Polaris Sensor Technologies produces the Pyxis[®] camera that captures both the thermal and polarization IR content of a scene [www.polarissensor.com]. It is a compact instrument that is <2 in³ and 83 grams. Pyxis[®] operates in the long wave infrared (LWIR) portion of the spectrum, thus it images the infrared energy emitted and/or reflected from a surface. Polarization, along with intensity and wavelength, is a fundamental aspect of light, and the three entities are independent of each other. This means that two beams of light, with the same intensity and wavelength (or spectral distribution), can have very different polarization states. An object can therefore be completely invisible in a standard IR intensity image, while simultaneously exhibiting a strong polarimetric signature.

Pyxis[®] can differentiate between oil and water as a result of differences in their optical properties. In particular, water has minimal long wave infrared (LWIR) linear polarization (random scattering), while surface oil has a measurable component of LWIR linear polarization. Furthermore, because the polarization signal is based on emitted energy, Pyxis[®] can be used for oil detection both day and night. Of particular value for the SMART protocol, Pyxis[®] can differentiate between oil on the surface and oil dispersed just beneath the water surface that is typically difficult to distinguish visibly or with other sensors. For example, an oil slick that is being effectively dispersed will begin to disappear from the surface as it is dispersed by wave energy. Once oil has left the surface as a result of dispersant application, even if the oil is only millimeters deep in the water column, the optical characteristics of the surface are that of water. Thus, the polarimetric IR response will change from that of oil to that of water, giving a clear indication that oil is dispersed or is dispersing.

Initial testing of Pyxis[®] was conducted at Ohmsett from 2016 to 2018. The testing confirmed the ability of a LWIR polarimeter to robustly detect oil on water under a wide variety of

conditions. Figure 6 shows an example from an overcast day with breaking waves. The oil is clearly visible in the visible image (upper left panel) primarily due to the high contrast provided by the light-colored bottom of the Ohmsett wave tank. The oil is virtually undetectable in the thermal intensity image (upper right panel) due to the overcast skies and the presence of breaking waves. The oil is very clearly delineated in the polarimetric image (lower left panel) and the eTherm image (lower right panel), which is a fusion of the polarimetric signature onto the thermal intensity image. Many additional tests between 2016 and 2018 under many different conditions yielded similar results, namely that the contrast between oil and water in the polarimetric image was significantly greater than in the thermal intensity image. Thus, the polarimetric sensor consistently provides a more robust oil on water detection capability than the thermal intensity signal.

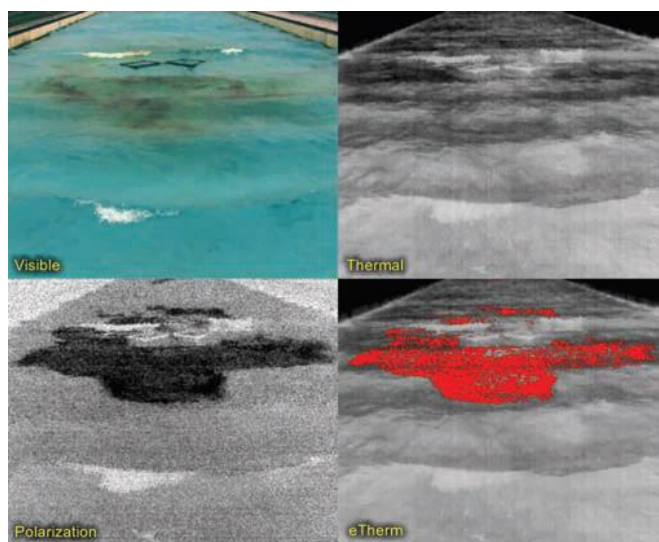


Figure 6: Top left panel: visible. Top right panel: thermal intensity. Lower left panel: polarization. Lower right: eTherm, a fusion of the polarization signature onto the thermal intensity image.

The ability of the Pyxis[®] to image and characterize dispersant effectiveness was tested at Ohmsett in November 2019. For these tests, ten gallons of Thunderhorse light crude oil (API Gravity of 32; Viscosity of 15 cSt at 20°C) was poured onto the water surface from buckets

under quiescent conditions after which a backpack sprayer was used to spray Corexit[®] 9500 dispersant onto the surface oil at a ratio of 1 to 20 (0.05 gallons of dispersant total). The wave maker was started and Pyxis[®] imaged the slick for approximately 20 minutes during the buildup and development of quasi-steady state wave breaking conditions.

Pyxis[®] was mounted in the crow's nest of the main bridge at an elevation above the water of about 30 feet and oriented to be looking down at the oil/water. Pyxis[®] was clearly able to image the oil on the surface under quiescent conditions. Once Corexit[®] 9500 was applied, the oil began to rapidly disperse under wave breaking conditions. Figure 7 and 8 show images as dispersion progressed for the dispersant-treated slick and the untreated slick, respectively. Pyxis[®] was able to capture the transition as oil was dispersed from the surface into the water column. As the oil dispersed beneath the surface, the signature of the oil was lost at the surface and the polarimetric signal became that of water.

Figure 9 shows a graph generated by counting the red eTherm pixels generated by the Pyxis camera as the Ohmsett experiment progressed for both the dispersant-treated slick and the untreated slick. This graph clearly shows the rapid loss of surface oil as the dispersion progressed. In fact, at 3 minutes the Pyxis eTherm image found essentially zero surface oil or sheen. Compare this to the pixel count of the untreated oil slick that actually increased over the same time period.

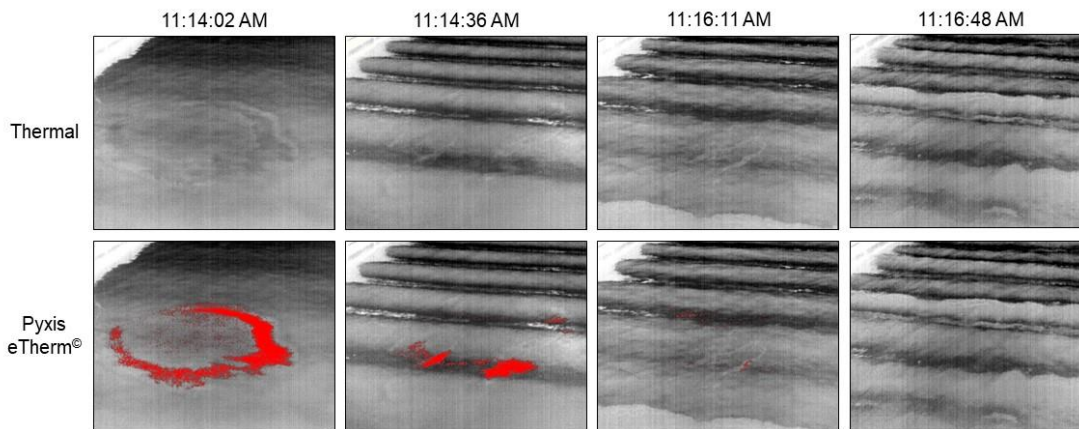


Figure 7: Time series of the dispersion process for **dispersant-treated** Thunderhorse crude as imaged by IR only (top row) and by the Pyxis eTherm[®] system (lower row). The eTherm[®] is a fusion of the polarization signature onto the thermal signature.

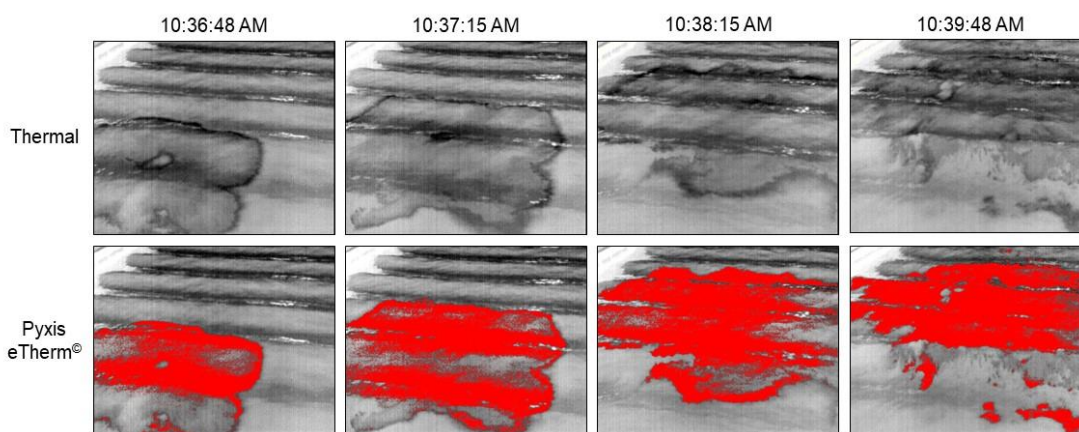


Figure 8: Time series of the **untreated** Thunderhorse crude as imaged by IR only (top row) and by the Pyxis eTherm[®] system (lower row). The eTherm[®] is a fusion of the polarization signature onto the thermal signature.

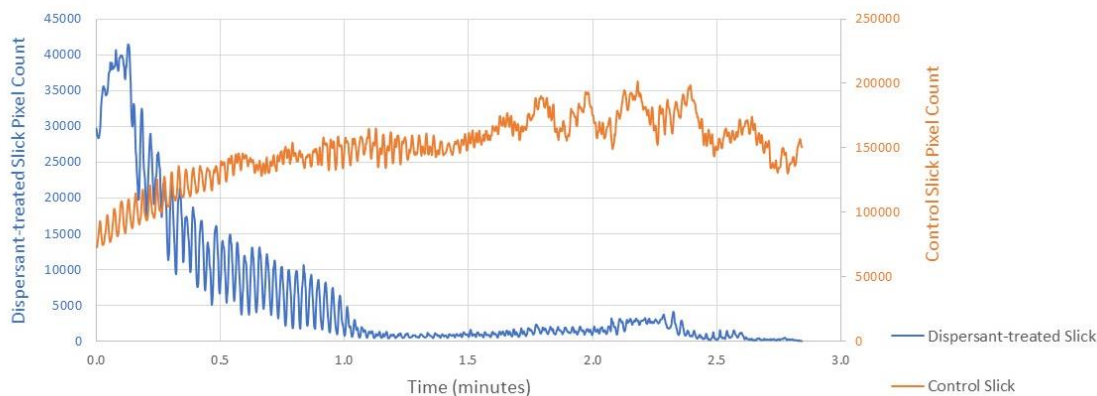


Figure 9: Dispersion process quantification generated by counting the eTherm red pixels over time for both the dispersant-treated slick and the untreated slick.

SUMMARY & CONCLUSIONS

We used the SIMAP oil spill fate model to evaluate the ability of the SMART protocol to identify fluorescence intensities under a dispersant-treated oil slick that are five times greater than under an untreated oil slick. We did this by predicting the maximum concentration of aromatics (both mono and polycyclic) anywhere in the dispersed oil plume at each time step over 48 hours. We modeled slicks with thicknesses between 0.2 and 1.0 mm. We chose Alaska North Slope crude oil for the modeling because it has a high aromatic content. We used conservative assumptions to maximize aromatic concentrations in the dispersed-oil plume by forcing 100% dispersion and initiating dispersant spray only 6 hours after the start of the spill.

Based on the modeling, it would not be possible to meet the SMART guidance of five times fluorescence intensity under the dispersant-treated slick even if the measurement operations occurred immediately after dispersant-spray operation stopped and happened to be in the location with highest aromatic concentrations. This was the case for all three slick thickness scenarios modeled. This finding was obtained because the volatile and soluble aromatics in the surface slicks had mostly leach from the oil prior to dispersant application.

A second effort on this project was to evaluate the potential of an aerial polarized infrared camera to substitute for the fluorometer measurements currently prescribed in the SMART protocol. We conducted dispersant effectiveness tests in the Ohmsett test basin using a polarized IR camera produced by Polaris Sensor Technologies, Inc. (the Pyxis[®] camera). We found that the Pyxis[®] camera qualitatively captured the very rapid dispersion process to provide image documentation. In addition, we used a numerical algorithm to count image pixels identified by the Pyxis[®] camera that had either thicker surface oil or sheen. Comparing these pixel counts over time allowed for a quantification of the dispersion process. Both the qualitative images and graphs of the pixel counts can be used to support the efficiency of dispersion.

We conclude that the rapid loss of aromatics from surface slicks, even one with high initial aromatic concentration, challenges the ability of a fluorometer to assess field dispersant effectiveness and could result in confused decision making during a response. In addition, we concluded that the Pyxis[®] camera mounted in an aircraft could provide a method of monitoring dispersion both qualitatively and quantitatively more rapidly and safely than the current method of deploying monitoring teams and equipment by boat.

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