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# Characterization of surface oil thickness distribution patterns observed during the Deepwater Horizon (MC-252) oil spill with aerial and satellite remote sensing

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ABSTRACT

Knowledge of the spatial distribution of oil thickness patterns within an on-water spill is of obvious importance for immediate spill response activities as well as for subsequent evaluation of the spill impacts. For long-lasting continuous spills like the 2010 3-month Deepwater Horizon (DWH) event in the Gulf of Mexico, it is also important to identify changes in the dominant oil features through time. This study utilized very high resolution (≤5 m) aerial and satellite imagery acquired during the DWH spill to evaluate the shape, size and thickness of surface oil features that dominated the DWH slick. Results indicate that outside of the immediate spill source region, oil distributions did not encompass a broad, varied range of thicknesses. Instead, the oil separated into four primary, distinct characterizations: 1) invisible surface films detectable only with Synthetic Aperture Radar imaging because of the decreased surface backscatter, 2) thicker sheen & rainbow areas (<0.005 mm), 3) large regional areas of relatively thin, “metallic appearance” films (0.005–0.08 mm), and 4) strands of thick, emulsified oil (>1 mm) that were consistently hundreds of meters long but most commonly only 10–50 m wide. Where present within the slick footprint, each of the three distinct visible oil thickness classes maintained its shape characteristics both spatially (at different distances from the source and in different portions of the slick), and temporally (from mid-May through July 2010). The region over the source site tended to contain a more continuous range of oil thicknesses, however, our results indicate that the continuous injection of subsurface dispersants starting in late May significantly altered (lowered) that range. In addition to characterizing the oil thickness distribution patterns through the timeline of one of the world's largest oil spills, this paper also details the extension of using high resolution aerial imagery to calibrate medium resolution satellite data sources such as USA's Thematic Mapper (30 m) to provide larger-scale spatial views of major spills, and discusses implications for utilizing such data for oil spill characterizations and spill response.



## 1. Introduction

Timely information about the spatial extents of an at-sea oil spill and the distribution of oil thickness patterns within it is very important for planning and managing immediate response activities. A common rule-of-thumb for marine oil slicks is that 90% of the oil exists in 10% of the area. Traditional aerial visual observations by trained observers cannot distinguish oil thicker than the black oil that forms when slicks become approximately 0.1 mm thick.

Efficient allocation of response resources using vessels, booms and skimmers depends on knowing which parts of the slick contain the most recoverable oil. Likewise, successful in-situ burning and aerial or vessel-based dispersant application planning requires knowledge of both the relative thickness and weathering/emulsification states of the potential oil targets. This intelligence is traditionally obtained through visual observations from fixed-wing and rotary aircraft, however, these are being increasingly augmented by satellite and aerial remote sensing.

The majority of marine oil spills are of the “batch” variety where a finite amount of petroleum is released during an event lasting a few hours (e.g. from a ruptured tank vessel or pipeline that is quickly shut down). The released oil undergoes evaporation, drift due to currents and winds, dispersion from waves, entrapment of water droplets (emulsification), UV and biological degradation, etc. that affect its spatial extents and thickness patterns. Over time, oil from batch releases tends to reflect the same advanced weathering parameters. “Continuous” spills, where fresh oil is released over long periods, are very uncommon relative to “batch” spills. Although the same weathering and advection parameters affect the discharged petroleum in both types of spills, the continuous discharge spill differs in that it usually lasts for a significantly longer time period, with both freshly discharged oil and

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extensively weathered oil being simultaneously present within the slick through the event. The spatial distribution of thickness and weathering state of oil features from a continuous spill and any potential temporal changes in such patterns through the extended spill period has not previously been studied. Such knowledge could advance better preparedness for response strategies in future large spills.

On 20 April, 2010 the Deepwater Horizon (DWH) oil rig exploded in the Gulf of Mexico and continued to spill oil into the sea until 15 July 2010 when the wellhead was finally capped. The spill was the largest accidental spill and second largest in history, exceeded only by the Mina al Ahmadi spill during the first Gulf War in 1991 (NOAA, 2011). Due to the size of the spill, traditional visual aerial surveys could not provide complete coverage of the spill area on a daily basis. As part of the response, multiple remote sensing technologies and sensors were mobilized. The most frequently utilized data during the response were provided by Synthetic Aperture Radar (SAR) sensors, and Side-Looking Airborne Radars (SLARs) flown by Transport Canada and Icelandic Coast Guard, which were used to render the full extents of the oil slick (regardless of thickness) and their changes in time. Very high resolution multispectral visible and thermal infrared aerial imagery flown by USA's Ocean Imaging Corporation (OI) was acquired near-daily over selected parts of the slick and was used to provide, for the first time, operational maps of oil thickness distributions over the imaged areas (Svejkovsky et al., 2012A). (Several other aerial imagers, both federal and corporate, collected data primarily for research, test or baseline documentation purposes but were not deployed on a routine, daily basis and did not provide the imagery to aid daily response activities.) Limited numbers of cloud-free images were also collected with various commercial high resolution optical satellites such as Digital Globe's WorldView-2 (WV-2), and medium-resolution satellites such as France's SPOT and USA's Landsat Thematic Mapper (TM). Coarse resolution satellite imagers such as USA's Moderate Resolution Imaging Spectroradiometer (MODIS) aboard National Aeronautics and Space Administration's (NASA's) Aqua and Terra satellites provided near daily coverage of the spill in the visible, near-IR and thermal-IR bands at resolutions of 255–1000 m.

The volume of remote sensing data collected from these sources and their daily application during the lengthy spill represents to-date the most intense utilization of remote sensing technologies during an oil spill incident. Although all the aerial and very high resolution satellite image sources captured only portions of the extensive spill slick on a particular day, they are sufficiently varied in space and time to provide representative data with very fine detail from different parts of the slick area throughout the event timeline. This paper describes results of a study utilizing this unique high and medium resolution imaging archive to characterize the spatial and temporal distribution of oil thickness patterns within the DWH slick, and effects on those distributions by major natural (Tropical Storm Alex) and anthropogenic (subsurface dispersant injections) events during the 3-month spill.

## 2. Materials and methods

### 2.1. Principles of crude oil on water characterization

The presence of a floating crude oil film alters the sea surface's reflectance, emittance and radar backscatter characteristics in the visible-nearIR, thermal IR, and microwave portions of the electromagnetic spectrum respectively. The alterations provide a means to detect and in some cases quantify the presence and thickness of the oil film with various aerial and satellite remote sensing instruments. Numerous review articles summarize the underlying principles (e.g. Brekke and Solber, 2005; Jha et al., 2008; Fingas and Brown, 2011; Leifer et al., 2012) and, in the last few years, the volume of both laboratory and operational research on the subject has been steadily increasing. For the purposes of this study we summarize here only the core properties that allow easily verifiable distinction between crude oil sheens, thin and thick fresh oil films, and emulsified oil accumulations with combined use of SAR, multispectral visible-nearIR, and thermal IR sensors.

Crude oil spilled on open water tends to spread out very quickly. The thinnest layers are referred to as "sheens". For our purposes, we adopt NOAA's definition of this term, which encompasses thicknesses from the thinnest, near-monomolecular, to grey/silver, to rainbow-appearing films (NOAA, 2012). This category thus includes films up to approximately 5 μm in thickness (Bonn Agreement, 2007, NOAA, 2012). The presence of sheens tends to increase reflectance in the ultraviolet range (Grüner et al., 1991). Because even very thin sheens suppress capillary waves on the sea surface, they suppress the microwave backscatter return from SAR sensors, making such instruments very sensitive to oil film detection (Gade et al., 1998; Minchew et al., 2012). All sheens are transparent in the visible wavelength region and, except for the silver and rainbow-appearing ones, tend to alter the underlying water color to a minimal degree, making their detection with visible-wavelength sensors a function of the instrument's sensitivity and signal-to-noise ratio. As is discussed below, during the DWH spill OI's 12-bit aerial sensor was able to detect "silver" and thicker sheens (i.e. approximately >0.2 μm), primarily due to increased reflectance (relative to surrounding water) in the 451 nm channel. The 8-bit TM satellite sensor, on the other hand, could reliably detect only the thickest rainbow sheens. Sheens also tend to be undetectable for the most part in thermal IR imagery. Their thermal detection is dependent on registering sufficient negative thermal contrast (due to petroleum's lower-than-water emissivity) to reliably separate them from surrounding water areas. Laboratory and open-sky test tank experiments have shown that even with very sensitive instruments, the minimum detectable oil film thickness is in the 10–20 μm range (Belore, 1982; Hurford, 1989; Svejkovsky et al., 2012A; Svejkovsky and Muskat, 2009). The thicker rainbow sheens tend to become detectable (both during day and night) by showing a decidedly cooler-than-surrounding-water signature.

Petroleum films thicker than sheens tend to appear, in the visible portion of the spectrum, as a combination of the underlying water color, sky reflectance and progressively more of the oil's dark brown/black "true color". The color characterization of oil films just thicker than sheens has been subject to debate. Through its Bonn Agreement Oil Appearance Code (BAOAC), the European Union introduced the term "metallic" for oil films in the thickness range of 5–50 μm (Bonn Agreement, 2007). This terminology has also been more recently adopted by NOAA (NOAA, 2012). A distinguishing feature of metallic oil films is that they are transparent, making it possible to see submerged objects through them. Because of the transparency, a significant portion of the reflectance profile in the visible wavelengths parallels the profile of the surrounding water reflectance, a distinguishing feature in multispectral classification analysis. In thermal IR, the metallic thickness range films exhibit a negative thermal contrast signature, believed to be primarily due to the petroleum's lower emissivity relative to water (Shih and Andrews, 2008). The negative contrast can be >1 °C and decreases with increasing thickness (Svejkovsky and Muskat, 2009). In SAR data the metallic thickness films are readily discernible due to their backscatter suppression, but are not distinguishable from sheens.

Crude oil films thicker than approximately 50 μm tend to progressively attain more of their natural dark brown/black color as less light gets reflected back through the film from the underlying water column. The Bonn Agreement refers to these thicknesses as "Discontinuous True Colors" (50–200 μm) and "True Colors" (>200 μm), and NOAA uses "Transitional Dark (True) Color" and "Dark (True) Color" labels. In the visible range crude oil films become completely opaque at approximately >100 μm and no longer change their reflectance characteristics in multispectral imagery (Svejkovsky et al., 2008). They generally exhibit significantly reduced reflectance from the surrounding water signal, particularly in the blue and green wavelength range. During nighttime with no solar heat input, crude oil films thicker than 50 μm were found to retain a negative thermal contrast during summer air temperatures, which increased with increasing film thickness