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Multi-frequency and polarimetric quantitative analysis of the Gulf of Mexico oil spill event comparing different SAR systems

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ABSTRACT

Synthetic aperture radar (SAR) images were acquired over the Deepwater Horizon spill's main slick with a number of different instruments during response to the catastrophic accident in 2010. These included instruments operating in different microwave frequency bands (L-C-X band), and, for TerraSAR-X and COSMO-SkyMed, more than one acquisition system operating in the X-band. In this work, for the first time the diverse SAR data acquired over the Deepwater Horizon spill have been compared and quantitatively analyzed with the goal of determining the different capabilities of the last generation SAR systems in the analysis of this important test case. Using the nearest acquisitions in time over the same areas, backscattering coefficients and polarimetric features, when available, have been evaluated. The derived information and comparison of sensors is discussed, in particular taking into consideration the Noise Equivalent Sigma Zero (NESZ) value characterizing each instrument. Although, as expected, an increase of the damping ratio values is noted at higher frequencies, the best slick discrimination capability has been obtained with the L-band UAVSAR sensor, characterized by a more effective NESZ value, while the satellite SAR sensors are shown to have in some cases significant noise contamination to polarimetric parameters. Anomalous behavior at X-band measurements has been also registered and discussed. Through the analysis of all the available data an evaluation of the impact of low noise SAR for oil characterization in the considered context is provided.

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1. Introduction

The increasing demand for petroleum has led to a need to discover and exploit new oil fields, which are often located in offshore areas. For example, Italy currently has nine active offshore platforms, an additional nineteen areas authorized for investigations, and another forty-one areas under evaluation for obtaining authorization (Zampetti, Ciafani, Di Matteo, & Minutolo, 2012). This gives sixty potential drilling sites in addition to the nine already active, effectively covering 29,700 km^2 of sea area. The expanded drilling is supported by new drilling techniques and technologies that now make it possible to drill in deep water, avoiding to some extent the contamination of the marine environment. However, as the Deepwater Horizon accident showed, the risk of accident is still present, so we need tools for monitoring drilling sites to protect the marine ecosystem and nearby coastal areas. Among the available remote sensing instruments, Synthetic Aperture Radar (SAR) products are commonly used to detect oil pollution. The great advantage of SAR over optical instruments, in addition to actively generating its own energy source instead of relying on surface reflectance or emissivity, is that radiation in the microwave region of the electromagnetic spectrum is not appreciably affected by atmospheric water, so the backscattered pulses are detectible except during very heavy storm events. SAR, being an active sensor, can acquire data equally well in day or night, and has large area of coverage and short revisit capabilities, ensuring continuity of observation and analysis for tracking oil releases. SAR is an effective instrument for slick detection primarily because of the backscatter sensitivity to surface roughness at the scale of the radar wavelength, which lies in the short gravity-capillary wave portion of the ocean wave spectrum. An oil film damps small-scale waves through increased viscosity of the surface layer, which manifest as dark areas in a SAR image (Alpers & Hühnerfuss, 1988). For thick oil layers, part of the signal reduction can be ascribed to the dielectric constant difference between the oiled surface and clean water based on the equations for electromagnetic scattering (Minchew, Jones, & Holt, 2012). This opens up the possibility of oil characterization based on the dielectric properties of the surface slick, which vary greatly depending upon the relative amounts of oil and water in the surface layer. However, careful interpretation is required because low winds, currents, rain cells or natural slicks can also cause dark areas (Reed et al., 1999), and because the instrument noise can be comparable to or exceed the backscattered signal from the slick surface.

During the last decades, research activities have focused on developing SAR techniques to distinguish oil spills from look-alikes with a high

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degree of accuracy. The most common approach makes use of statistical algorithms, e.g., a Bayesian classifier (Solberg, Brekke, & Husøy, 2007; Nirchio et al., 2005) based on the backscatter intensity variation between dark spots and surrounding sea surfaces. In a first stage, the classifier learns patterns from training examples including oil and look-alikes, creating a decision rule based on probability. The second stage consists in applying the obtained decision rule to classify unknown dark spots and measuring the accuracy of the result. Similarly, the use of machine learning methods, i.e., neural networks (Del Frate, Petrocchi, Lichtenegger, & Calabresi, 2000) or fuzzy logic techniques (Karathanassi, Topouzelis, Pavlakis, & Rokos, 2006) have been demonstrated to provide valid classification results. Recently, the availability of coherent dual-polarization and quad-polarization SAR sensors has made it possible to study methods of detection and characterization based on polarimetric decomposition (Schuler & Lee, 2006) or the correlation between co-polarized channels (Skrunes, Brekke, & Eltoft, 2014).

Although many efforts have been carried out to improve automatic oil spill detection (Garcia-Pineda et al., 2013) and, hence, to optimize the binary decision problem of differentiating real oil spills from look-alikes, multi-frequency quantitative analysis of the variables of interest such as the damping ratio or the backscattering coefficient of the dark spot and its surroundings has been addressed less often, particularly comparing the capabilities of different satellite SAR systems using data acquired over the same spill and at the same time. The earliest work was by Gade et al. (1998a and 1998b), who presented results obtained using SIR-C/SIR-X and HELISCAT systems. More recent studies have considered the last generation spaceborne instruments, but no more than two bands and two sensors have been examined (Skrunes, Brekke, & Eltoft, 2012; Latini, Del Frate, & Jones, 2014; Skrunes, Brekke, Eltoft, & Kudryavtsev, 2015). For comparative studies of different frequency instruments, near concurrent observations of the same area are needed because of the strong dependence of the backscatter on wind, sea state, and material weathering. The research goal of this paper is to provide a more comprehensive contribution to a multi-frequency, quantitative analysis of radar returns under comparable spill conditions considering more SAR systems, additional frequency bands, and a broader range of incidence angles than previously studied. The comparison uses data acquired during the Deepwater Horizon oil disaster in the Gulf of Mexico, a terrible environmental catastrophe that provided a unique opportunity to study a thick, spatially extensive slick using concurrent acquisitions from last generation SAR sensors. In this study, for the first time a comparative quantitative analysis considering five different instruments (four mounted on spaceborne and one on airborne platforms) and three different frequency bands focusing on the same oil dispersion event with near temporal acquisitions has been performed. The considered SAR instruments are Envisat ASAR (C-band), TerraSAR-X (X-band), COSMO-SkyMed (X-band), Radarsat-2 (C-band), and NASA's airborne UAVSAR system (L-band). Moreover, the analysis is supported by meteorological data collected for each imaging date from stations located near the spatially extensive spill.

The sea surface is a very dynamic environment in which the wind speed, wind direction, ocean currents, and wave interactions can vary rapidly. Moreover, oil on the sea surface is exposed to weathering processes that change its chemical characteristics (Fingas & Fieldhouse, 2012). The aforementioned aspects introduce a degree of variability that must be taken into account to evaluate the potential of SAR different sensors and analysis techniques. Our approach involves an analysis of radar backscatter from oil on the sea surface and clean seawater around it, in order to evaluate the detection capabilities and the signal levels with respect to the Noise Equivalent Sigma Zero (NESZ) of the specific sensor. Additionally, we take advantage of the full polarimetric capabilities available from some of the SARs to evaluate the potential of different sensors' polarimetric data for slick detection or characterization. Using the available polarimetric data sets, we compare the results retrieved applying the Cloude-Pottier decomposition technique to polarimetric products acquired in different bands and for which backscatter from the slick had values above the noise level in both co-polarized (HH, VV) and cross-polarized (HV) returns. Although the Deepwater Horizon oil disaster has been widely investigated (Migliaccio, Nunziata, Montuori, Li, & Pichel, 2011; Zhang, Perrie, Li, & Pichel, 2011; Liu et al., 2011), the importance of the NESZ has been little addressed in SAR slick characterization literature until relatively recently when Minchew et al. (2012) pointed out its importance in evaluating multi-polarization and polarimetric parameters. This work is the first to compare data from the UAVSAR instrument used by Minchew et al. (2012) with four different satellite SAR systems, and to include a cross comparison of the quad-polarization intensity and polarimetric performance between UAVSAR and the lowest NESZ of the satellite SARs, Radarsat-2, and an evaluation of the capabilities of other SARs evaluated based upon their multi-polarization intensities.

Section 2 of this paper introduces the characteristics of oil on sea surface and the weathering processes that act on it, along with the physical mechanisms underlying oil detection by SAR instruments. The analysis approach and techniques utilized are presented in Section 3, and the composition and technical details on the SAR dataset are reported in Section 4, along with further information on local conditions during the spill event. Section 5 shows the results of the analysis, from which the conclusions are deduced and reported in Section 6.

2. Slicks on the sea surface

The Normalized Radar Cross Section (NRCS) is a measure of a target's reflectivity, i.e., how efficiently it intercepts electromagnetic energy and scatters it back toward the radar instrument. For sea surfaces, the backscattered signal is strictly related to capillary and small gravity waves induced by wind/waves action. For intermediate angles of incidence (20° to 60°), the dominant scattering mechanism is Bragg scattering, according to which the maximum backscattered energy occurs when the SAR microwaves are coherently scattered by the Bragg waves, which are ocean waves of wavenumber.

$$k_B = 2k_r \sin\theta,$$

where k_r is the radar wavenumber and θ is the incidence angle (Valenzuela, 1978). The NRCS of the sea surface depends upon the wind speed and the wind direction relative to the look direction of the radar. Moreover, backscatter is sensitive to atmospheric effects (rain cells) or oceanic processes able to generate or modulate the Bragg waves, both of which can produce discernible signatures on SAR images (Vesecky & Stewart, 1982; Alpers & Melsheimer, 2004). In SAR data, the increase in incidence angle from near to far range is reflected in a decrease in the NRCS, especially in wide swath products. The backscattered signal is also a function of the transmitted and received polarizations used by the radar system, as well of the relative dielectric constant of the object under investigation. It is possible to observe processes that modulate the surface waves at different scales using different radar wavelengths. SAR L-band is sensitive to Bragg waves at the decimeter scale, while C- and X-band SAR reacts to waves of centimeter scale.

The presence of a surfactant film on the sea surface damps the short gravity-capillary waves (Alpers & Hühnerfuss, 1988). As a consequence, in SAR acquisitions and under proper wind conditions, a surface film results in a dark spot relative to the surrounding area of clean sea water. Surfactants have biogenic or mineral origins, and both can be generated by natural or man-made activities. Furthermore, surfactants have a much smaller dielectric permittivity than clean seawater. Plankton, bacteria, and algae blooms are responsible for natural slicks of a thickness on the order of nanometers (monomolecular film) (Hühnerfuss, 2006), which appear very similar to oil spills in SAR imagery, often leading to misclassification. In contrast to biogenic slicks, mineral spills assume specific characteristics depending on oil properties (viscosity,

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