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Effect of wind direction and incidence angle on polarimetric SAR observations of slicked and unslicked sea surfaces

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ABSTRACT

The objective of this paper is to investigate the dependency of oil spill observations in polarimetric SAR data on imaging geometry, i.e., on incidence angle and look direction relative to the wind. The study is based on quad-polarization data acquired by the Uninhabited Aerial Vehicle Synthetic Aperture Radar over experimental oil slicks under relatively high winds of 10–12 m/s over an 8-hour period. The data is collected over a wide range of incidence angles and alternates between looking upwind (UW) and downwind (DW). The unique time series enables a detailed study of the behavior of multipolarization parameters over clean sea and oil slicks under varying imaging geometry to be carried out for the first time. For clean sea backscatter, our findings are in agreement with previous studies, showing decreasing backscatter as the incidence angle increases and from UW to DW, with the highest sensitivity in the HH channel. We also find similar variations in oil covered areas. The results suggest that the oil slick backscatter is slightly more sensitive to the relative wind direction than the clean sea, and higher oil-sea damping ratios are found in DW than in UW cases, particularly in the HH channel. All multipolarization features investigated have some degree of dependency on imaging geometry. The lowest sensitivities are found in the magnitude of the copolarization correlation coefficient, the standard deviation of the copolarized phase difference, the polarization difference, the mean scattering angle and the entropy. Several features clearly change behavior when the signal approaches the sensor noise floor, and we find that the measurements and derived parameters may be affected at even higher signal-to-noise ratio (SNR) levels than previously proposed, i.e., closer to 7–9 dB above the sensor noise floor. Overall, the polarization difference is clearly identified as the most interesting parameter for oil spill observation, producing high oil-sea contrast in addition to low sensitivity to imaging geometry. The results show that both the relative wind direction and the incidence angle, in combination with the SNR, should be taken into account when developing operational methods based on multipolarization SAR data.

1. Introduction

Synthetic Aperture Radar (SAR) is a well-established remote sensing tool for detection of illegal and accidental oil spills, and can be useful in clean-up operations during oil spill events. Currently, low resolution single-polarization SAR images are used in daily operational oil spill services, but the application of multipolarization SAR for improving oil spill detection and characterization have been extensively investigated over the last decade (see, e.g., Nunziata et al., 2008; Migliaccio et al., 2009a; Minchew et al., 2012; Skrunes et al., 2014). The measurements and derived parameters are affected by a number of factors related to SAR sensor configuration and environmental conditions, which can complicate the data analysis and interpretation (see, e.g., Skrunes et al., 2015a, 2016a). Hence, before multipolarization data can be used operationally, better knowledge of these effects is needed to develop accurate and reliable methods with a large and known range of validity. It is also of interest to identify features with good detection capabilities as well as low dependency on sensor and environmental factors. This paper is a first attempt at a detailed investigation of these questions, made possible through use of multiple images acquired in close succession using an airborne SAR.

The objective of this work is to investigate how oil spill observations using polarimetric SAR are affected by the sensor incidence angle and the look direction relative to the wind (herein referred to in combination as *imaging geometry*). The effect on both the individual polarization channels and on multipolarization features are investigated for clean sea and for oil covered surfaces. Although the dependency of clean sea backscatter on imaging geometry is well described in the literature, few

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studies have looked at the effects on oil covered regions and their detectability, and on multipolarization parameters. This study provides new insight into these effects, by evaluating the features behavior for both changing incidence angle and relative wind direction, also enabling identification of parameters with less sensitivity to these factors. The study is based on data acquired over experimental oil slicks in the North Sea by the National Aeronautics and Space Administration (NASA) Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), which is an airborne L-band quad-polarization SAR instrument. The unique time series makes it possible to do a detailed investigation of the imaging geometry effects on polarimetric SAR data over slicked and unslicked sea surfaces for the first time.

The paper is organized as follows. Background information on ocean radar backscatter and application of polarimetric SAR for oil spill observation is given in Section 2, and the data set is described in Section 3. The results are presented in Sections 4 and 5, and Section 6 concludes the paper.

2. Background

The following subsections contain some background information on ocean radar backscatter and the effect of imaging geometry on polarimetric SAR measurements, particularly from the oil spill observation perspective.

2.1. Ocean backscatter

The SAR backscatter from ocean surfaces depends on a number of factors related to sensor properties and surface characteristics. The general behavior of the ocean backscatter is well known, see, e.g., Ulaby et al. (1986) and Donelan and Pierson (1987), and a vast amount of research has been done on the relation between SAR backscatter and wind conditions and imaging geometry (see, e.g., Dagestad et al., 2012 and references therein). For incidence angles above ca. 30°, the largest backscatter is found in the VV (vertical transmit and receive) channel, somewhat lower values in the HH (horizontal transmit and receive) channel, and the lowest signal in the HV (horizontal transmit and vertical receive) channel. The backscatter decreases when the incidence angle increases, with the steepest slope in the HH channel; increases with wind speed; and varies with the radar look direction relative to the wind direction (Ulaby et al., 1986). The latter dependency is specified as a function of the azimuth angle, ψ, defined as the angle between the radar look direction and the upwind direction, i.e., $\psi = 0°$ and $\psi = 180°$ denotes upwind (UW) and downwind (DW), respectively. In general, the backscatter maximum is found in UW, a smaller signal in DW, and minima when the sensor is looking perpendicular to the wind direction, i.e., crosswind (CW). The larger maxima in UW can be related to presence of foam and enhanced growth of short capillary-gravity waves on the downwind face of longer waves (Zhou et al., 2017). The backscatter difference between wind directions is larger in the HH channel than in VV (Ulaby et al., 1986).

Although most studies of ocean backscatter have been based on C-band SAR data, these general characteristics have been observed also for L-band in, e.g., Isoguchi and Shimada (2009), Yueh et al. (2010, 2013, 2014) and Zhou et al. (2017). At wind speeds comparable to the conditions in the data set investigated in this paper (ca. 12 m/s), the highest HH and VV backscatter were found in UW, slightly lower in DW, and lowest in CW for incidence angles between 29° and 46°. Isoguchi and Shimada (2009) found that DW backscatter exceeds UW backscatter for small θ below about 25°. The difference between UW and DW backscatter was lower in VV than in HH. Differences of about 0.5 dB and 2 dB were found in Yueh et al. (2013) for VV and HH, respectively. The sensitivity of the ocean backscatter to wind direction, especially the UW-DW difference, was found to increase with wind speed and incidence angle in Isoguchi and Shimada (2009), Yueh et al. (2010, 2013, 2014) and Zhou et al. (2017). However, at wind speeds above 20 m/s, Yueh et al. (2013) found a reduction in the ψ-dependency, which the authors suggested could be due to an increasing presence of breaking waves and sea foam that have more isotropic scattering signatures than wind-generated waves. Most studies have focused on the wind dependency of copolarization channels. However, some cross-polarization data are included in Yueh et al. (2010) and Yueh et al. (2014). Yueh et al. (2010) found similar ψ-dependency in all polarization channels, with peaks in UW and DW and dips in CW for $\theta = 45°$, but the UW-DW difference appeared to be smaller in the HV channel compared to in copolarization data. In Yueh et al. (2014), higher backscatter in DW than UW was observed for wind speeds above 12 m/s at θ of 29° and partly at 38°, which is the opposite of the general behavior in the copolarization channels. This was not observed at 46°.

The sensitivity to wind conditions varies between the different radar frequencies, as described in, e.g., Donelan and Pierson (1987). Isoguchi and Shimada (2009) found comparable wind sensitivity in C- and L-band at wind speeds > 10 m/s and small θ, whereas a lower wind sensitivity was found in L-band than in C-band for moderate wind and large θ. In Unal et al. (1991), larger variation between UW and DW was found in C-band compared to L-band at 10 m/s wind.

In the absence of long waves, the ocean backscatter within typical SAR incidence angles (~18°–50°) is dominated by Bragg scattering, i.e., waves with wavelength $\lambda_B = (n\lambda_r)/(2\sin\theta)$, where λ_r is the radar wavelength and $n = 1,2,\ldots$ is the order of resonance ($n = 1$ produces the dominant return) (Valenzuela, 1978; Ulaby et al., 1986, p. 842). For the UAVSAR instrument with a frequency of 1.26 GHz, λ_B varies from 13 cm (at $\theta = 67°$) to 32 cm (at $\theta = 22°$). The two-scale approximation is a more representative scattering model than the Bragg model, as it also takes into account the effects of longer ocean waves on the local incidence angle and roughness through tilt and hydrodynamic modulations (Holt, 2004; Vachon et al., 2004). The HH channel is more sensitive to changes in the local incidence angle than VV, and hence more affected by the tilt caused by larger waves (Thompson, 2004), and also more sensitive to whitecapping and wave steepness which can cause UW-DW difference (Donelan and Pierson, 1987). More recent scattering models describe the radar return as a sum of a polarized Bragg scatter component and a non-polarized component (Kudryavtsev et al., 2003; Mouche et al., 2006; Kudryavtsev et al., 2013). The non-polarized component has been shown to account for most of the differences observed between UW and DW backscatter (i.e., the so-called UW-DW asymmetry) (Mouche et al., 2006). This nonpolarized scattering can be specular reflections due to enhanced roughness or larger slopes of steep waves, e.g., associated with breaking waves. The relative contribution of the nonpolarized component increases from DW to UW, from low to high wind speed, from VV to HH and with incidence angle (Mouche et al., 2006). The latter may also be related to a closer proximity to noise floor at higher θ. Breaking waves were also included in the recent scattering model in Plant and Irisov (2017), and were found to produce UW-DW asymmetry mainly at incidence angles above 45° and in the HH channel. An additional term describing specular reflection from steep slopes can be included in the scattering models, in particular for describing the scattering at very low incidence angles, when applicable (Ulaby et al., 1986; Mouche et al., 2006).

In Section 4.2, the L-band ocean backscatter in the UAVSAR time series here investigated will be discussed and compared to these previous studies.

2.2. Oil spill detection and imaging geometry

Although the effect of imaging geometry on the characteristics of ocean backscatter in polarimetric SAR is relatively well described in the literature, few studies have been done looking at these effects for slick-covered water, including effects on the multipolarization parameters recently applied in the oil spill literature. The most relevant study is