Remote Sensing of Environment 201 (2017) 133–147

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Oil spill detection by imaging radars: Challenges and pitfalls

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ARTICLE INFO

Keywords:
Oil spills
Biogenic slicks
SAR
Polarimetry
Co-polarized phase difference

ABSTRACT

Criteria for discriminating between radar signatures of oil films and biogenic slicks visible on synthetic aperture radar (SAR) images of the sea surface as dark patches are critically reviewed. We question the often claimed high success rate of oil spill detection algorithms using single-polarization SARs because the SAR images used to train these algorithms are based usually on subjective interpretation and are not validated by on-site inspections or multi-sensor measurements carried out from oil pollution surveillance planes. Furthermore, we doubt that polarimetric parameters derived from fully-polarimetric SAR data, like entropy, anisotropy, and mean scattering angle, are beneficial for discriminating between mineral oil films and biogenic slicks. We challenge the often-made claim that another scattering mechanism than Bragg scattering applies for radar backscattering from mineral oil films than from biogenic slicks. This view is supported by data acquired by the Unmanned Aerial Vehicle Synthetic Aperture Radar (UAVSAR) of NASA/JPL, which operates at L-band and has an extremely low noise floor. We suspect that opposing results obtained from previous analyses of spaceborne polarimetric SAR data are caused by the high noise floors of the spaceborne SARs. However, most of the analyzed spaceborne polarimetric data were not acquired at L-band, but at C-and X-band. On the other hand, differences in the statistical behavior of the radar backscattering could be real due to the fact that, other than biogenic surface films, mineral oil films, can form multi-layers, whose thickness can vary within an oil patch. Radar backscattering from emulsion layers can also fluctuate due to variations of the oil/water mixture ratio. These effects could cause an increase of the standard deviation (STD) of the co-polarized phase difference (CPD) for scattering at mineral oil films and emulsions. In the special case of thick oil layers or oil/water emulsion layers, where the radar is sensitive to the dielectric constant of the oil, discrimination becomes possible due the fact that Bragg scattering depends on the dielectric constant of the scattering medium.

1. Introduction

Pollution of the sea surface by mineral or petroleum oil is a major environmental concern, as dramatically shown by the Deepwater Horizon (DWH) platform oil spill accident in 2010 in the Gulf of Mexico (Leifer et al., 2012; Garcia-Pineda et al., 2013). Despite the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), which entered into force in 1983, large quantities of mineral oil are still being discharged illegally from ships into the sea. Most of the anthropogenic oil pollution encountered at sea does not originate from ship accidents, but from routine ship operations, like tank washing, and engine effluent discharges (sludge). But there are also other anthropogenic sources of oil pollution: from offshore oil platforms, oil terminals, industrial plants, pipelines, and refineries. From the environmental point of view, there is a pressing need to monitor illegal discharges of mineral oil in order to reduce oil pollution at sea. It is estimated that at least 3000 major illegal mineral oil dumping incidents take place in the European waters per year, amounting to a total amounts of between 15,000 and 60,000 tons in the North Sea (Carpenter, 2016). To this end, spaceborne and airborne remote sensing techniques are being applied. Imaging radars, like the real aperture radar (RAR) and the synthetic aperture radar (SAR), are key instruments for oil spill monitoring, because they yield data independent of the time of the day and independent of weather conditions (see, e.g., Alpers and Espedal, 2004). However, identifying unambiguously mineral oil films on radar images is a very demanding task. A plethora of papers have been published in the last 30 years with the aim to establish algorithms to extract information on oil pollution from radar images.

Mineral oil spills floating on the sea surface are detectable by imaging radars because they damp the short surface waves that are responsible for the radar backscattering. Oil spills appear as dark areas

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http://dx.doi.org/10.1016/j.rse.2017.09.002
Received 10 October 2016; Received in revised form 22 August 2017; Accepted 2 September 2017

on radar images. The gray level in SAR images is related to the normalized radar cross section (NRCS or σ^o) representing the power of the backscattered radar signal. However, dark areas or areas of reduced NRCS values, do not always originate from mineral oil spills. They can, e.g., originate from: 1) natural surface films which are produced by plankton or fish, 2) low winds as often encountered in the lee of islands or coastal mountains, 3) cold upwelling water which changes the stability of the air-sea interface, 4) divergent flow regimes associated, e.g., with internal waves, tidal flow over underwater sand banks, and oceanic eddies, 5) dry-fallen sand banks during ebb tide, 6) turbulent water as encountered in ship wakes, 7) rain drops impinging onto the sea surface generating turbulence in the upper water layer, which damp the short waves, 8) grease or frazil sea ice, 9) discharged waste water from land-based industrial or urban plants (sewage plants), 10) storm water (flowing from land into the sea after strong rain events carrying surface active material, 11) floating macro-algae including sargassum and kelp, 12) plant oil spilled into the sea during tank cleaning of ships transporting palm oil, or 13) fish oil as encountered during fishing operations. The radar signatures caused by these phenomena are called "oil spill look-alikes". Pollution due to plant oil, in particular from palm oil, is usually not considered (or forgotten) in studies of oil pollution using radars. They also give rise to dark patches on radar images similarly to mineral oil. There exists a large fleet of tankers transporting palm oil. (Palm oil is used in Europe mainly (45%) to make diesel oil and the quantity shipped to Europe has increased from 456,000 tons in 2010 to 3.2 million tons in 2014). The tankers clean their tanks usually after leaving their port of destination, which is at present not illegal. Therefore it is expected that often dark patches visible on radar images taken close to ports do not originate from mineral oil, but from palm oil.

The great challenge is to single out those dark areas visible on SAR images of the sea surface that originate from oil pollution and not from oil spill look-alikes (Brekke and Solberg, 2005). The most challenging task is to separate radar signatures caused by mineral oil spills from those caused by biogenic surface films. Many remote sensing scientists have accepted this challenge and have developed discrimination algorithms based on differing criteria (see, e.g., Brekke and Solberg, 2008). First they used radar images that were acquired at a single polarization and developed discrimination algorithms based on 1) the degree of the NRCS reduction relative to the background, 2) the position/shape of the dark area, and 3) the texture of the dark feature. But it turned out that algorithms based on these properties often gave unsatisfactory results (false alarms). The main deficiency of these algorithms is that they often fail to discriminate between mineral oil spills and biogenic surface films.

After using single-polarization SARs for oil spill detection, which is the preferred approach in terms of sensor and operational costs, with moderate success, remote sensing scientists had hoped to achieve better success rates by using multi-frequency or/and multi-polarization SARs. A multi-frequency/multi-polarimetric SAR was first flown in space during the SIR-C/X-SAR Space Shuttle missions in 1994. During this mission, experiments were carried out with the aim to explore whether multi-frequency SARs were capable of discriminating between mineral oil films and monomolecular surface films (for details see Gade et al., 1998b). The rationale behind this approach was that the reduction of the NRCS caused by monomolecular surface films have another dependence on Bragg wavenumber than mineral oil films due to Marangoni damping (Alpers and Hühnerfuss, 1989; Gade et al., 1998a). It was concluded from this experiment that discrimination could be possible at low to moderate wind speeds, but not at high wind speeds (Gade et al., 1998b). The SIR-C/X-SAR data were also used to carry out polarimetric studies, but no positive results concerning discrimination between both types of surface films using polarimetry were obtained.

Since then, studies of oil film detection using multi-frequency SARs have not been pursued further, since after 1994 no multi-frequency SARs have been flown in space. But satellites carrying single-frequency polarimetric SARs, i.e., SARs that have the capability to emit and receive radar signals at different polarizations, are presently flying in space: on the German TerraSAR-X satellite, the Italian Cosmo-SkyMed satellites, the Canadian Radarsat-2 satellite, the Japanese ALOS-2 satellite, and the European Sentinel-1 satellites, and more multi-polarization SARs to be launched in the near future. The polarimetric SARs flown on TerraSAR-X, Radarsat-2, and ALOS-2 have the capability to operate in the fully-polarimetric (full-pol or full-quad) mode. In this mode, two orthogonal polarized radar signals (horizontal and vertical polarizations) are transmitted and are received at both polarizations. Thus it is possible to measure in this mode the full scattering matrix or Mueller matrix (see, e. g., Ulaby et al., 1992). However, when using multi-polarization SARs for oil spill detection, one has to keep in mind that their swath width is quite narrow, which is unfavorable for operational oil pollution monitoring, which aims at large coverage. Furthermore, using multiple SAR channels increase system and operational costs significantly.

In the last years, expectations have been high that fully-polarimetric SARs would turn out to be the ideal means to discriminate between mineral oil films and biogenic slicks. The rationale behind this approach is that the scattering mechanism for radar backscattering from sea surfaces covered with mineral oil films is different from that covered with biogenic slicks or from clean sea surfaces. It is claimed that in the case of scattering from mineral oil films Bragg scattering does not apply and that polarimetric SARs can detect this difference from Bragg scattering. To this end, various parameters (or features) calculated from polarimetric SAR data, like entropy (H), anisotropy (A), mean scattering angle (α), and copolarized phase difference (CPD) have been applied to reveal this difference.

Many papers have appeared in the last years dealing with oil spill detection using polarimetric SAR (for a review, the reader is referred to the paper of Migliaccio et al., 2015). However, the power of the backscattered radar signal from film covered sea surfaces is often so low, that it is near or even below the noise level of the instrument. As a consequence, the fully-polarimetric parameters calculated from these data could have been contaminated by instrument noise and therefore their usefulness for discrimination purposes is questionable, in particular when cross-polarization data are involved. In early papers, problems associated with the low signal-to-noise ratio of spaceborne polarimetric SARs have often been underestimated. However, measurements carried out over the Gulf of Mexico with the airborne Jet Propulsion Laboratory's (JPL) Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), which has an extremely low noise floor with a noise-equivalent sigma zero (NESZ) of -53 dB, have not confirmed previous results inferred from the analyses of the spaceborne polarimetric SAR data. In particular, they have not confirmed that for scattering from mineral oil films another scattering mechanism applies than for scattering at clean sea surfaces or sea surfaces covered with biogenic slicks (Minchew et al., 2012). However, there seem to be differences in the statistical behavior of the radar backscattering from mineral oil films and biogenic slicks as shown by Migliaccio et al. (2009), who analyzed data from the SARs flown on Space Shuttle during the SIR-C/X-SAR mission (Gade et al., 1998b), and by Skrunes et al. (2014) who analyzed Radarsat-2 SAR data. Assuming that these measured differences are real and not noise-related, we shall present in Section 5 a possible physical explanation for this experimental finding. We will attribute the difference in the statistical behavior of radar backscattering from mineral oil films and biogenic to the fact that mineral oil can form multi-layers and water/oil emulsions, while biogenic surface films can stay on the sea surface only as monolayers.

The paper is organized as follows: In Sections 2 and 3 we describe the physico-chemical differences between mineral oil films/emulsions and monomolecular biogenic slicks. In Section 4 we critically review conventional methods which are widely used for discriminating between mineral oil films and biogenic slicks. Then we review in Section 5 methods using statistical properties of the radar backscatter, in Section 6 methods using differences in the dielectric constant, and in Section 7