CURRENT ADVANCES IN SAR REMOTE SENSING OF OIL SLICKS AND A LOOK-AHEAD

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ABSTRACT

The 4th Synthetic Aperture Radar (SAR) oceanography workshop, SEASAR 2012, entitled "Advances in SAR Oceanography", was held in Tromsø, Norway, 18 to 22 June 2012. This paper describes the consensus on the state-of-the-art and gives a look ahead into the future on the field of radar remote sensing of oil slicks.

1. INTRODUCTION

The field of oil slick remote sensing covers science, technologies and operational services. Science, consisting of theoretical and applied research, must sustain the physical comprehension of the problem. New remote sensing systems or operational modes derived from technology give opportunities to new science and can make operational services more effective and reliable. Operational services must always be receptive of these advances in science and remote sensing technologies to provide high quality results and an effective product to the end user, even in terms of costs. Examples of end users are operational surveillance and monitoring agencies, and stakeholders in the oil and gas sector interested in oil spill response and preparedness as well as reservoir search activity. This paper gives a summary of the most recent advances in the field, from the scientists' point of view, and points out future challenges and research opportunities

Operational oil spill detection seems, to a large extent, still to be done by manual inspection based on single-channel SAR imagery, i.e., transmitting and receiving vertical polarization (VV) or transmitting and receiving horizontal polarization (HH). It is known that single-channel oil spill services suffer from false detection caused by look-alikes (e.g., slicks caused by freshwater runoff, regions of low wind, wind shadow zones, and biogenic slicks).

The core modules of classical, automatic or semi-automatic, oil spill detection and classification algorithms for one channel amplitude or intensity SAR imagery are: (i) region selection/dark spot detection, (ii) feature extraction, and (iii) oil spill versus look-alike classification [4]. For the task of single-channel oil slick versus look-alike classification, the importance of feature identification has been demonstrated [17]. Due to the heterogeneity of the look-alike class, Gambardella et al. [17] proposed to do one-class classification, where only features describing the oil slick class are utilized. In [32], it was shown by Migliaccio et al. how it is possible to deal with full-resolution SAR single-polarization data once a physically consistent speckle model is exploited. However, these, and other, studies also demonstrate the intrinsic limits of the single-polarization approaches and the need to move to polarimetric SAR sensor systems to solve some of the physical and operational challenges.

With polarimetric SAR sensor capabilities now operationally available, techniques on slick characterization are emerging and belong in the above mentioned framework as well. We here consider the term *characterization* to involve slick characteristics, such as slick thickness and other physical properties as well as slick type. Development of polarimetric SAR sensors, and related analysis techniques for oil slick monitoring, is considered one of the areas of greatest progress over the last five to ten years within the field.

Several physical studies considering dual- and full-polarimetric SAR have been done and show superiority with respect to single-polarization SAR cases [31,33-37,41,43,45,63]. New polarimetric SAR satellites are planned or soon to be launched in view of more effective operational services. Europe and Canada are particularly active in the field of polarimetric satellite SAR systems but also some key Asian countries have made contributions. The satellite revisit time, swath coverage and spatial resolution (especially for micro oil slicks) is of particular relevance for marine SAR applications. Unfortunately, classical polarimetric radar design degrades these key numbers. New technologies have been conceived and are planned to be operational in forthcoming satellite SAR missions.

In this paper, we review the state-of-the-art in SAR oil spill remote sensing. Topics covered range from multi-frequency, multi-polarization, and compact polarimetry SAR systems and techniques to physical modelling of sea and oil slicks. We also discuss the possibilities new satellite borne SAR sensors will provide us in terms of increased oil slick detection and characterization capabilities, as well as upcoming challenges related to increased activity in the Arctic.

Current state-of-the-art and future trends in sensors and missions are discussed in section 2. Section 3 covers the status and main research questions on polarimetric SAR techniques currently pushed forward by the scientific community. Physical modelling is discussed in section 4. Some thoughts on SAR remote sensing of natural oil seeps is presented in section 5. Section 6 discusses experimental work in the field. Conclusions are drawn in section 7.

2. STATE-OF-THE-ART SAR SYSTEMS

With the launch of Advanced Land Observing Satellite (ALOS) in 2006 and TerraSAR-X and RADARSAT-2 in 2007, coherent dual- and quad-polarimetry SAR measurements became available from space. However, due to limitations in the current technology, only narrow swath modes are available.

2.1. TerraSAR-X (Germany), RADARSAT-2 (Canada) and CosmoSkyMed (Italy)

C-band SAR has been conventionally used for oil slick applications. X-band, with its short wavelength, is in general considered more sensitive to damping of the Bragg waves on the sea surface. However, attention should be paid to other parameters as well that have an impact on the sensors applicability to do oil slick monitoring. Examples are the system noise floor and atmospheric attenuation of the signal.

It is often claimed that SAR can operate irrespectively of weather conditions, i.e., ensuring SAR oil slick services with real revisit time and swath coverage coincident with nominal ones. This statement is true with modifications. Very heavy rain can attenuate the signal of the higher frequencies such as X-band. Occasionally, this also impacts C-band, but it is a much more pronounced problem for X-band and higher frequency bands. The attenuation of radar signals by heavy rain is described in Danklmayer et al. [7], together with examples of X-band scenes containing these artifacts.

The noise equivalent sigma nought (NESZ) is an important factor to consider for oil slick detection applications, as the measured normalized radar cross section (NRCS) must be higher than the NESZ to make sure that the signal is not corrupted by noise. For single channel SAR oil slick detection, the signal from the sea needs to lie above the system noise floor, i.e., NESZ. This is important to consider for the cross-polarization channels, as the signal over the sea is known to be weaker in HV and VH compared to co-polarization channels [57]. However, when the phase is used, both the oil and sea measurements need to lie above the NESZ. This is particularly important if dark spot characterization is a requirement. Note that the NESZ of the X-band sensors (e.g., TerraSAR-X and COSMO-SkyMed) are higher than that for C-band SAR sensors (e.g., Radarsat-2) [56].

X-band has proven applicable for oil spill monitoring, but it is not clear if and when X-band would be preferred over C-band. Other sensor parameters, such as incidence angle may also affect the sensors sensibility to wave damping by slicks [59]. In general, new scientific and technological challenges call for multi-frequency SAR sensors and greater multi-sensor (satellite borne and not satellite borne) interoperability. However, more research is needed on this topic.

The major limitation of the available quad-polarimetric or dual-polarization (VV and HH) SAR data is the reduced spatial coverage that makes the acquisition modes more or less unsuitable for large-scale operational oil slick monitoring. The quad-polarimetric mode on Radarsat-2 has only a spatial coverage of 25 x 25 km^2. The VV and HH dual-polarization is only available for Stripmap mode on TerraSAR-X, which has a narrow swath width of 15 km and a nominal length of 50 km. The X-band CosmoSkyMed also offers polarized SAR data, but the swath width is only 30 km for the Ping-Pong mode. Moreover, the CosmoSkyMed Ping-Pong mode also suffers from long time delay between the transmissions of the H- and V-channels that leads to an incoherent imaging of the surfaces with short coherence time, like sea surfaces [44]. However, the CosmoSkyMed constellation consists of four satellites and is thereby still an attractive choice for operational oil slick monitoring. The CosmoSkyMed second generation of SAR satellites will have operational dual- and quad-polarimetric modes.

2.2. CSK second generation – upcoming mission

The SAR sensor to be operated on board the CosmoSkyMed second-generation mission is an enhancement of the SAR operated on board the four satellites in the current CosmoSkyMed constellations.
The second CosmoSkyMed SAR series will interoperate with the first CosmoSkyMed series to enhance the operational capability. The carrier frequency will continue to be X-band.

The main advancement, with respect to SAR oil slick applications, is the presence of dual- and quad-polarimetric modes.

2.3. Sentinel (ESA) – upcoming mission

Sentinel is a planned satellite system operating in polar orbit. The first Sentinel-1 satellite is a C-band SAR satellite scheduled to be launched by European Space Agency (ESA) in 2013. Sentinel-1 is planned to have four operational modes: Strip Map Mode (80 km swath and 5x5 m spatial resolution), Interferometric Wide Swath Mode (250 km swath, 5x20 m spatial resolution), Extra-Wide Swath Mode (400km swath and 25x100 m spatial resolution), and Wave Mode (sampled images of 20x20km at 100km intervals along orbit) [2].

For operational oil slick detection it is expected that the Wide Swath Mode and the Extra-Wide Swath Mode will be used. Sentinel-1 is planned to support dual-polarization VV/VH and HH/HV, but not VV/HH. From an oil slick monitoring point of view, the cross-polarization channels are of little use compared to like polarizations.

2.4. UAVSAR (NASA)

National Aeronautics and Space Administration (NASA) has equipped their Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) with an L-band quad-polarimetric sensor. This instrument has an excellent noise floor of -53 dB at its minimum, near the midrange of the swath, allowing cross-polarization (as well as co-polarization) channels to be utilized in oil spill investigations [38]. Compared to X- and C-band, L-band is less affected by alternations of the signal when propagating through the atmosphere and airborne SAR can have a rapid repeat capability. However, it still should be noted that wide swath spaceborne surveillance is considered more efficient for wide area coverage and as a tool in early warning systems.

2.5. Missions with compact polarimetry

There are at least four Earth observing satellite missions that will provide a compact polarimetry mode. These are RISAT-1 (India), ALOS-2 (Japan), SAO-COM-1 (Argentina), and the Radarsat Constellation Mission (RCM, Canada). For instance, the upcoming RCM will be particularly tailored to marine applications by offering a compact polarimetry mode with a swath width of 350 km and a resolution of 50 m, or a low noise mode with the same swath width and a resolution of 100 m. Such spatial coverage is well suited for large-scale oil slick monitoring, and will provide new capabilities in terms of reduced false alarm rate and increased oil slick discrimination.

The availability of polarimetric SAR missions and data acquisitions have triggered scientists to exploit its potential for improved oil slick detection and characterization, and the number of publications on this topic is currently increasing. Advances in oil slick monitoring by polarimetric techniques are covered next.

3. POLARIMETRIC TECHNIQUES

Operational oil slick monitoring services like e.g., the CleanSeaNet service provided by the European Maritime Safety Agency (EMSA) are mainly based on single polarization SAR data (VV or HH).

Dual-polarized SAR that transmits on either H- or V-polarization and receives both H- and V-polarization is supported by most SAR systems, and often provides the same spatial coverage as single-polarized SAR data. However, since the co-polarized and cross-polarized channels are often uncorrelated (the reflection symmetry hypothesis) for sea surfaces where Bragg-scattering is considered to be dominant, the phase information between the co- and cross-polarized channels are not useful in many marine applications.

This is *not* the case for phase and correlation between the two co-polarized channels (VV and HH), and during the last decade, polarimetric SAR that alternately transmits two orthogonal polarizations and record one or both received polarizations, has been investigated in several oil spill detection studies, e.g., [14,29,21,33]. In many of these studies, it has been demonstrated that the use of polarimetric SAR increases the oil slick detection performance, and makes it possible to discriminate oil slicks from biogenic slicks (e.g., [29] and [33]). It is in particular the *co-polarized phase difference* (CPD) between the VV and HH channels that provides additional discrimination power to the oil spill detection problem [33]. While many of the studies have focused on the SIR-C data obtained by the space shuttle in April and October 1994 [14,33], some also considered L-band

ALOS PalSAR [34], Radarsat-2 quad-pol [65] and TerraSAR-X dual-pol VV/HH [21] SAR data.

3.1. Multi-polarization SAR features

At SeaSAR 2010 it was stated that "a need of technological improvement exists with respect to distinguishing slicks from look-alikes." In 2012 we ask: what is the current status on new techniques related to multi-polarization SAR for oil spill versus look-alike discrimination? It turns out that several multi-polarization parameters or features have been evaluated for oil versus look-alike discrimination in the literature. A short summary of the main findings follows.

In Migliaccio et al. [31], the H/A/alpha decomposition of Cloude and Pottier is evaluated on polarimetric SAR data recorded during the SIR-C/X-SAR mission in October 1994. The entropy, H, is found able to distinguish between some biogenic and anthropogenic slicks. Tian et al. [62] evaluate the use of H-α-plots for dark spot classification of Radarsat-2 Fine quad-polarized imagery. This preliminary study concluded that the parameters are valid for discrimination between sea surfaces, biogenic slicks, and oil slicks with different chemical properties. In Migliaccio et al. [33], the CPD is found useful for oil spill observation in C-band under low to moderate wind conditions. The data set used was acquired by the sensor SIR-C/X-SAR in April 1994 and September and October 1994. The CPD method acts as a filter to highlight oil spills while de-emphasizing biogenic slicks. Velotto et al. [63] finds the method useful also for TerraSAR X-band data. In Nunziata et al. [41], a model for oil slick observation based on the Mueller matrix under low to moderate wind conditions is presented and applied to C-band SIR-C/X-SAR data. A simple filtering technique without any external threshold is proposed to distinguish slick-free sea and biogenic slicks from oil-covered sea surfaces. In Nunziata et al. [45] the co-polarization signature, which is the plot of the synthesized normalized radar cross section as function of ellipticity and orientation angles, is exploited for oil slick observation. The pedestal of the signature is used to discriminate oil slicks from weak-damping look-alikes. Migliaccio et al. [34] found some of the methods above useful also for L-band polarimetric SAR. In June 2011 and in June 2012, Radarsat-2, TerraSAR-X imagery and auxiliary data were collected during Norwegian Clean Seas Association for Operating Companies' (NOFOs) annual oil-on-water exercises at the Frigg-field outside the Norwegian coastline (see an example of a SAR acquisition from the 2011 exercise in Figure 1). In recent studies by Skrunes et al. on this data set [57,58,59,60], a number of multi-polarization features are evaluated and a potential for mineral oil versus biogenic slicks discrimination is found. One of the features considered in this study is visualized in Figure 2.

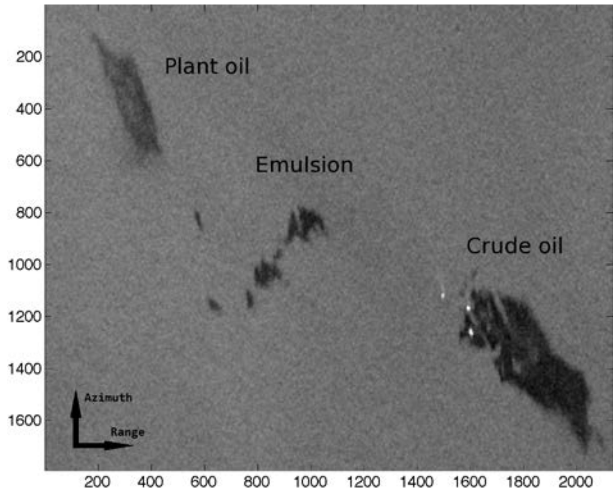

Figure 1: Radarsat-2 scene from an oil-on-water exercise in June 2011. VV intensity, multi-looked by 9 x 9 window. RADARSAT-2 Data and Products ©MDA LTD. (2011) – All Rights Reserved.

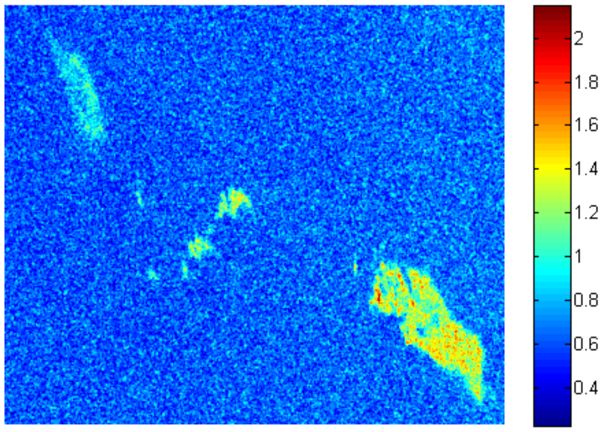

Figure 2: Standard deviation of co-polarized phase difference computed from the image in Figure 1 [59].

Thickness estimation of oil slicks is highly desirable and of relevance in e.g., oil spill clean-up operations. Skrunes et al. [58,59] report that classification by clustering the slick pixels, based on selected sets of multi-polarization features, also show internal oil spill variations and zoning along the edges. The zones correlate with expected thickness variations, but these results are still considered preliminary. During the BP Deep Water Horizon oil spill in 2010, images along the Gulf of Mexico coastline and over the main part of the slick were acquired by the UAVSAR. Analysis of the data showed variations within the slicks that could relate to oil slick thickness, coverage, and/or emulsion characteristics [28, 38]. However, there is limited ground truth available to date to verify these results. Using data from UAVSAR that cover the Deepwater Horizon oil spill in the Gulf of Mexico, Shirvany et al.

[55] show maps of the degree of polarization over oil and water claiming that this parameter can reveal oil sheens along the edges, dark patches and narrow bands within the slick.

3.2. Compact polarimetry

Due to the reduced capabilities, pointed out in section 2.1, for operational oil slick monitoring using dual-polarization VV and HH or quad-polarimetric SAR data, the possibilities of using *compact polarimetry* for oil slick detection has been investigated by simulating compact polarization from Radarsat-2 quad-polarimetric SAR data [54,55,65].

Compact polarimetry is a name for SAR schemes in which one polarization is transmitted, and two orthogonal polarizations are received, together with their relative phase. However, compact polarimetry differs from conventional dual-polarization schemes in that it relies on transmitting the H- and V-polarization simultaneously, and not in series. For an introduction to compact polarimetry we recommend the excellent paper by Raney [53].

The objective of compact polarimetry is to realize many (but not all) benefits of quad-polarimetric or dual-polarization HH and VV, without the reduced swath width [53]. There exist several compact polarimetry modes that have been tested. The π/4-mode transmits a linear polarized field at 45^o ($H+V$) and receives coherently in both the H and V channels. The circular polarization mode transmits either a right or left circular polarized field ($H \pm i \cdot V$, where "+" and "-" denotes left and right circular polarization, respectively, and i denotes the complex identity), and receives in both the left and right circular polarized channels. The "hybrid" compact mode transmits circular polarization $H \pm i \cdot V$ and receives in both the H and V channels. Among these three compact polarimetry modes, the latter has been ranked to be the most promising in terms of performance and receiver complexity [53].

In SAR-based oil slick detection, only a few studies have considered compact polarimetry. The papers by Zhang et al. [65], Salberg et al. [54], and Shirvany et al. [55], all considered the hybrid polarization mode. The paper by Zhang et al. [65] showed that the conformity coefficient, derived from the compact polarimetry data, might be applied to discriminate oil spills from look-alikes. The study by Salberg et al. [54] showed that by using the hybrid compact polarization mode and assuming an X-Bragg scattering mechanism, the correlation coefficient between the H+V and H-V channels, which only depend on the sea surface roughness [18], may be derived and applied to suppress look-alikes. The work by Shirvany et al. [55] demonstrated that the degree of polarization provides valuable information for man-made object and oil slick detection under different polarizations and incident angles.

Why consider compact polarimetry for oil spill detection applications? The major motivation is that there are several planned Earth observing satellite mission with possibility for compact polarimetry acquisitions (as discussed in section 2), and the results provided by Zhang et al., Salberg et al., and Shirvany et al. show that compact polarimetry has a great potential in oil slick monitoring, and may in many cases provide results comparable to those obtained by quad-polarimetric sensors. With the potential performance enhancement in terms of look-alike suppression in addition to the increased swath possibilities, we expect that SAR systems that provide compact polarimetry modes will have a high impact on operational oil slick monitoring in the future.

4. PYSICAL MODELLING

Physical modelling is of crucial importance for understanding the scattering of electromagnetic waves from slicks and ambient water surfaces, as well as for development of oil slick detection algorithms and their discrimination from look-alikes. Physical modelling includes description of both short wind waves in the slicks and surrounding areas, and scattering of the electromagnetic waves from the sea surface with "known" properties.

4.1. Sea surface

Depending on the sensor, informative parameters of the sea surface are: wind wave spectrum around the Bragg wavenumber and slope of tilting waves (2-scale Bragg scattering model), parameters of breaking waves providing radar returns, the mean square slope of the sea surface (in the range up to shortest capillaries), its skewness and peakedness that define brightness of the sea surface in visible range due to reflection of sky and sun radiation. Physical modeling presumes that these parameters have to be defined from solution of wind wave energy balance equation where the main sources are: wind input (S_w), viscous (D_v) and non-linear (D_{nl}) dissipation, resonant wave-wave interactions (S_{nl}), and generation of short waves by breaking waves (S_{wb}) including generation of parasitic capillaries [48,49,25]. Donelan and Pierson [8] considered truncated balance ($S_w - D_v - D_{nl} = 0$) and fitted their model to available radar data. In order to improve the physics of wave generation, several studies [23,24,25] took into account mechanism of generation of parasitic capillaries and non-resonant generation of short waves due to mechanical disturbances of the sea surface by "largerscale" wave breaking. Short wave spectrum in this case results from solution of the following energy balance: $S_w - D_v - D_{nl} + S_{wb} = 0$. Kosnik et al. [22] provided a further insight in physics of short wind wave dynamics. In addition to the energy balance considered in Kudryavtsev et al. [24], they included rigorous expression for 3-wave interaction, term S_{nl}. They found that resonant 3-wave interactions do not modify significantly the shape of the short wave spectra. This result, on the one hand, suggests that the role of 3-wave interactions in the wave energy balance equation is rather weak (in comparison with impact of wind input, viscous dissipation and generation of parasitic capillaries), and on the other hand, justifies use of "quite primitive" wave energy balance for the slicks simulations.

Once a solution of the energy balance equation (wave spectrum) for "clean" surface is found and fitted to measurements, the same equation must be used for the slick studies. The input parameters for physical modeling of short wind waves in biogenic and oil slicks are the surface viscosity coefficient and surface tension, which are both modified in presence of a film.

4.2. Viscous-elasticity properties of surface films

Biogenic films

The action of films on surface waves is determined by the physical characteristics of the films, such as film elasticity, viscosity and surface tension. These characteristics were mainly investigated for monomolecular films supposedly related to the biogenic marine films (see, e.g., [19] and [40]). Film elasticity plays a governing role in wave damping. The elasticity of the biogenic films is rather large, up to 30-40 mN/m, [10, 3]. A new "parametric wave method" developed by Ermakov and Kijashko [12] has been extensively used to investigate damping of gravity-capillary waves by various "artificial" monomolecular films, to retrieve their elasticity and to find an "artificial" film simulating biogenic films in new field experiments on slick remote sensing. Some studies, [30] and [42], were carried out on real SAR measurements. As anticipated, these results will stimulate development of the advanced models based on a better physics.

Oil films

Unlike biogenic films, our understanding of viscous-elasticity properties of crude oil films is insufficient. The reason is that oil films, in general, are characterized by a larger number of parameters, which are: interfacial and surface elasticity, viscosity and tension, volume viscosity, and film thickness. The theory of wave damping by oil film of arbitrary thickness was developed by Jenkins and Jakobs [20]. They showed that both elasticity and viscosity impact the wave damping. Recently, using the "parametric wave" method, Ermakov et.al. [13] showed the first attempts to retrieve oil film elasticity/viscosity for oil films of different thicknesses. They revealed that oil films can be characterized by an effective elasticity which depended on film thickness. As found, the elasticity of crude oil films with thickness less than 0.5 mm is rather low, about 5-10 mN/m, but at larger film thickness its value increases up to 20mN/m.

4.3. Wave spectra contrasts in the slicks

An example, of measurements of wave spectral contrasts for different type of surface slicks measured by Ermakov et al. [9] is shown in Figure 3. The data demonstrate a "known" trend, increasing the spectral contrasts towards the shorter waves. Thus use of a higher frequency radar for surface slicks detection is more efficient. Another remarkable feature is that the spectral contrasts in the crude oil slicks are systematically lower than in simulated biogenic slicks based on OLE and vegetable oil. This fact confirms that elasticity of thin crude oil films is smaller than for the biogenic ones, and this phenomenon may potentially be used for development of oil spills discrimination mechanism. Model simulations shown in the same Figure (performed using Kudryavtsev et al.'s [25] model) are in general agreement with the data. However, apparent discrepancy of model calculations for the "crude oil" case with E=4 mN/m indicates that the real elasticity of crude oil film should be larger.

Kudryavtsev et al. [26] used sun-glitter imagery to retrieve the mean square slope (MSS) contrast for the crude oil spills. They found that MSS contrast in the mineral oil slicks is remarkably lower than that observed by Cox and Munk [6] for the slick generated by fish oil. Model simulations of the MSS contrast led Kudryavtsev et al. [26] to conclude that a plausible elasticity of the crude oil is about 10-15 mN/m. They also showed that joint use of SAR and sun glitter imagery of oil slicks may provide a good opportunity to estimate the thickness of oil spills, if the oil film thickness is comparable to or larger than the visible wavelength.

4.4. Radar back-scattering contrasts in slicks

Radar backscattering features of biogenic and oil slicks have been reported [1, 16, 15]. There is a general consensus that slick contrast is larger at higher radar frequency and that the contrast decreases with increasing wind speed. There is also experimental evidence that the magnitude of the radar contrast in slicks is smaller in the biogenic cases [15]. At the same time, the quality of the model aimed on simulation of radar backscatter from the slicks still suffers serious shortcomings. One reason is that NRCS of the real surface, σ_0^{pp}, is not properly described within the frame of 2-scale Bragg scattering model (σ_{br}^{pp}). Thus the NRCS contrast cannot be associated one-to-one with wave spectra contrast (shown e.g., in Figure 3).

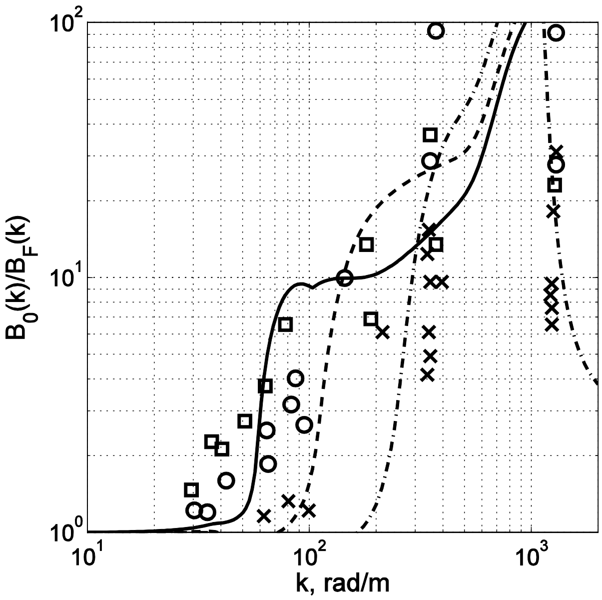

Figure 3: Spectral contrasts (ratio of wave spectra for clean over slick surface) measured by Ermakov et al. [9] for different types of surface films at wind speeds 6-7 m/s: OLE (squares), vegetable oil (circles) and crude oil (crosses). Lines show model calculations for surface films with elasticity E=25 mN/m (solid line), E=12 mN/m (oil, dash line), and E=4 mN/m (dash-dotted lines) simulating the effect of OLE, vegetable and crude oil slicks correspondingly.

Radar returns from steep and "rough" non-linear features of the sea surface associated with breaking of waves in the wide range of wavelength significantly contribute to the NRCS even at low wind speed conditions: $\sigma_0^{pp}=\sigma_{br}^{pp}+\sigma_{wb}$, where σ_{wb} is the contribution of non-polarized radar returns to the NRCS [50,24]. Significant deviation of the polarization ratio, $P=\sigma_0^{hh}/\sigma_0^{vv}$, from Bragg model prediction is a clear indicator that σ_{wb} plays an important role (see e.g., [24,39] and corresponding references). In this case, the effect of wave breaking on NRCS must be taken into account in slick simulations. We may anticipate that unlike Bragg waves (well damped in slicks), σ_{wb} (supported by breaking of relatively long waves) is not affected by the slicks. In this case NRCS contrasts in slicks $K\equiv\left(\sigma_0^{pp}\right)_{clean}/\left(\sigma_0^{pp}\right)_{slick}$ should rather reflect relative contribution of wave breaking to the total NRCS than damping properties of the film, i.e. $K\approx\sigma_0^{pp}/\sigma_{wb}$. Much more information can be deduced when dual co-polarization data are available [51, 27]. In this case the polarization difference $\Delta\sigma=\sigma_{br}^{vv}-\sigma_{br}^{hh}$ (where non-polarized impact of wave breaking is removed) is governed by the Bragg scattering mechanism, thus slick contrasts in $\Delta\sigma$ should be equal to the wave spectral contrasts at Bragg wavenumber, and might possess information about the type of film (see Figure 3). Besides, since Bragg waves are effectively damped, the polarization ratio in the slick area should be close to $P=1$, i.e. remarkably higher than over the ambient clean area. Polarization ratio is weakly dependent on wind speed, thus this fact may serve for discrimination of a slick from their dark look-alikes related to the local depression in wind speed field. An effective methodology using satellite high resolution dual co-polarization information to interpret and quantitatively assess various surface ocean phenomena is suggested by Kudryavtsev et al. [27].

Doppler frequency recently became a standard product routinely available from satellite SAR imagery, see e.g. [5]. Ermakov et al. [11] revealed that Doppler shift in the slick area significantly deviates from its value over the ambient "clean" area. This finding (together with slicks features in the NRCS and sun-glitter brightness) opens new opportunities for development of advanced oil slicks detection and discrimination algorithms.

5. CHALLENGES IN THE ARCTIC

Much attention is currently directed towards the Arctic sea ice cover. The reduction in Arctic sea ice is viewed as an indicator of global climate change. The melting of the Arctic sea ice makes new shipping routes and natural resources more easily accessible. The Arctic regions are also expected to hold a large reserve of oil and gas offshore. Increased activity is expected in the Arctic regions from the international maritime industry and the oil and gas sector in the coming years. It is anticipated that this will challenge the oil spill remote sensing community in two ways in particular:

- New knowledge on and development of technology for oil spill detection under, on and within sea ice will be required. This is important for both illegal and accidental oil spill monitoring activity and clean-up operations. To the authors' knowledge, there are few publications on this topic [46].
- More knowledge on and technology development for identification of natural oil seeps in the Arctic regions. SAR remote sensing, detection and identification of natural oil seeps are of relevance for oil reservoir search activity, but also for discrimination of natural slicks from man-made pollution caused by e.g., leakage from oil installations and pipelines.

5.1. Natural oil seeps

Natural petroleum slicks occurring on the ocean surface can be regarded as a positive indicator of hydrocarbons moving vertically within the ocean column. Repeated remote sensing acquisitions, in time and space, of such films could increase the confidence that the slicks are related to offshore seepage accumulation structures. This is valuable information in oil exploration activities [38,47].

Examples of known natural oil seeps exist in the Gulf of Mexico, the Caspian Sea, offshore California, Brazil, West Africa and Indonesia [64]. The Cantarell field is a giant seepage area in the southern Gulf of Mexico. The slicks here are spatially associated with oil pollution from oil production and transportation installations [47]. A topic of current interest is to investigate the potential of detecting natural seeps but also to discriminate between natural ocean bottom oil seeps and marine man-made oil pollution.

Several studies have been conducted to study satellite sensors' ability to detect and characterize natural seeps. Quintero-Marmol et al. [52] aimed at establishing the origin and magnitude of hydrocarbon contributions by natural seeps in the southern Gulf of Mexico. They examined 83 Radarsat-1 SAR scenes from 2000 to 2002. Note that Radarsat-1 only provides single channel (HH) SAR imagery, hence excluding potential polarimetric analysis techniques. The Cantarell natural oil seep was found to be the dominant source of hydrocarbon contribution with respect to both spatial distribution and temporal frequency in the region. An example of natural oil slicks in the Gulf of Mexico is shown in Figure 4.

Thankappan et al. [61] report a brief study of X-band SAR detection capabilities of oil seeps. The study was apparently done by mainly visual interpretation of 8 single polarized (HH or VV) TerraSAR-X data sets (ScanSAR, StripMap, and SpotLight) from two Australian study sites containing slicks of unknown origin. However, the influence of important aspects such as multi-polarization SAR and incidence angle seems to be suppressed in this study. Pellon de Miranda et al. [47] suggest looking into polarimetric techniques for enhanced oil seepage detection.

An extensive study of the Gulf of Mexico using nearly 700 Radarsat images has resulted in an extensive seep map and included the development of a detection algorithm based on texture and neural networks [Garcia-Pineda et al., Canadian J. Remote Sensing, 2009].

Recent experimental work on controlled oil releases indicate that multi-polarization SAR data acquisitions adds to the capability of oil slick characterization and slick type discriminations [57,58,59]. Today, multi-polarization SAR data is available on a regular basis from several satellite platforms such as TerraSAR-X and Radarsat-2, allowing repeated recordings in both time and space of known seepage fields. Exploiting the additional information in multi-polarization SAR measurements would be a logical step forward aiming at identifying and characterizing natural seepage slicks.

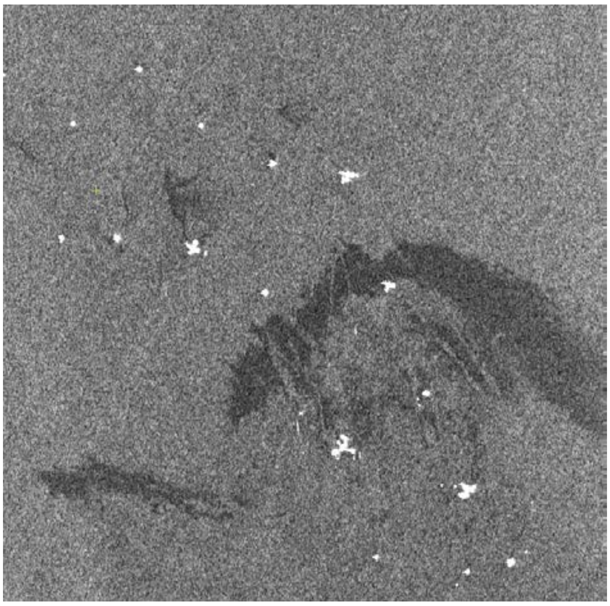

Figure 4: Seepage at the Cantarell field in the Gulf of Mexico. Some releases from offshore installations (characterized as strong bright points) are also visible. The image is a part of a scene captured by TerraSAR-X StripMap mode on 17 July 2012. VV polarization presented. Copyright © 2012 DLR.

6. FIELD EXPERIMENTS

In order to develop techniques for discrimination of oil types and oil slick thickness estimation, data obtained from controlled experiments is desirable. It is difficult to get a permit to release oil into the sea to simulate accidental or illegal pollution. However, in Norway, NOFO, oil industry and satellite service providers have shown an increasing interest in remote sensing research and technique development over the last few years. Releases of various oil types, data collection, and participation in annual large-scale oil-on-water exercises in the Norwegian Sea have taken place. These kinds of events are valuable laboratories for scientific work, however, conflicting needs are often experienced between the operational and scientific community.

7. WAY FORWARD

The 2010 BP Deepwater Horizon oil spill in the Gulf of Mexico gave the oil spill community insight into strengths and weaknesses of today's oil spill sensors, technology, and response capabilities. However, it is pointed out that developments and progress in the field need to take place independent of such large-scale accidents and not during actual oil spill response [28].

Over the last few years, advances in polarimetric SAR systems and techniques have taken place. A clear potential for improved oil slick detection and characterization based on multi-channel SAR measurements and compact polarimetry is evident from the recent literature.

The main issues to be addressed by the community in the near future cover research and algorithm development for compact polarimetry, multi-sensor oil slick observation, e.g., multi-spectral optical in combination with SAR, slick drift modeling, slick characterization, and enhancement of the revisit time by new polarimetric sensor technologies, e.g., staggered SAR. For characterization and potentially thickness estimations, knowledge of slick properties is of importance with respect to clean-up operations, including dispersion activity, and reducing the number of false alarms e.g., by discriminating among various slick types. It is also anticipated that the increased focus on the Arctic, and accelerating oil and gas activity in the region, will act as an external force to stimulate remote sensing oil detection studies in that challenging region.

To better prepare for future events, a larger effort should be made to lift promising new research results to the operational stage.

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