The Interaction of Crude Oil on the Sea Surface with Ocean Fronts observed by SAR in NRT

Susanne, Lehner, DLR, Susanne.Lehner@dlr.de, Münchner Straße 20, D 82234 Wessling, Germany
Alexander, Soloviev, Cayla Dean, Nova Southeastern University, soloviev@nova.edu, cd821@nova.edu,US
John Kluge, Georgia Parks, Nova Southeastern University, jk1083@nova.edu, gp693@nova.edu, US
Egbert, Schwarz, DLR, Egbert.Schwarz@dlr.de, Germany
William Perrie, Bedford Institute of Oceanography, Halifax, william.perrie@dfo-mpo.gc.ca, CA

Abstract

Fine scale features on the sea surface associated with change in roughness are, e.g., Lee waves, wind rolls due to atmospheric rolls, wind shadows, swell waves and oceanographic effects due to upwelling, Langmuir cells, current fronts and wakes as well as natural and man-made slicks. Such features can be observed on synthetic aperture radar (SAR), because of the change in Bragg backscatter of the radar signal by damping of the resonant ocean capillary waves. Further this change in sea surface roughness can as well be observed in the sun glint area of optical imagery.

Fine scale features like oceanographic fronts, turbulent currents, eddies and small slicks of natural origin or oil seepages are best observed on high resolution imagery, that is now freely available to the scientific community. Especially using new radar frequencies like the L- and C- band or the high resolution from X-band satellites as well as new modes of polarization, sea surface features have been analyzed in several campaigns, bringing very different datasets together thus allowing for new insight in small scale processes at a larger area.

1 Introduction

SAR intensity images are a measure of the roughness of the sea surface and are thus usually interpreted as a measurement of sea surface wind speed [1], [2]. Oil seeps and spills smooth the roughness of the sea surface and can thus be easily detected by synthetic aperture radar (SAR), causing dark areas on the satellite images due to reduced backscatter [3], [4]. Using complex SAR imagery the change in the variability of the phase difference between the Co-polarized channels (VV, HH) is used to differentiate between oil and natural slicks [5]. Oil spills cause sheen and a change of color at visual inspection or on optical imagery which can be interpreted as oil thickness, e.g., using the NOAA scale.

During a field experiment in the Gulf of Mexico at the estuary of the Mississippi river in April 2017, we collected a variety of different SAR and optical datasets both showing persistent oil seeps South of the Mississippi delta. We investigated oil spill imaging under different environmental conditions as well as for different radar wave lengths and polarizations together with optical and in Situ data. On TerraSAR-X and Sentinel data we used algorithms for oil spill detection and for the derivation of meteo-marine parameters based on intensity images [6], [7] to be able to distribute near real time products. Additionally we tested ESA´s SNAP toolbox for Sentinel-1 and RADARSAT-2 and investigated polarimetric SAR imagery.

2 Oil Detection by SAR

We acquired radar data from the two C-band satellites, RADARSAT-2 and Sentinel-1, as well as TerraSAR-X band imagery and compared the detected slicks and oil to in situ data as part of the GOMRI (Gulf of Mexico Research Initiative) Campaign SPLASH, Submesoscale Processes and Lagrangian Analysis on the Shelf.

Figure 1: Oil seep observed next to the small campaign boat (left). Slick on the sea surface (right) observed during satellite SAR acquisitions

During the cruise oil seeps were detected visually, see Figure 1 for examples and described by the NOAA scale. It could be shown that the areal size of visually detectable oil is much smaller than the dark areas on the SAR image, which is caused by reflection of the radar beam away from the antenna due to the smoothing of the sea surface. We compare the extent of the detected dark area for different environmental situations, i.e., in different wind speed, sea state and tidal front situations, parameters which can be derived directly from the SAR imagery. When comparing the in Situ inspection to the imagery, none of the SAR detected oil slicks had a thickness of more than 0.3 to 5 micrometers. Still the damping on the SAR image was in the range of the system noise level (NESZ) of more than -30 dB for, e.g., RADARSAT.

2.1 Satellite Datasets in NRT

We acquired SAR satellite data from the Gulf area near the Mississippi delta between April 15th and April 30th 2017 at DLR´s ground station in Neustrelitz, see Table 1

04-2017	Time UTC	Sensor	Mode
15	23:49	TS-X	SM-VV
16	00:01	S1A	IW-HH
19	12:08	TS-X	DP
20	23:57	R2	WFQ
20	23:57	TS-X	DP
22	23:53	S1A	IW-HH
24	12:17	TS-X	SM-VV
25	12:01	R2	FQ8W
26	23:49	TS-X	SC-VV
28	00:01	S1A	IW-HH
30	12:08	TS-X	SM-DP

Table 1: SAR data acquired for SPLASH.

TS-X derived products on wind speed, sea state and oil coverage were available to the in Situ campaign 30 minutes after acquisition. Datasets were acquired and processed into SAR images in 15 minutes, further processing into derived meteo-marine products usually took another 5 minutes.

Figure 2 shows an example of a TerraSAR-X image of oil detection near the Mississippi delta. The data were acquired on April 15th (date by local time), 2017 while the seep was surfacing directly from under the river front and dragged into it, finally submerging.

The interaction of the seep with the freshwater front of the Mississippi river can be observed and will be used as a validation for respective modelling of the process. In addition to the oil detection meteo products on wind speed at sea surface height u_{10} derived by the algorithm of [6] and significant wave height after [7] are available in near real time (NRT), see an example of TS-X derived wind speed from April 27th 23:49 UTC in Figure 3.

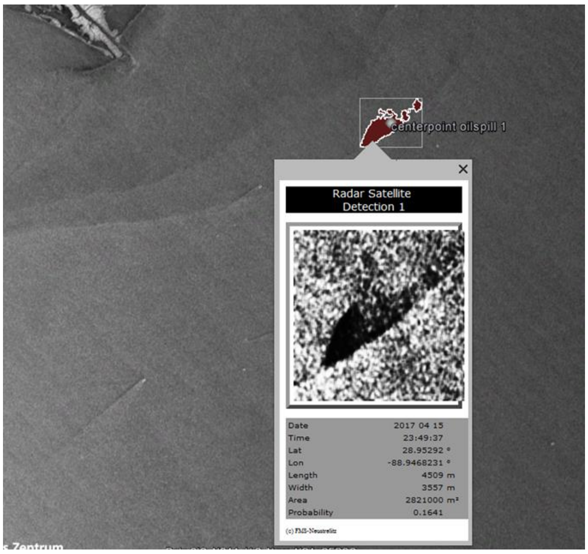

Figure 2: Oil seep on a TS-X image acquired over the Mississippi delta as NRT product from April 15th, 2017.

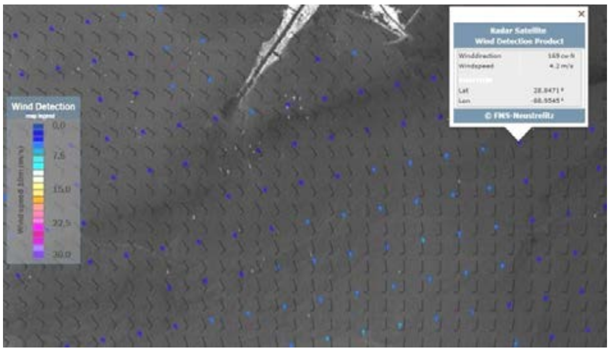

Figure 3: TS-X derived wind speed u_{10} for the Mississippi delta on April 27th 23:49 UTC. Wind direction from WRF, wind speed derived to be 4 -6 m/sec.

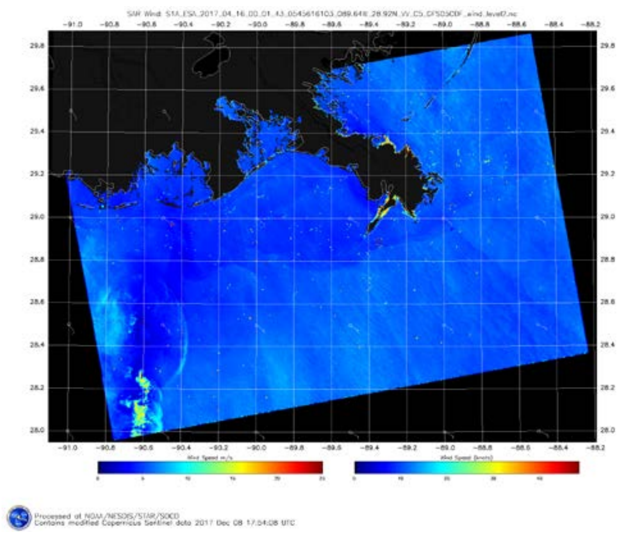

Figure 4: Sentinel-1 derived wind speed of about 4 m/sec from NIC SAR wind server, April 16th. The oil seep is visible in the front by reduced backscatter

Sentinel-1 SAR wind speed data are as well available at the NIC SAR wind server, see Figure 4. In addition to wind speed measurements on such images oil seeps can as well be deduced from the reduced backscatter.

Sentinel-1 and RADARSAT-2 data were processed after the campaign. We processed the Sentinel SAR data for different dates and found the slick to be surfacing at the same site. The extent of the slick was mainly dependent on the location of the front. If the oil is surfacing in the front, the slick would again submerge or stay confined to a small area. If the freshwater front is located north of the seep, features related to smoothing of the sea surface could be observed to extend up to 70km into the Gulf towards the East, see Figure 6..

2.2 In Situ measurements

The physical structure of the surface microlayer (SML) consists of the viscous sublayer (~1500 µm thick), thermal sublayer (~500 µm thick), and salinity diffusion sublayer (~50 µm thick). Under moderate wind speed conditions, these molecular sublayers are mainly controlled by microscale wave-breaking associated with capillary waves and have a great impact on the gas exchange between the ocean and atmosphere [8]. We investigated the seep and the slick and sampled the SML in order to derive the abundance of surfactant associated bacteria [9] in an oil enriched environment, see Figure 5. The methods and results on slick measurements during the LASER during in Feb. 2016 are available in [10].

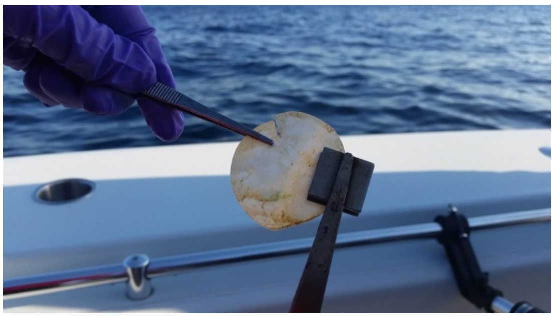

Figure 5: Sea surface and oil slick sampling using filter techniques during SPLASH in the oil seep

3 Discussion of SAR Results

The observed seep, originating from a platform located in the Mississippi delta, which was destroyed during hurricane Ivan in 2004 is observed on all SAR imagery acquired during the SPLASH experiment as well as before and after. The shape and area would not only depend on the sea surface wind speed, but as well on the location of the Mississippi freshwater front.

In cases were the front is located northward of the seep, the oil slick features were observed to extend more than 70 km far into the eastern Gulf as well as being dragged into an eddy, without actually oil being visibly present at the sea surface, see Figure 6. The eddy delineated by the oil is actually present in the results of the HYCOM model, see Figure 7. Thus the oil features can be usedas well to validate current models at the surface.

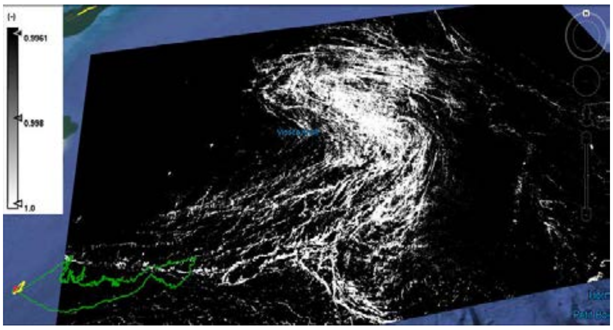

Figure 6: Extent of the oil seep features from the same location derived from 4 different SAR acquisitions by different sensors and color-coded by acquisition date. The contours of the seep are derived by ESA SNAP

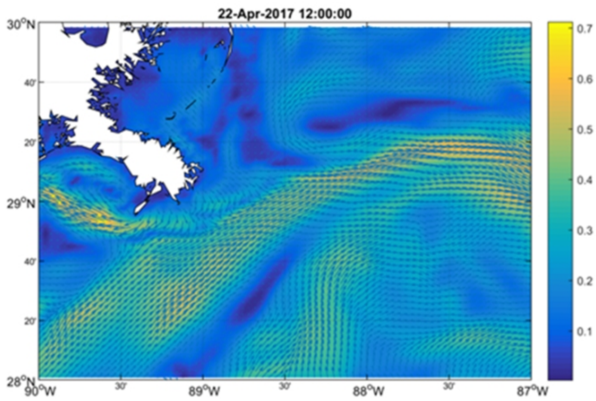

Figure 7: Sea surface current in m/sec as derived from the HYCOM model

The surface slick traces the outline of an eddy with center at 29deg 30 min North, 88deg 20 min West, surface currents shown are as computed by the HYCOM model, see, Figure 7. It should be noted, that higher resolution features of the frontal system between fresh and salty water as observed in Figure 2 cannot be reproduced by the model.

We acquired both TS-X Stripmap and RADARSAT-2 fine quad-polarisation mode data at the same time to investigate processes at the front in high resolution on April, 20th. Figure 9 shows the interaction between the slick and the front on RADARSAT-2, the same area is acquired by TS-X at the same time, see Figure 10. On both images the oil seep can be detected. The seep extends to the Mississippi front, gets drawn into the front towards the West and part of the slick submerges under it.

The X band TerraSAR image shows bright frontal features due to interaction of the ocean waves from the Gulf with surface currents at the front. Fronts are better detectable on the X- than on the C-band imagery, due to the higher backscatter from breaking waves. Small filament slick features are detectable in a large area behind the front. Visually on the ocean surface only the smooth sea surface is observed, in the zone behind the front no oil was detectable, see Figure 1 b.

The NRCS on the RADARSAT image diminishes from -18 dB on the sea surface to -30dB in the slick covered area as well for the slick entrained in the front as for the oil in the seep area. Thus the question whether there is a similar thickness of oil in the front as at the seep cannot be answered just from the SAR intensity image. In addition or TS-X data the oil slick damping causes the intensity to drop below the NESZ of -19dB.

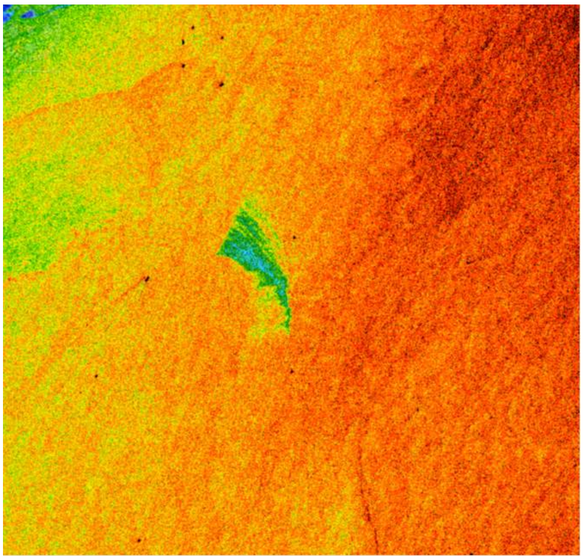

Figure 8: Radarsat-2 calibrated NRCS, VV April 25th, the image is colour-coded to show the stronger damping in the center of the slick (blue) in comparison to the outside (green). The front at which the slick appearance vanishes is not detectable.

This shows the high potential of SAR to detect slick features that may consist only of surfactants of a nanometer thickness. On the other hand this means that SAR imagery can easily be misinterpreted, when used in operational oil spill detection. Users of oil spill detection often complain about a too high numbers of alarms. The cause for this is not just the presence of look-alikes from algae, the cause is that an extremely thin layer of oil, often just a monomolecular layer of crude oil, not visible by a change of colour at the sea surface, smooths the sea surface and thus results in dark areas on SAR.

In Figure 8 we show the NRCS of a RADASAT 2 image from April 25th, color-coded to highlight the slightly stronger damping at the center of the slick. Methods to detect thicker oil due to illegal spills, that have to be removed, and to distinguish these from nano-to micrometer layers, have to still be developed or improved. In operational systems human operators tend to overestimate the likelihood of a spill.

For detecting oil on optical imagery in sun glint similar arguments apply, as this glint is as well due to sunlight reflection on a smooth sea surface.

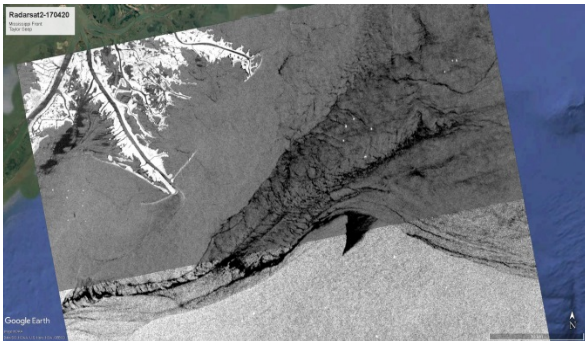

Figure 9: RADARSAT 2 Quad fine pol, VV, April, 20th 23: 57 UTC

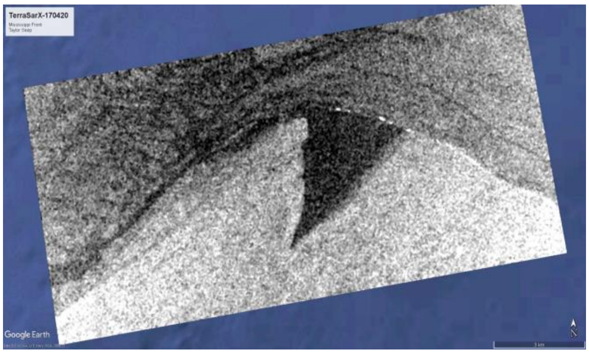

Figure 10: TerraSAR X Stripmap image, VV April 20th 23:57UTC

It has been shown, that polarimetric SAR data can be used to differentiate between crude oil and so called look-alikes [5], [11]. [12], [13]. For future SAR systems special care should be taken to design for the necessary NESZ and coherence of the VV and HH channels, which is not sufficient for the respective methods. Of further importance is to determine in SAR images the much smaller area that is covered by visibly detectable oil.

4 Conclusions

SAR data from different sensors namely Sentinel-1, RADARSAT-2 and TerraSAR-X were acquired to investigate the possibility to detect oil seepage and observe its interaction with the Mississippi river fresh water front during the SPLASH field campaign. The acquisitions will be a basis to model the processes at the front in high resolution.

The seep was detectable on all SAR images at all environmental conditions down to a wind speed u_{10} of lower than 3 m/sec. The NESZ of the SAR systems needs to be better than -30 dB at low wind speed for X and C-band to distinguish between oil coverage and slicks or smooth sea surface. New complex methods involving the co-pol phase difference and thus distinguishing between crude oil on the surface and a smooth sea surface again need a NESZ better -30dB in low wind conditions (around 3 m/sec) and incidence angles larger than 30 degrees.

This may be important for the design of new systems, especially in L-band, where the NESZ would need to be larger than -50dB. For C- and X- band -32 dB is observed in oil seeps. For the detection of the surface oil only the co-pol channels are needed. Coherent Co-Pol channels of NESZ of better than -30dB are useful not only to distinguish between between crude oil and look-alikes, but mainly to determine the significance, i.e. thickness, of an oil spill.

To observe the interaction of oil seeps with river fronts, in detail a resolution better than 5m is needed. Freshwater fronts showed up to be more prominent in X than in C-band imagery

Acknowledgements

TerraSAR-X data were ordered via a TS-X science AO from DLR, Sentinel-1 data were downloaded from ESAs science hub and RADARSAT data were made available by the R-2 science licence at DLR

References

[1] Susanne Lehner, Jochen Horstmann, Wolfgang Koch, Wolfgang Rosenthal: *Mesoscale Wind Measurements using recalibrated ERS SAR Images,* Journal of Geophysical Research, Vol. 103, NO. C4, pp. 7847-7856, 1998

[2] Jochen Horstmann, Wolfgang Koch, Susanne Lehner, Rasmus Tonboe: *Wind Retrieval over the Ocean using Synthetic Aperture Radar with C-band HH Polarization*, IEEE TGARSS, Vol38, pp., 2122-2133, 2000.

[3] Werner Alpers, Heinrich Hühnerfuss, *Radar signatures of oil films floating on the sea surface and the Marangoni Effect*, Journal of Geophysical Research, 93, NO. C4, pp. 3642-3648, 1998.

[4] Daniele Latini, Fabio del Frate, Cathleen Jones, *Multi-frequency and polarimetric quantitative analysis of the Gulf of Mexico oil spill event comparing different SAR systems*, ,Remote Sensing of Environment, 183, pp. 26-42, 2016

[5] Domenico Velotto, Maurizio Migliaccio, M. Nunziata, S. Lehner: Dual-Polarized TerraSAR-X data for oil-spill observation. *IEEE TGARSS,* Vol 93, pp. 4751-4762.

[6] Xiaoming Li, Susanne Lehner: *Algorithm for Sea Surface Wind Retrieval from TerraSAR-X and TanDEM-X Data*. *IEEE TGARSS,* Vol 52, pp. 2928-2939, 2014.

[7] Pleskachevsky A, Rosenthal W, Lehner S, *Meteo-marine parameters for highly variable environment in coastal Regions from Satellite Radar Images*, ISPRS J Photogram Remote Sens.,doi:10.1016/j.isprsjprs., 2016.

[8] Alexander Soloviev, R. Lukas, *The Near-Surface Layer of the Ocean: Structure, Dynamics and Application,* Springer, pp 537. DOI: 10.1038/srep05306, 2014

[9] N. Kurata, K. Vella, B. Hamilton, M. Shivji, A. Soloviev et al., *Surfactant- associated bacteria in the near-surface layer of the ocean*, Nature 6, 2016

[10] Katherine Howe, C. Dean, J. Kluge, A. Soloviev, A. Tartar, M. Shivji, S. Lehner, W. Perrie, *Relative abundance of Bacillus spp., surfactant-associated bacterium present in a natural sea slick observed by satellite SAR imagery over the Gulf of Mexico*, Elem Sci Anth, 6: 8, 2018.

[11] Maurizio Migliaccio, Ferdinando Nunziata & Antonio Buono, *SAR polarimetry for sea oil slick observation,* Int. Journal of Remote Sensing, 36, pp. 3243-3273, 2015

[12] Stine Skrunes, Camilla Brekke, Cathleen E. Jones, Benjamin Holt, *A Multisensor Comparison of Experimental Oil Spills in Polarimetric SAR for High Wind Conditions*, IEEE JSTARS, Vol 9, pp. 4948-4961,2016

[13] Suman Singha, Rudolf Ressel, Domenico Velotto, Susanne Lehner, *A Combination of Traditional and Polarimetric Features for Oil Spill Detection Using TerraSAR-X,* Vol 9, pp. 4979-4989, *2016*