Oil Slick Detection and Characterization by Satellite and Airborne Sensors: Experimental Results with SAR, Hyperspectral and Lidar Data

M. LENNON*‡, N. THOMAS*, V. MARIETTE*, S. BABICHENKO† and G. MERCIER‡

*SAS ActiMar
24, Quai de la Douane
29200 Brest - France
lennon@actimar.fr
http://www.actimar.fr

†AS Laser
Diagnostic Instruments
113A Kadaka Str.
2915 Tallin - Estonia
sergeyb@ldi.ee

‡GET/ENST Bretagne, dpt ITI,
TAMCIC, team TIME, CNRS UMR 2872,
Technopôle Brest-Iroise, CS 83818,
F-29 238 Brest Cedex, France.
gregoire.mercier@enst-bretagne.fr

***Abstract*— Efficient observation means are required for regional-scale detection of oil slicks at sea, as well as for local-scale quantitative mapping in order to support operational fight and recovering operations, including reliable choice and guidance of maritime and airborne fighting means. An efficient oil slick detection algorithm based on a multiscale approach is proposed for operational regional-scale detection from satellite SAR images. The potential of combining airborne passive hyperspectral imagery and active fluorescence laser technology is proposed for local-scale quantitative characterization. The ways towards the use of both satellites and airborne remote sensors for use in operational emergency scenarios are discussed.**

I. INTRODUCTION

The potential of satellite SAR images for regional-scale detection of oil slicks at sea has been demonstrated in the past [1]. Detection schemes are often based only on radiometric properties induced by oil slicks on SAR images. Those algorithms usually suffer from high false detection rates due to environmental parameters (sea state, wind, upwellings...) that can induce the same radiometric properties as oil spills on SAR images [2]. An algorithm based on a multiscale approach, including radiometric as well as textural information, is proposed for operational use in this paper.

In May 2004, three real oil spills at sea have been performed during a three days campaign off the coasts of Britanny, France. The campaign, named DEPOL04, was carried out under the responsibility of the French Navy represented by the CEPPOL ("Commission d'Etudes Pratiques sur les Pollutions") and of the French Customs, and managed by the CEDRE ("Centre de documentation de recherche et d'expérimentations sur les pollutions accidentelles des eaux"). Joint data sets have been collected using an airborne hyperspectral imager (CASI-2) [3, 4] and a Fluorescence Lidar System (FLS-AU) [5, 6], and fused for local oil slicks detection and quantitative mapping. Location, extents, volume of the oil spilled and its high resolution (metric) spatial distribution are the main parameters that could be estimated. The data processing strategies and results are quickly presented. The potential and limits of the approach are discussed.

The complementarity of satellite SAR and airborne passive and active optical sensors for oil slicks mapping is discussed. Recommandations are made for their operational use as reliable observation means in the case of emergency scenarios.

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II. OIL SLICK DETECTION WITH SATELLITE SAR SENSORS

SAR sensors are to be used to perform efficient oil slick detection at medium scale in routine monitoring.

A. Sea surface observation with SAR data

The oceanic sea surface is complex and often governed by non-linear dynamic systems. On the one hand, capillary waves are generated by friction, and more specifically by friction velocity, related by wind speed and surface properties, which die down when the friction decreases. On the other, gravity waves are generated indirectly by sea spectrum energy spreading and propagating over long distances far from their origins. Radar electromagnetic waves are backscattered by the sea surface. Most SAR sensors that are used on civil satellites use the C band. By considering incidence angles from 15 to 45° according to the sensors and their acquisition modes, gravity-capillary waves of wavelengths from 4 to 14 cm intervene in the scattering process [7]. Nevertheless, SAR image resolution is much larger than the wavelength and the sensor is sensitive to large scale oceanographic phenomena. Hence, surface roughness induced by short waves is modulated by longer waves allowing SAR imagery to characterize "indirectly" oceanophysical phenomena such as swell, internal waves, coastal bathymetry or oil slicks.

B. Multiscale strategy

The basic idea to perform slick detection is to segment the local sea surface wave sprectum. More precisely, it can be stated that:

- the SAR sensor is only sensitive to surface roughness (at a centimeter scale) which is modulated by larger scale phenomena that induce shades of texture;

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- the increase of viscosity, due to the presence of an oil slick on the sea surface, affects the sea surface wave spectrum shape;
- oil slicks induce dark areas on the SAR images under certain conditions, such as a limited wind (*i.e.* under 10-14 m/s).

It seems that to take into consideration sea surface wave spectrum shades is more appropriate than most of techniques from the state of the art which are mostly oriented to radiometric considerations [2].

C. Detection strategy

The detection strategy, which is fully detailed on [8], is based on the characterization of the "normal" behavior of the sea surface. This characterization is performed by using kernel expansion of equation:

$$f(\boldsymbol{x}) = \sum_{i=1}^{m} \alpha_i K(\boldsymbol{x}, \boldsymbol{s}_i) - \rho \quad \underset{\text{Hypothesis}_{\text{abnormal sea}}}{\overset{\text{Hypothesis}_{\text{normal sea}}}{\gtrless}} \quad 0, \qquad (1)$$

where the $\boldsymbol{s}_i$ are the m support vectors defined through a ROI to characterize normal sea surface. $f(\cdot)$ defines a hyperplane of the feature space that divides samples into two categories: normal sea surface observation or anbormal sea surface observation. This technique is known as *Support Vector Novelty Detection* [9].

In order to make novelty detection act as an oil slick detection from SAR image, the kernel $K(\cdot, \cdot)$, that defines the behavior of the dot product into the feature space, has to be carefully defined. In this study, the kernel takes the observations from the multiscale representation of the SAR image. The kernel is then defined in order to place the samples representing polluted areas closer to the origin of the feature space than the other samples. It includes pointwise observations but also local neighbourhoods comparison to perform a texture segmentation. The way the feature space is defined induces also the existence of the hyperplane.

It performs an accurate slick detection that still need to be validated with various meteorological conditions and different sensor modalities. Nevertheless, it proved to be an appropriate strategy to detect slicks from a given sea state [8].

III. Oil slick quantitative mapping with airborne passive and active optical sensors

A. Instrumentation

CASI-2 and FLS-AU are installed onboard a fixed-wing aircraft (Cessna 404). The flight altitude is limited by the maximum flight altitude of the FLS-AU, which is equal to 500m (about 1500ft). Using the Cessna 404, the speed is fixed at 100kts. CASI-2 data spatial resolution on the ground is 1m. CASI-2 configuration include 18 spectral bands in the range 400-1000nm with 30nm spectral resolution. The laser excimer of FLS-AU is fixed at 308nm wavelength / 20Hz pulse frequency. 500 spectral bands are simultaneously recorded in the range 300-500nm. The whole details of the data acquisition operational aspects can be found in [10].

The data processing steps are briefly explained below. The full development of the processing chain can be found in [11].

B. CASI-2 data processing

Radiometrically calibrated CASI-2 data are geometrically corrected and georeferenced thanks to INS/dGPS data. Across-track illumination corrections are performed, and a mosaic of flight lines is built. A standard three layers optical model including air, a thin layer of oil, and water is used to relate the reflectance above the water surface to the thickness of the oil layer. The model is used for the simulation of the signal reaching the sensor as a function of the thickness of the oil layer, in the whole spectral range of CASI-2 data. A procedure for the inversion of the model is built in order to compute, from the CASI-2 data, a parameter called "A" which is proportional to the oil thickness. The linear coefficient relating "A" to the thickness is a function of the diffractive index of water and oil and remains hence unknown. In order to take also into account the specular reflexion on the slick surface, as well as the "saturation variability" induced by the thickness varibility over the slick, two other parameters, called "L" and "S", are computed as n-dimensional extensions of the "Lightness" and "Saturation" parameters used in the standard RGB to HLS color transform. Those parameters allow the main information regarding oil and water to be reduced to three dimensions, which is very convenient to visually highlight the useful information into a "ALS" color enhanced vizualization map. That ALS image is then segmented in order to provide the localization and geographical configuration map of the slick.

C. FLS-AU data processing

After georeferencing with handheld GPS data, and low-pass filtering of the data in order to increase the signal to noise ratio, along-track sampling is around 25m. Raman scattering beeing possibly influenced by external factors, only the fluorescence information is used for detection of oil on the sea surface. Thickness is then computed from each of the raw spectra where oil has been detected, thanks to the Raman scattering information. Standard or in-lab measurements of attenuation coefficients of water and oil are used to calibrate an empirical model relating the thickness of oil to the intensity of Raman scattering. Raman scattering is saturated after a certain threshold which depends on the type of the oil.

D. CASI-2 + FLS-AU data fusion

After CASI-2 and FLS-AU registration, the parameter "A", is extracted from the CASI-2 spectral pixels for which an absolute value of the thickness as extracted from the FLS-AU data is available. The two datasets are then linearly correlated. The parameters of the linear correlation model are applied on the whole CASI-2 image pixels in order to provide a high resolution map of the spatial distribution of the thickness.

E. Quantification of the parameters

Surface and volume are estimated thanks to the integration of local estimated values over the whole pixels of the slick.

F. Results

1) CASI enhanced vizualization map: An example of a CASI enhanced color vizualization map computed from the ALS decomposition is shown on Fig. 1. That map allows one to get a first qualitative assessment of the pollution. The distribution of the volume of the oil is highly revealed in the image (from blue to red). Fig. 1 shows that the maximum concentration of oil is located on the west side of the slick in a small area compared to its whole extent.

2) Localization and geographical configuration map: The segmentation of the ALS map is shown on Fig. 2. From that map, localization and geographical configuration of the slick are derived. The exact extents of the slick can be computed.

3) High Resolution thickness distribution map: The CASI-2 and FLS-AU data fusion process leads to the computation of the thickness distribution map shown on Fig. 3. The colors associated to the estimated thicknesses are quantitatively reported in the legend. This map confirms the qualitative assessment of the CASI enhanced vizualization map, and allows the whole volume of oil spilled to be estimated.

4) Quantitative results and critical study: Three 10 m^3 oil slicks, alpha, bravo, and charlie, have been spilled during the DEPOL04 experiment. The alpha slick was crude oil, while bravo and charlie included 65% HFO + 35% LCO. The quantitative results are listed in Tab. I. The results show that the volumes have been under-estimated for each slick, with an error factor ranging approximately from 5 (alpha) to 30 (bravo). Those errors are mainly due to the saturation of the optical measurements (and induced non validity of the radiative transfer model used) after a critical thickness which depends on the type of the oil observed. In the currrent experiment, the FLS-AU measurements were saturated at approximately 10μm for alpha, and 5μm for bravo and charlie. Those saturation threshold differences explain the best estimations over the alpha slick. The estimated thicknesses are quite accurate over thin layers, while saturated over thick layers. The most dispersed the volume is over a large surface, the most accurate the estimation of the volume is. In the current experiment, the slicks were not so much dispersed since data acquisition was performed a few hours after the spill. The system capabilites are hence limited to provide the minimal bound of the real volume of oil spilled, which should however be considered as reliable. It has to be noticed that the high resolution thickness distribution maps allow, despite the saturation areas, the limits of the slick and the spatial distribution of volumes to be reliably represented. Those informations are *a priori* the most important for the support of operational aerial and/or maritime recovering operations.

TABLE I

QUANTITATIVE RESULTS

Slick	Estimated surface (km^2)	Estimated Volume (m^3)	Volume error factor
Alpha	0.97	2.08	4.8
Bravo	0.34	0.36	27.8
Charlie	0.39	0.49	20.4

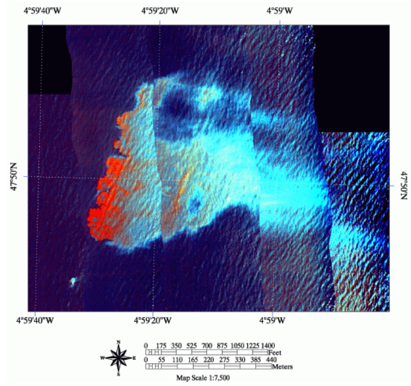

Fig. 1. "ALS" enhanced vizualization map

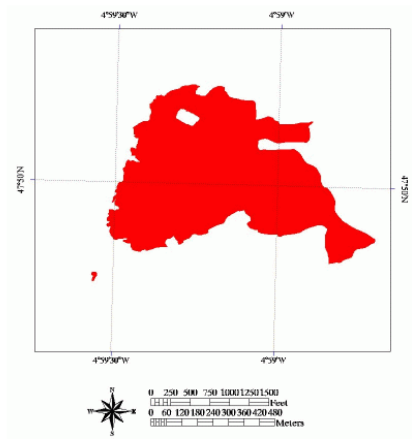

Fig. 2. Localization map

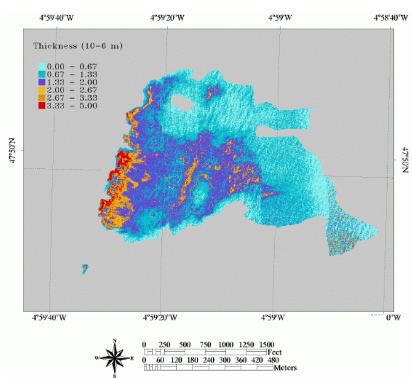

Fig. 3. High Resolution thickness map

TABLE II

COMPLEMENTARITY OF SENSORS

Sensor	Mode	Range (μm)	Use	Capabilities
Sat. SAR / Airb. SLAR	Active	C-band	Regional-scale surveillance and detection	N / D Clouds
Thermal IR	Passive	8-12	Regional (SLAR blind zone compensation) + local detection	N / D
UV	Passive	0.2-0.4	Regional (SLAR blind zone compensation) + local detection	D
μwave	Active		Local detection + Thickness estimation $>$ 100 μm	N / D Clouds
Hyperspectral VNIR	Passive	0.4-1.0	Local detection + mapping of volume distribution	D
FLuo Lidar	Active	0.3-0.7	Local detection + Thickness estimation $<$ 100 μm	N / D

IV. Complementarity of remote sensors

The remote sensors used in the current study are not aimed at replacing the current systems in use, they are rather aimed at completing the suite of sensors available. Tab. II highlights the most common sensors, their uses and capabilities (D: Day; N: Night), including satellite SAR (which are usable even by cloudy sky) and airborne optical sensors. The following observations can be made:

- Satellite SAR and airborne SLAR systems are useful for regional-scale observation and detection. Airborne optical sensors are not convenient for that task because of their reduced swath.
- Micro-wave and fluorescence lidar sensors are complementary, regarding the different thickness ranges that can be estimated by both sensors.
- Hyperspectral and lidar sensors could be used in the same manner as IR/UV sensors for regional scale detection (compensation of the SLAR blind zone). Hyperspectral data would allow a better spatial resolution to be reached, but could not be used during night flights however.
- Thermal IR and hyperspectral VNIR sensors are complementary as far as their detection capabilities are concerned: thin oil slicks can not be detected by thermal IR sensor because of the sea surface thermal balance (they can be with an hyperspectral sensor) while thick oil slicks still influence the signal recorded by a thermal IR sensor (quick saturation of the signal as a function of oil thickness in the case of an hyperspectral sensor) [3].
- Joint use of hyperspectral and fluorescence lidar sensors allow high spatial resolution thickness distribution maps to be obtained, while SAR, SLAR, and IR/UV are only used for detection.

V. Ways to their operational use

Satellite data are currently not convenient for real-time operational oil pollution monitoring because of their quite low repetitivity rates. Near-future micro-satellites constellations (such as the ORFEO project including CNES-Pleiades* and ASI-Cosmo-Skymed†) including the disposal of a ground receiving station, should mitigate that problem thanks to the large increase of regional-scale data availability. The combination of satellite SAR and optical data could then be used to build a regional-based early emergency system. From that early detection, quick airborne surveys could be triggered using a multi-sensor airborne platform including hyperspectral and fluorescence lidar sensors in order to get accurate quantitative maps of the pollution. Those maps would be used for supporting recovering operations including guidance of aerial and maritime fighting means. An information system including the different parts of such a kind of multi-scale system (satellite / air / sea) could turn out to be a valuable decision-making tool for public institutions in charge of the management of pollutions at sea.

*http://smsc.cnes.fr/PLEIADES/

†http://www.asi.it/sito/programmi_cosmo.htm

VI. Conclusion

This pilot project allowed us to make a step towards answering environmental concerns associated with accidents in oil storage and transportation. Multiscale Oil slick detection scheme from satellite SAR data has proved to be useful in an operational scenario. Passive and active hyperspectral sensors have been shown to be complementary. In particular, data fusion from both sensors allows high resolution spatial distribution of oil thickness to be geographically mapped. We think that a regional-based early emergency system based on the satellite data available, used in combination with an airborne platform including optical sensors among others, could provide with valuable information an information system that could be fruitful for helping in the decision process and management of a crisis scenario, as well as for supporting the recovering operations at sea.

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References

[1] G. Mercier and F. Girard-Ardhuin, "Oil slick detection by sar imagery using support vector machines," in *Proc. of the IEEE Oceans'05 Europe*, Brest, France, June 20–23, 2005.

[2] C. Brekke and A. H. Solberg, "Oil spill detection by satellite remote sensing," *Remote Sensing of Environment*, vol. 95, no. 1, pp. 1–13, Mar., 15, 2005.

[3] V. Byfield, "Optical remote sensing of oil in the marine environment," Ph.D. dissertation, Univ. of Southampton, UK, Oct. 1998.

[4] M. Lennon, V. Mariette, A. Coat, V. Verbeque, P. Mouge, G. Borstad, P.Willis, R. Kerr, and M. Alvarez, "Detection and mapping of the november 2002 *PRESTIGE* tanker oil spill in galicia, spain, with the airborne multispectral CASI sensor," in *3rd EARSEL Workshop on Imaging Spectrospcopy*, Oberpfaffenhofen, Germany, 13-16 May 2003.

[5] R. Reuter, H. Wang, R. Willkomm, K. Loguay, T. Hengstermann, and A. Braun, "A laser fluorosensor for maritime surveillance: Measurement of oil spills," in *EARSEL Advances in Remote Sensing*, vol. 3, 1995, pp. 152–169.

[6] S. Babichenko, A. Dudelzak, and L. Poryvkina, "Laser sensing technologies in studies of marine and coastal environments," in *7th International Conference on Remote Sensing for Marine and Coastal Environments*, Miami, Florida, USA, 20-22 May 2002.

[7] T. Elfouhaily and B. Chapron, "A comparison of wind wave spectra used in ocean remote sensing modeling," in *Proc. of the IEEE IGARSS'96*, vol. 1, Lincoln, NE (USA), 27-31 May 1996, pp. 606–608.

[8] G. Mercier and F. Girard-Ardhuin, "Unsupervised oil slick detection by sar imagery using kernel expansion," in *Proc. of the IEEE IGARSS'05*, Seoul, Korea, July 25–29, 2005.

[9] V. N. Vapnick, *Statistical Learning Theory*. John Wiley and Sons Inc., 1998.

[10] M. Lennon, N. Thomas, V. Mariette, S. Babichenko, and G.Mercier, "Operational quantitative mapping of oil pollutions at sea by joint use of an hyperspectral imager and a fluorescence lidar system on-board a fixed-wing aircraft," in *IEEE OCEANS'05*, Brest, France, 20-23 June 2005.

[11] M. Lennon, S. Babichenko, N. Thomas, V. Mariette, and G.Mercier, "Combined passive hyperspectral imagery and active fluorescence laser spectroscopy for airborne quantitative mapping of oil slicks at sea," in *4th EARSEL Workshop on Imaging Spectrospcopy*, Varsaw, Poland, 27-29 April 2005.