Oil slick detection by SAR imagery: potential and limitation

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Abstract- **Ocean pollution by oil slicks is a major environmental hazard highlighted by the spectacular accidents of *Exxon Valdez*, *Erika* and *Prestige*. But, these oil tanker accidents only account for 5% of total oil pollution worldwide, 95% coming from wild discharges. In order to monitor and therefore to detect surface pollution, an effective tool has to be found. Satellite detection is well adapted to this problem, and especially Synthetic Aperture Radar (SAR) can fill the lack of pollution survey which affects seas and coasts. Indeed SARs image oil slicks allowing estimation of the pollution risk in coastal areas. On satellite or aircraft, SAR is an interesting tool because, on the one hand, SAR images can be acquired through clouds unlike infrared or optical images. On the other hand, it is well suited to the detection of slicks because slicks modify seawater viscosity, producing a strong impact on short waves measured by SAR. The backscatter is attenuated and oil spills appear as a dark patch on the SAR image. Studies had shown that it is not easy to always detect oil slicks as backscatter depends strongly on wind and sea surface conditions among other restrictive factors. A comprehensive synthesis of previous studies shows the suitable SAR acquisition modes to detect slicks, function of the influence of SAR parameters such as polarization (VV), wavelength (C-band), incidence angle (20 to 45°), satellite or aircraft flight direction, waves and wind directions. We present here cases of easy and ambiguous detection to show the possibilities offered by SAR to automatically detect slicks, in order to improve the pollution detection and the drift forecasting in case of accidents for example. For this, ERS SAR and ENVISAT ASAR ocean images examples are shown, applying segmentation algorithms and a new approach with original method based on ocean surface characterization.**

I. INTRODUCTION

Ocean pollution has been recently highlighted by the *Prestige* accident in Europe, like those of *Exxon Valdez*, *Erika* or *Aegean Sea* previously. These oil tanker accidents hide the regular pollution, for example in important traffic zones like the Mediterranean and the Baltic seas, the Atlantic ocean, and the Malacca strait (around Singapore), caused by sea drillings, illegal discharges or war damages as during Gulf War. Impacts of oil pollution are not only related to the quantity but also on location, season, ocean depth, meteorological and oceanic conditions. Mediterranean sea, for example, is strongly impacted by pollution because it is almost closed (water renewal is about 70 to 90 years by the strait of Gibraltar), it receives 30% of the shipping traffic and 20 to 25% of petroleum traffic whereas it only covers 1% of the total world oceans surface; at last, this is a dangerous area favorable to accidents because of straits, islands...

Natural slicks are also common, of biological origin made by photo-oxydation process or bacterian decomposition (fish trash, plankton, plants…) or of geological origin (deep sea floor escape). With regular passes over oceans, satellites are useful to get statistical information: slicks are observed all over the world seas and half of the satellite images presents at least one slick as in Mediterranean sea (study with 1600 SAR ERS images in [1]), Baltic sea [2] and South-East Asiatic area [3]. Counting every kind of slicks, 10% of ocean surface is estimated to be covered by slicks.

The stake of slick detection is on several points. When tanker accidents happen, we need to know precisely where polluted areas are and to evaluate slick drift in order to protect coasts. At present, this work is done punctually by airborne survey; an automatic detection by satellite would be helpful. Moreover, it would be useful to fight against illegal discharges. Otherwise, in global climate change, slicks make fence in sea/air exchanges, reducing evaporation surface, modifying formation process of white cap and spray, implying reduction of CO_2 exchange notably [4, 5] and heat transfers. The slicks thus must be taken into account in climate change models. In other way, natural slicks are of interest for biologists and fishermen since they show intense biological activity in the water column [5].

For these reasons, efficient detection means have been implemented, with airborne and satellite measurements. Satellite detection is well adapted since it produces regularly images in difficult access areas. Several kinds of measurements have been tested: optical, infrared, radars with different frequencies. Synthetic Aperture Radar (SAR) seems to be one of the most suitable instruments to this kind of study since it does not depend on weather (clouds) nor sunshine, which allows showing illegal discharges that most frequently appear during night; it can also survey storms areas, where accident risks are increased.

Automatic analysis of SAR images is not applied routinely yet. For that, the first step is to detect slicks in the image, and then to classify them in order to determine their nature (pollution, natural slick…). Automatic detection algorithms linked with statistic classification allowing to distinguish kind of slick would reduce significantly the delay to analyze the data and then, to speed up decision process when a pollution occurs.

In this presentation, after a bibliographical synthesis showing the most suitable SAR acquisition configuration for this study (radar frequency, polarization, incidence angle…) in section II, some detection algorithms will be applied on SAR images in order to highlight the interest of the preliminary step in the image analysis in section III. A conclusion about the different approaches of analysis will follow in section IV.

II. RADAR MEASUREMENTS OF SLICKS

A. Effect of slick on ocean surface

Slicks often appear at ocean surface, as had been noticed since long, along with their effects on waves. Ancients testified the waves damping by slicks. This principle has been even used, without being understood, to save boats during storms, tipping out oil slicks to break waves [4, 6]. From the XVIIIth century, scientists have tried to find possible explanations. In 1872, Marangoni explained that damping is function of slick elasticity [7, 8].

When gravity-capillarity waves propagate, their successive compressions and extensions increase dissipation. When a slick covers the surface, wind has less effect on the surface, the amplitude of wave crest/trough decreases, implying a surface stress gradient, with opposite strength to this alternated motion. The Marangoni waves are created since a stress gradient exists, i.e. with visco-elastic film. The Marangoni wave is partly longitudinal in the upper layer where dissipation is attenuated and partly tangential linked with stress gradient associated with visco-elastic film properties. Visco-elastic surfaces only carry two kinds of waves: gravity-capillarity waves and Marangoni waves. The high frequency waves damping is maximum when these two kinds of waves are in resonance. The surface waves damping is linked with surface stress decreasing, which is associated with film elasticity, the most important parameter with nature, density and surface viscosity. Elasticity stabilizes the surface and avoids wave generation with wind.

Waves can be presented by their energy, composed of three terms: wind energy, wave-wave non-linear energy transfer and dissipation. It is expected that the two first parts are modified by slicks, but the third one is changed as well: the damping of the longest and the shortest waves suggests that non-linear interactions are important [8]. Whereas short waves energy is reduced by slick, energy is available for non-linear transfer to higher and smaller frequencies to balance viscosity dissipation. The more the spectrum is distorted by Marangoni damping effect, the more the non-linear transfer is important [8]. Three mechanisms interact on gravity waves: direct slick influence (energy dissipation performs principally by viscosity dissipation where there is Marangoni resonance which is linear effect), wind-wave coupling and wave-wave interactions change [9, 10]. The spectral peak moves in frequency to high frequencies, linked with slick chemical structure and with meteorological and oceanic conditions, like wind.

A film at the ocean surface damps waves, implying then an energy decrease with distribution to high and short waves, and a spectral peak shift corresponding to the important surface stress decrease.

B. Influence of some parameters on slick radar measurement

Radar is sensitive to surface roughness, presented by gravity-capillarity waves, damped by slicks.

Radar backscattering level is decreased with slick, which appears as a dark patch with weak backscattering in comparison with surroundings in radar image, with at least 3 dB contrast.

From a synthesis of experimental previous studies, we deduce the best parameters to use to detect slicks, function of radar configuration, slick nature and meteorological and oceanic conditions.

1) Wavelength

Each frequency band is differently affected, function of wind speed and slick nature [10]. Several experimental studies with multi-frequencies consisting of tipping artificial slicks (MARSEN79, SAXON FPN, SAMPLEX92) have shown most important contrast with C, X and Ku-bands [11], with 5 dB contrast for a slick made with “light” fuel, and 10 to 15 dB contrast for an “heavy” fuel. Wave numbers less than 80 m^{-1} (L and S-bands) are weakly affected by slicks [12].

Strong winds are a real problem to the damping measurement. C-band frequency seems to be the most suitable frequency allowing to measure strong contrasts until wind speed about 13 ms^{-1} [13]. With ERS SAR (5.3 GHz frequency in C-band), contrasts from 6 to 17 dB are observed over slicks [14].

2) Polarization

The choice of polarization is function of radar frequency and wind speed. Some experiments have shown that there is no real difference between HH and VV polarization for slick study; however, VV polarization seems to be the most suitable for C-band, notably with strong wind [12].

3) Incidence angle

Reflection mode of the incident radar wave is function of incidence angle, there are two backscattering mechanisms: Kirchhoff mechanisms for 0 to 15° incident angle, and Bragg reflection for 20 to 70° angle which allows observing, with Bragg resonance phenomena, gravity-capillarity waves highly damped by slicks. Reflection backscattering coefficient decreases as incidence angle increases [15], it is also function of wind speed. With the 23° incidence angle of ERS SAR, theoretical damping for a slick is about 5 dB under weak wind and 3-4 dB under 10 ms^{-1} wind speed.

According to wind constraints and radar frequency used, the most suitable incident angle is about 20 to 45°.

4) Angle between flight direction and wind direction

For wind speed higher than 9 ms^{-1}, this angle has to be taken into account, as shown in the experimental studies SAXON FPN and SAMPLEX92 [11]. Ref. [10] shows that this angle has to be less than 30° with L and X-bands in order to get a significant contrast over slicks.

5) *Slick nature*

Wave damping, function of slick nature, is more important for oil slicks than for natural films [11]. The higher the elasticity, the higher the image contrast is, but there is no linear relation. Therefore, it is not easy to distinguish slick nature with contrast.

Thickness is also related to slick nature: oil slicks are thicker than natural films. Marangoni damping is valid for thick layers [7], but no experiment specifies thickness boundary size corresponding to boundary damping effect. Thus, this is not a good criterion in order to classify slicks. Otherwise, a radar measurement limitation is that slicks can only be detected if they are "new" slicks (radar wave does not penetrate ocean surface), and they are quickly carried in sub-surface, due to wave mixing.

6) *Influence of meteorological and oceanic conditions*

Some conditions induce same effects as slick appearance on satellite images: for example, weak backscatter areas exist for weak wind place, like in the lee of an island. Some other conditions like oceanic internal waves for example, quickly distort slicks which become less dense, thus less easy to be detected. SAR measurement is also limited to sea state related to meteorological conditions. When there is not enough wind, capillary waves are not created, radar backscattering becomes weak, and contrast is insufficient. Otherwise, so much wind induces an important backscattering and thus contrast decreases. Moreover, waves induced by strong wind quickly drag slicks in the ocean sub-surface, where it can not be detected.

For correct SAR measurement with C-band frequency, the wind speed has to be higher than 2-3 ms^{-1}, the upper wind speed value is less obvious to show, but some images have been made up to 10-14 ms^{-1}, function of parameters previously discussed (wavelength, incident angle, slick nature…). In other way, wind is a limitation for natural film generation, which can only exist for wind speed up to 3-5 ms^{-1}, it can help for classification step for wind higher than these values.

III. SLICK ANALYSIS

1) *Approaches*

Several approaches exist for slick analysis from satellites images. In prospect to obtain operational analysis, the first step consists of locating slicks and in detecting outlines with segmentation methods. The example of *Prestige* has shown that analysis must still be supervised. In cases of such disasters, quick results have to be obtained. One operational way consists of letting this step be the most automatic as possible.

Next step is slick classification: oil slick, upwelling, biological trash, etc… For that, statistical methods have been tested. Ref. [2] for example, shows that using statistical methods, 94% of cases are well analyzed. The principle consists of oil pollution observation that is mainly located in intense traffic area, near to harbors, refineries or offshore oil rigs, associated with thick slicks. The knowledge about favored locations of upwelling appearance and slick shape and size observations is of importance: illegal discharges are often associated with straight slick; natural film cannot cover a huge size... Recently, wind and tidal currents history have been added to images in order to determine slick age [16]. Satellite survey by ERS SAR has been used complementary to airborne survey during *Aegean Sea* wreck in 1992 for example [17], and ENVISAT ASAR satellite images have been analyzed during the *Prestige* disaster in 2002. These cases show that the main problem concerns the analysis speediness, and for this reason, automatic algorithms have to be tested quickly.

We present in this paper some examples of segmentation methods. Segmentation allows the knowledge of length, size and shape of slick with reliability, criteria which are used with statistical methods for slick classification. Segmentation methods can be performed with simple algorithms such as mathematical morphology only considering detecting black pixels on the image. Here, we show some original methods based on multi-scale analysis for surface characterization, presented by [18].

2) *Examples*

SAR image analysis starts with slick detection. This step works very well with method like Sobel filter or mathematical morphology for simple cases without any ambiguity, where slick boundaries are clearly marked and surroundings present important backscattering. Fig. 1 shows a case like this.

This is a SAR ERS1 image at 5.3 GHz frequency and 23° incidence angle, acquired on October, 3rd, 1992 near the Egyptian coast with at least five visible slicks with different shapes. We choose to study the area located on the right of the image, delimited by a square in Fig. 1 (Fig. 2a). It appears to be a simple case, and a method like Sobel filter is self-sufficient to delimit the slick outlines (Fig. 2b).

We propose to analyze now a part of ASAR ENVISAT image acquired on November, 17th, 2002, four days after *Prestige* wreck near Portuguese coast (Fig. 3). This case is very interesting in order to test segmentation methods because it is ambiguous. Two polluted parts seem to appear in the image, probably caused by the spread of two kinds of oil mixed in the tanker (source: *Le Cedre*). Although slick is clearly defined around the tanker (15 km South-West from white square lower left corner in Fig. 3), because outlines are sharply stood out, the part we chose to study, indicated by a white square in Fig. 3, is more complex. We have applied some algorithms on it.

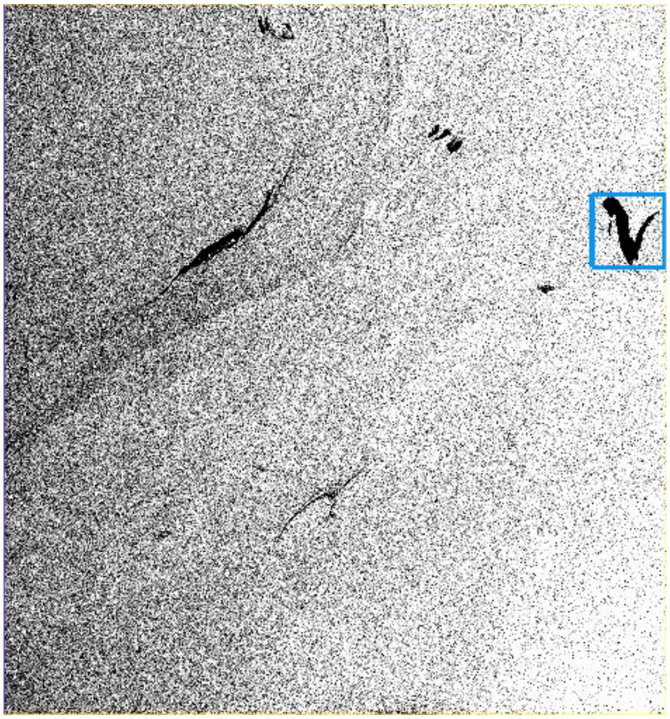

Fig. 1. Image from ERS1 SAR satellite, October, 3rd 1992 off the Egyptian coast (orbit: 6364 ; frame : 2961). The square shows the study area. ©ESA

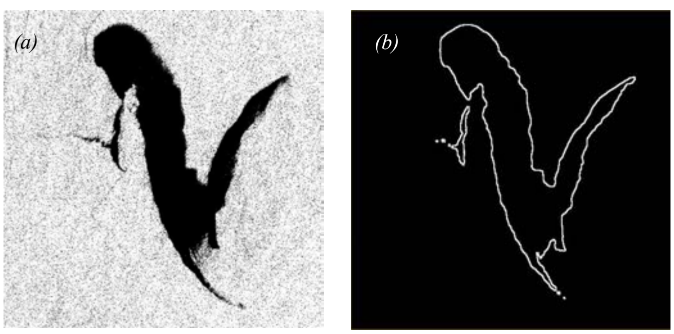

Fig. 2. a) Study area from Fig. 1 and b) analysis with Sobel filter.

A simple threshold segmentation method, applied with Sobel filter (Fig. 4a), highlights top and bottom outlines and shows a non-polluted part around the right of Fig. 4a, corresponding to an area in the middle of the two principal polluted parts (top and bottom). To avoid this ambiguity, we experiment a new approach, applying an ocean surface characterization, based on multi-scale analysis of the observed data, considering distribution systems with Markov chains algorithm for example, because oil and sea spectra have different distribution signatures. An example Fig. 4b presents three classes: black corresponds to oil, grey to clean sea and white an intermediate between these two first classes. Grey part corresponds well to Fig. 4a result, the white color allows to bring another information that we have to characterize (is it an area where oil is in sub-surface or is it a mixture between oil and water?) Fig. 4c and 4d concern the exact white square area shown in Fig. 3, where we applied a Gaussian distribution, with three classes (Fig. 4c) and four classes (Fig. 4d). The two oil polluted « arms » are visible. In Fig. 4c, black is oil, white is clean sea and grey is the intermediate area. This result highlights a grey zone from North to South. This ambiguity is probably not due to pollution (see Fig. 3), but related to weak wind with low radar backscattering.

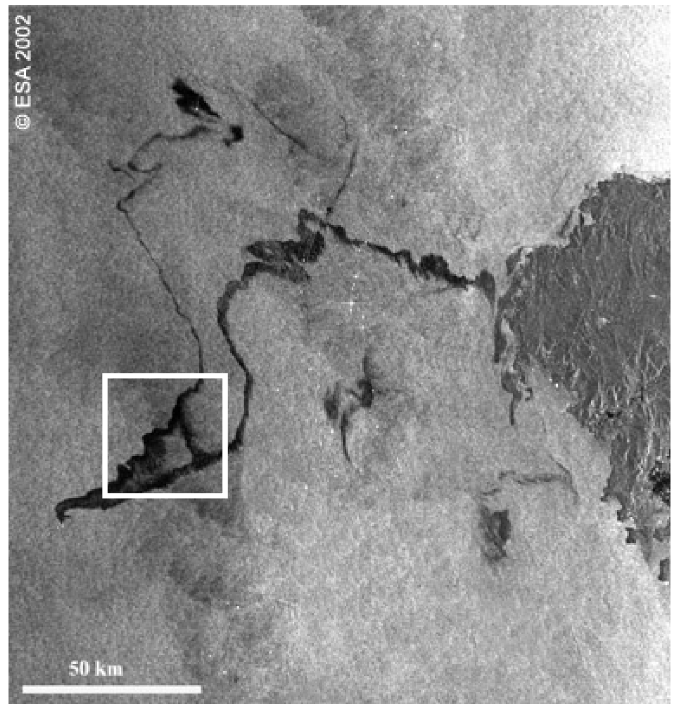

Fig. 3. ENVISAT ASAR image, November, 17th, 2002 off the Portuguese coast after *Prestige* wreck on November 13th (Wide Swath mode, orbit: 3741). The white square shows the study area. ©ESA

The problem is that Fig. 4c presents the same information for the probably non-polluted area from North to South and the area between the two « arms » of pollution in lower left corner. This result shows that it needs expert report in order to process this part. The analysis with four classes in Fig. 4d shows thinner polluted slicks than in Fig. 4c, and suggests a solution to the ambiguity previously discussed.

A segmentation method based on a multi-scale analysis allows characterizing each class and then better understanding ambiguous parts of the image.

An important work must be made to provide algorithms which would be able to analyze satellite images, simple and complex. With this example, the results have shown errors that we could make without expert report such as on the case of Fig. 4c for example. Fig. 4d analysis seems to be the most suited one, but the ambiguous part between the two polluted « arms » is not classified: covered with a mixture of oil and water or corresponding to a sub-surface oil polluted layer?

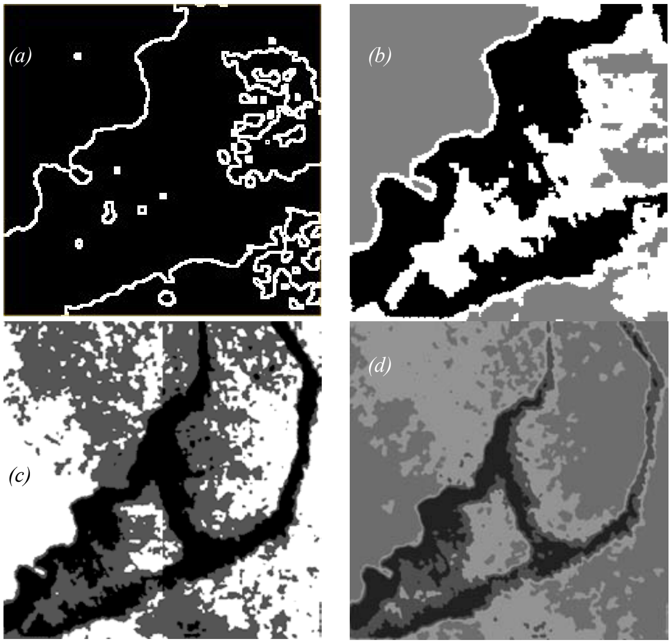

Fig. 4. Study area analysis on area defined in Fig. 3:
a) segmentation with Sobel filter, b) Markov chains with Pearson distribution system, c) Markov chains with Gaussian model distribution with 3 classes, d) idem as c) with 4 classes.

IV. CONCLUSION

SAR seems to be a suitable instrument for the ocean pollution study, well adapted because it does no depend on weather nor sunshine, which is an advantage when compared to optical measurements, for example, which is also used for pollution study.

The most suitable SAR radar configuration for oil pollution study is C-band radar frequency with VV polarization, with a 20 to 45° incident angle. This is the case for ERS and ENVISAT satellites. The constraints related to SAR measurements are of several kinds. First, wind speed value has to be between 2 to 10-14 ms^{-1}. Secondly, the image will be reliable only if pollution is still on the ocean surface, i.e. the measurement must be made just after slick generation, before it goes down in sub-surface layer. The spatial coverage is adapted to pollution survey (100 x 100 km for ERS; 300 x 300 km for RADARSAT, 400 x 400 km for ASAR Wide Swath ENVISAT). A problem is the satellite coverage frequency (35 days for ERS), but now ASAR ENVISAT allows covering every 3-4 days for accident cases, for example for *Prestige* wreck, but in operational context, it would be useful to improve this to have regular survey. The delay between acquisition and analysis must be shortened. Moreover, SAR image must be completed by another sensor measurement, for example in order to find slick thickness and nature (LIDAR? Imaging spectroscopy? Ultraviolet? Infrared?).

The importance of detection and classification steps have been highlighted in this paper, with a simple case on ERS image and with complex and ambiguous case with ENVISAT image of recent *Prestige* disaster, in which slick are visible from the tanker over an area of about hundred kilometers. Some algorithms have been proposed, and their tests show their respective defaults and qualities. An original approach based on ocean surface characterization works on simple and ambiguous cases here; it must be tested on several cases and is a new approach to follow. This is the first step in the way of operational survey, with regular satellite passes, quick data transmission and rapid detection analysis, that would be helpful for the following classification step and speed up decision process in case of illegal discharges for example.

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