Marine Pollution Bulletin 60 (2010) 91–102

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

On the SAR derived alert in the detection of oil spills according to the analysis of the EGEMP

Guido Ferraro [a,*], Björn Baschek [b], Geraldine de Montpellier [c], Ove Njoten [d], Marko Perkovic [e], Michele Vespe [a]

[a] European Commission (EC) – Joint Research Centre (JRC), Institute for the Protection and Security of the Citizen, Via E. Fermi, 21027 Ispra, Italy
[b] Federal Institute of Hydrology, Am Mainzer Tor 1, 56068 Koblenz, Germany
[c] Management Unit of the North Sea Mathematical Models (MUMM), 100 Gulledelle, 1200 Brussels, Belgium
[d] Norwegian Coastal Administration, Nostegaten 30, 5010 Bergen, Norway
[e] University of Ljubljana, Faculty of Maritime Studies and Transport, Pot Pomorscakov 4, 6320 Portoroz, Slovenia

ARTICLE INFO

Keywords:
Sea satellite monitoring
SAR
Oil spills
Alert system designs
Maritime surveillance

ABSTRACT

Satellite services that deliver information about possible oil spills at sea currently use different labels of "confidence" to describe the detections based on radar image processing. A common approach is to use a classification differentiating between low, medium and high levels of confidence. There is an ongoing discussion on the suitability of the existing classification systems of possible oil spills detected by radar satellite images with regard to the relevant significance and correspondence to user requirements. This paper contains a basic analysis of user requirements, current technical possibilities of satellite services as well as proposals for a redesign of the classification system as an evolution towards a more structured alert system. This research work offers a first review of implemented methodologies for the categorisation of detected oil spills, together with the proposal of explorative ideas evaluated by the European Group of Experts on satellite Monitoring of sea-based oil Pollution (EGEMP).

1. Introduction

Among the different types of marine pollution, oil is a major threat to the worldwide seas ecosystems. The source of the oil pollution can be the mainland or directly at sea. Sea-based sources are mainly discharges coming from ships or off-shore platforms.

Oil pollution from sea-based sources can be accidental or deliberate. Fortunately, the number of marine accidents and the volume of oil released accidentally are on the decline. On the other hand, routine tanker operations can still lead to the release of oily ballast water and tank washing residues. Furthermore, fuel oil sludge, engine room wastes and foul bilge water, produced by all type of ships, also often end up in the sea. Therefore, oil tankers and other kinds of ships are among the suspected offenders of deliberate (operational) oil discharges.

The international legal regime concerning pollution from ships is defined in the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), which in Annex 1 deals specifically with prevention of pollution by oil. MARPOL distinguishes between oil pollution outside or inside "Special Areas". Almost all the seas around Europe have been designated Special Areas according to Annex 1 of MARPOL 73/78. Only the Norwegian Sea, the Bay of Biscay and the Iberian Coast are not covered by the Special Area status. In Special Areas, oil discharges from ships have been completely prohibited, with minor and well-defined exceptions.

Satellites equipped with Synthetic Aperture Radar (SAR), can provide information on the presence of oil at sea. The presence of oil film on the sea surface damps the small capillary and short-gravity waves and drastically reduces the Bragg scattering and therefore the measured backscattering energy, resulting in darker areas in SAR imagery (Kubat et al., 1998; Solberg et al., 1999; Del Frate et al., 2000). However, dark areas may be also caused by other phenomena, called 'look-alikes', such as organic film, grease ice, wind front areas, areas sheltered by land, rain cells, current shear, internal waves and up-welling zones. As a consequence, an important factor to be taken into account for the analysis of oil at sea is related to wind information, which can be obtained by external data sources or derived from SAR images (Salvatori et al., 2003) through the inversion of the CMOD IFR2 or CMOD4 model (Stoffelen and Anderson, 1997; Monaldo and Kerbaol, 2004). Prior to the wind speed, the wind direction can be extracted by 2D-FFT image processing as discussed by Horstmann et al. (1998). A detailed state-of-the-art for oil-spill detection methodologies by SAR remote sensing is offered by Brekke and Solberg (2005) and Topouzelis (2008).

* Corresponding author. Tel.: +39 0332 789488; fax: +39 0332 78915.
E-mail address: guido.ferraro@jrc.ec.europa.eu (G. Ferraro).

0025-326X/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2009.08.025

Several studies (among them: Ziemke (1996), Kubat et al. (1998), Solberg et al. (1999), Del Frate et al. (2000), Fiscella et al. (2000), Pavlakis et al. (2001), Topouzelis et al. (2002, 2007), Nirchio et al. (2005), Ferraro et al. (2007, 2009), and Karathanassi et al. (2006)), European projects (OCEANIDES, ROSES, MARCOAST) and operational services (e.g. European CLEANSEANET, and the Canadian ISTOP) aiming at oil-spill detection have been implemented. Most of these studies rely on the detection of dark areas, which have a high probability of being oil spills. Any formation on the image which is darker than the surrounding area has a probability of being an oil spill and needs further examination. Such probability is associated to the discrimination capability between oil slicks and look-alikes, and is fostered in order to provide consistent support to law enforcement for the detection of perpetrators of operational spills. The SAR derived oil-spill detection probability estimation has been mathematically explored as an intrinsic aspect of oil spill classification, which fundamentally computes the likelihood that the detected dark area and its extracted features are related to an oil spill. Brekke and Solberg (2008) and Topouzelis (2008) gave a full state-of-the-art overview of the currently investigated approaches. In this paper, the term “detection” is used to address the dark objects appearing on the SAR image that identify potential oil spills, whereas the term “feature” is associated to typical characteristics exhibited by objects of interest. The specific feature extraction and evaluation is tuned by a set of descriptive parameters. Ultimately, the decision making process represented by oil spill discrimination and confidence level estimation is represented by mathematically modelled “criteria”; i.e. empirical conditions and rules applied to the evaluated features.

The SAR derived discrimination boundary allows the estimation of a measurable degree of confidence, which is especially useful when a set of priorities are to be defined and a contingency plan has to be outlined after significant oil pollution. The data fusion operated on a set of heterogeneous sources of information, namely (i) the SAR based image processing and extracted features, (ii) met-ocean information, (iii) contextual information and (iv) potential impact information. The possibility of verification shall eventually determine the alert level associated with the detection. This methodology has been widely accepted although not yet investigated for automatic implementation and therefore is considered in strong experience dependency. Although looking at different phenomena, it is worth mentioning similar directions followed for oil seep classification. Williams and Lawrence (2002) proposed a categorisation of natural seepage into ranking levels according to context (geologic and geographic), backscattering contrast, repetition of the emission and geometric features of the detected dark patches.

In this research work, the Bonn Agreement requirements are introduced in Section 2. An overview of the state-of-the-art of oil spill alert systems approaches is then given in Section 3, in particular describing different detection and classification categorisation methodologies that are currently implemented. The consequent rationale for the confidence level estimation is presented according to the EGEMP analysis in Section 4. Conclusions are eventually drawn in Section 5.

2. The need for clarification. The Bonn Agreement request

In the framework of the Bonn Agreement (Bonn Agreement website) the issue of confidence level has also been discussed and the need to agree on a common terminology has been raised (Bonn 07/2/4, 2007). The Bonn Agreement is the first regionally-developed framework for executing surveillance as an aid to detecting and combating pollution and preventing violations of anti-pollution regulations (Bonn Agreement website). This international agreement was signed in 1969, following some major oil spills, and entirely revised in 1983. The agreement was developed to encourage the North Sea States to jointly improve their basic capacity for combating and monitoring oil pollution. The Bonn Agreement has been ratified by North Sea coastal States (Belgium, Denmark, France, Germany, the Netherlands, Norway, Sweden, and the United Kingdom) together with the European Community. Ireland is in the process of acceding to the agreement and Spain follows the activities with observer status. The accession of Ireland will greatly enlarge the maritime areas covered by the Bonn Agreement, and this is in line with the MARPOL Convention (Annex I) which has already enlarged the North Sea Special Area to the Celtic Sea around Ireland. With its history of more than three decades of cooperation among North Sea states, the Bonn Agreement can be seen as the leading regional agreement in the field of surveillance and combating marine pollution.

Special attention has been paid by the Bonn Agreement Contracting Parties to the use of satellite imagery in the last few years. At present, Bonn Agreement Contracting Parties in their routine daily surveillance operations receive, through the CLEANSEANET service (CLEANSEANET website), satellite imagery taken by ENVISAT and RADARSAT satellites. The Contracting Parties of Bonn raised in particular the counterproductive issue, in case of legal proceedings, that the terminology of “confidence levels” could cause.

Also in the evaluation workshop of a large scale joint surveillance operation called “Super-Cepco”, held in Brest 11–13 September 2007, the issue was raised that the terminology applied may cause a problem in a court case. If a satellite image is included as a part of the evidence, “low confidence” could be regarded as doubtful as to whether the suspected vessel released oil. This could result in counter productive evidence especially when the radar data is the main indication of a violation of MARPOL regulations. According to the Bonn Agreement, however, with the term “confidence level”, the provider only indicates the quality of the radar detection. Wind speed and direction, sea current, natural phenomena and also release of substances that influence the surface tension of the seawater cause an effect on the quality of the radar detection. Among Bonn Agreement Contracting Parties it is commonly known that interpretation of a Side Looking Airborne Radar (SLAR) image by aerial surveillance operators involves a professional judgement of the image of the sensor: to determine whether the detected slick and the total SLAR image is of high quality. For instance, during hours of darkness and very low wind speed the operator may decide to cancel the flight because the quality of the SLAR image will be too low.

The currently applied “confidence levels” and the corresponding definitions, even if considered useful, can be misinterpreted in a legal framework. Therefore it may be worth considering, in order avoiding debates in court, revising this classification approach. The analyst, after evaluating the image, has to raise the awareness of the receiver that in the satellite image there is something (detection) that calls for follow-up “and thus that, based on the overall quality of the SAR detection, the likelihood of a possible pollution is present in the image” (Bonn 07/2/4, 2007). What is important is to discriminate between the quality of the SAR image and the possible presence of an oil slick, since the analyst may reduce the probability of the presence of an oil slick in a weak satellite image.

Considering the necessity of attaching an indicator to an image, the Bonn Agreement Contracting Parties proposed by to apply the following terminology (Bonn 07/2/4, 2007):

a. *Red alert:*
   - a trail attached to a ship (AIS data available) or platform;
   - a slick in a ship traffic separation scheme of at least 10 miles or a radius of 5 miles.

b. *Alert:*
   - a slick or trail with a ship or platform, not connected, but within 10 miles distance.

c. *Informative alert:*
   - a free floating slick or trail in a ship traffic separation scheme; or
   - a free floating slick within 12 miles from the nearest land.

Last but not least, the Bonn Agreement invited discussion of the issue at the EGEMP meetings to further elaborate on the terminology taking into account the various aspects, including the legal proceedings (Bonn Agreement minutes 2007, see Bonn Agreement website).

3. Satellite based oil-spill detection services; detection approaches and "confidence level classification systems

Today, operational satellite based oil-spill detection services are mainly utilising SAR sensors onboard satellites such as ENVISAT and RADARSAT-1 and -2. In order to reduce the problem of reporting "look-alikes" as potential spills, the human satellite-service operators use additional information such as wind velocity (model or SAR wind) or other sea-state conditions to support the classification of the extracted features. Moreover, visual inspection of the image may provide additional information about the specific shape, surroundings and edges of the feature.

Following the common approach, the specificity of these features is used to deduce a probability that the detected dark object is caused by oil. The combination of such criteria and the judgment of the operator yield a conclusion as to whether the feature is finally reported as a possible oil spill. Due to the manual detection approach, the quality of the resulting product is not always constant as there are differences between the individual operators of one service and their subjective judgment of the features in the satellite images.

In order to objectify the SAR analysis and to provide decision support to the user, the detected potential oil spills are classified according to confidence levels, which are supposed to describe the probability that an observed dark feature in the satellite image is caused by an oil spill.

3.1. Classification systems

Tables 1 and 2 provide details on the different confidence level systems existing today. In addition to the currently used classification criteria, other information are often delivered (e.g. size of observed detection, distance of detection to the coast), which are not directly used to assign a certain probability that the observed detection has been correctly identified as mineral oil. This information is rather intended to support decisions on follow-up actions to be taken by the responsible organization.

A further issue becomes evident when taking a look at the above mentioned confidence criteria: commonly, a ship or an oil rig, which is connected to the detection, is regarded as a significant characteristic of an illicit discharge. However, the fact that a possible polluter is directly connected to the observed detection or is visible in the vicinity of it (i.e. a white dot in the SAR image is connected to an observed black spot; sometimes AIS is also available) does not automatically increase the probability of a true positive. At best, it represents an indication but it may especially be misleading in areas of dense ship traffic. Such information may

Table 1
Existing satellite based oil-spill detection services – oil-spill detection approaches and classification systems.

No.	Service name	Service provider	Project/ organization	Detection approach	Classification system
1	North Sea and Baltic Sea oil-spill detection service	KSAT	MarCoast	• Manual • Inspection of SAR image by operator under consideration of additional information • Classification by operator	• *Oil spill:* high, medium, low confidence level • *No oil spills:* no classification
2	French oil-spill detection service	BOOST Technologies	MarCoast	• Semi-automatic • Inspection of SAR image by operator (supported by image segmentation processing) • Consideration of additional information	• *Oil polluted area:* no classification • *Feature of interest:* no classification • *Clean sea notification:* no classification
3	Oil-spill detection service in the Mediterranean Sea	TELESPAZIO	MarCoast	• Semi-automatic • Inspection of SAR image by operator (supported by image segmentation processing) • Consideration of additional information (met-ocean data, automated ship detection and AIS correlation) • Classification by operator	• *Oil spills:* high, medium, low confidence level • *No oil spills:* clean sea status high, medium, low confidence level
4	Canadian oil-spill detection service	Integrated Satellite Tracking of Pollution (ISTOP) project	Environment Canada	• Classification by operator	• *Potential oil spill:* Categories 1A, 1B, 2 and 3
5	CleanSeaNet	KSAT/TELESPAZIO/ EDISOFT	EMSA	• Semi-automatic (but KSAT – manual) • Inspection of SAR image by operator under consideration of additional information • Classification by operator	• *Oil spill:* high, medium, low confidence level • *Clean sea notification:* high, medium, low confidence level
6	Norwegian Oil Spill Service for NOFO (Norwegian Clean Sea Organization) Off shore operators	KSAT	NOFO	• Manual • Inspection of SAR image by operator under consideration of additional information • Classification by operator added in a risk matrix	• *Oil spill:* high, medium and low based on a risk matrix • *Clean sea:* high, medium, low

Table 2
Confidence level criteria of existing satellite based oil-spill detection services. The numbering of the services follows Table 1.

No.	Confidence level criteria		
1	High • The slick has a large contrast to grey-level surroundings • The surroundings are homogenous, with a constant grey-level • The wind speed is moderate to high, i.e. approximately 6–10 m/s, or above • Ship or oil installation directly connected to slick	Medium • The wind speed is moderate to low, i.e. approximately 3–6 m/s • The slick has a diffuse/low contrast to the grey-level surroundings in moderate to high wind speed • The shape of the slick is irregular, i.e. the edges are not smooth	Low • Low wind areas are located nearby • Natural slicks (e.g. biological, algae or fractal streaks at very low wind) are located nearby • The slick has diffuse edges and an irregular shape
2	• This service distinguishes between (a) oil spills, (b) features of interest and (c) clean sea notification		
3	• The operator determines the following criteria for potential oil spills: - Contrast (weak, medium, strong) - Edges (diffuse, sharp and diffuse, sharp) - Slick type (tail, angular, linear, patch, droplet) - Slick shape (smooth, irregular, fragmented) - Source (ship, oil installation, AIS, other) - Surrounding (homogeneous, inhomogeneous) - Wind (speed, direction) • Based on these criteria, the confidence level is determined		
4	• The following categories are determined for potential oil spills: - *Cat 1A:* potential oil present with target attached - *Cat 1B:* potential oil present with target in area (defined by a 50 km sq radius from centre of potential pollution) - *Cat 2:* potential oil present, no source in area - *Cat 3:* potential oil present, low confidence (e.g. due to low contrast of feature), no source in area [unsure, if oil present]		
5	• The confidence level criteria are similar to the services of KSAT and Telespazio within MarCoast and are applied by the service providers in all service areas		
6	• Same as row 1		

be relevant and valuable for decisions on follow-up activities concerning the prosecution of potential polluters. Such criteria for one specific possible follow-up procedure should not be mixed with the criteria determining the probability of a correct oil-spill detection based on SAR image interpretation. Tables 1 and 2 provide details on some of the confidence level systems existing today (Table 1), the currently used classification criteria (Table 2), and the summary of parameters used for classification (Table 3). In particular, Table 2 shows how different approaches have been implemented to assigning confidence levels by the existing satellite services. These approaches differ in the number of classes, the mathematical model mapping of the criteria (e.g. different ways to define how a shape is irregular), and the implemented separation criteria (e.g. classification thresholds and rules).

3.2. Confidence level defined by OCEANIDES project

The problem of standardising as much as possible the analysis of a SAR image to detect an oil spill was raised and tackled in the framework of the OCEANIDES project (OCEANIDES website). In particular, Solberg et al. (2005) analysed the benchmarking of oil spill recognition as performed by Kongsberg Satellite Services (KSAT website), QinetiQ (QinetiQ website) and the Norwegian Computing Center (NR website). One of the questions was "Do all operators have the same confidence of finding a slick and do they all assign the same confidence?" Even if the conclusion was that in general there is reasonably good agreement between KSAT, QinetiQ, and NR of detected high-contrast slicks, there are variations in the confidence assigned by the different algorithms and operators, and more consistent rules for assigning confidence should be investigated.

In the OCEANIDES project, KSAT detailed its oil-spill detection approach. In particular, to confirm the reliability of a detected possible instance of oil pollution the operators utilize information about wind speed and direction, which is provided from weather models by meteorological institutions. Information about oil rig/pipeline locations, national territory borders and coastlines can also be overlaid on the image to assist in the analysis. After oil pollution is detected it is classified as a high, medium, or low probability/confidence of being actual oil pollution. KSAT operators used the guidelines presented in Table 2, row 1, to determine the confidence level of a slick.

A similar procedure for assigning a confidence level was performed by QinetiQ, but the rules were not detailed.

For the analysis of ENVISAT images, the automatic algorithm at the Norwegian Computing Center was based on a statistical model. For RADARSAT images, NR tried to implement an automatic confidence assignment based on the set of rules described by KSAT. Confidence High is assigned if a ship or platform is directly connected to the slick, the wind speed is medium or higher, the surroundings are homogeneous and contrast high. Confidence Medium is assigned if the contrast is fairly good, surroundings fairly homogeneous. Otherwise Confidence Low is assigned. The criteria for assigning Confidence High turned out to be so strict that no slick in the benchmark data set was assigned Confidence High.

3.3. The Canadian system of categorisation of assimilated SAR data environment Canada and MDA ISTOP project

The Integrated Satellite Tracking of Pollution (ISTOP) program has been operational since 2006 and was implemented by the Canadian Ice Service as described by Gauthier et al. (2007). The detected slicks are delivered through the product distribution system first as a preliminary alert (De Abreu et al., 2006). The potential candidates are further analysed and subsequently categorised according to ship and oil-spill detection operations performed on the basis of visual and automatic techniques (Armstrong, 2007). Namely, the event can be characterised as reported in Table 2, row 4.

The listed categories represent an alert level associated to the detected oil spill. It is worth noting that the contextual information of the proximity of the discharging vessel has a substantial impact on the likelihood to be able to assign a polluter to a potential spill. Furthermore, the potential spill aerial verification is performed

Table 3
Summarized classification criteria.

Type of information	Classification criteria	Examples
Feature related (by image analysis)	Geometry of slick	Tail shaped
	Structural aspects	Irregularities in shape
	Appearance of the edges	Sharp edges
	Grey-level values and contrast to surroundings	High contrast to homogeneous surroundings
Detection constraints	Sea-state conditions (at position of feature and concerning surroundings)	Feature in low wind areas
	Other features in area	Possible algae blooms
Maritime situation	Information on possible polluters	Ship connected to feature

only for Categories 1A, 1B and 2, whereas for the Category 3 events, the detection is further investigated only if assets are in the proximity of the region of interest.

3.4. Oil spill confidence level classification within the MARCOAST project

Within the MARCOAST project (MARCOAST website) there were three different classification schemes by three different services in use. These schemes differed in the number of classes, the used technical separation criteria, as well as in the character of classes; i.e. if there is a class with "features of interest" – rather not considered as a possible oil spill – or not (Tables 1 and 2). The MARCOAST validation (MARCOAST website, MARCOAST service validation protocol) was performed following a standardized service validation protocol (Baschek et al., 2007). Ideally, the applied confidence level assignments should be reflected in the available validation data by a significantly higher percentage of confirmations for "high confidence" satellite derived oil spill candidates. However, the validation of the MARCOAST services (MARCOAST validation reports, not published, summary available on the MARCOAST website) showed that the difference in level of confidence of detected features did not always correspond to the probability of finding an oil slick, e.g. by checking the site by aerial surveillance. The possible reasons for this discrepancy are manifold; however, three main causes are (i) the quality and reduced size of the validation data sets, (ii) limitations due to the applied SAR based technology, and (iii) the classification system itself. Validation results showed that different circumstances render it complicated to receive suitable and large validation data sets. A major constraint of in situ validation data is the time lag until a feature can be validated by an aircraft or a ship. Even if an oil spill has been present at the time of the satellite overpass, there are many processes altering the pollution in such a way that it may no longer be visible at the time the validating aircraft (or ship) is at the site. Besides, fresh oil might have been spilled in the meantime, which may appear to the crew of the aircraft as a "false negative", i.e. missed oil-spill detections. Therefore, false positive rates and false negative rates have to be considered with care. Furthermore for an improvement of the data basis for validation, the feedback formats for reporting the outcome of checks by aircraft or ships of the satellite detections need to become better standardized and harmonized. However, for operational purposes a significant difference in probability between the levels of confidence is important. Thus, the necessity for an improvement of the existing classification systems towards a decision support tool was stated. This reflects the fact that there is not a unique set of requirements to an oil spill satellite service. Local differences in, for example, mission, legal background, regional maritime effects, lead to different operational requirements. Above all, in some cases the main focus lays on pollution combat and in others on prosecution of polluters.

3.5. Confidence level defined for the Norwegian national service

KSAT, the Norwegian Coastal Administration and the Norwegian Space Centre have recently focused their attention on improving the assessment process for the detection of oil spills in SAR imagery. The Operator's Manual for Slick Analysis in SAR images (Furevik et al., 2005) constitutes the basis for the KSAT assessment of SAR images with respect to oil pollution detection and reporting. The final outcome of this methodology is a *confidence value* – high, medium or low. The confidence setting process is based on a wide range of parameters related to the probability that the observed slick is caused by oil, as illustrated in Fig. 1. The assessment process is divided into four steps:

A. identification of suspicious slicks;
B. determination of slick type;
C. slick source identification; and
D. confidence setting.

KSAT is a major oil detection service provider, mainly to EMSA – the European Maritime Safety Agency – but also to private customers and national agencies with special needs. One of the private customers already requires KSAT to use a risk-based notification scheme.

3.6. The EMSA CLEANSEANET Service

The EMSA CLEANSEANET (CSN) satellite service offers all EU Coastal Member States, Iceland and Norway a near-real time marine oil-spill detection service by using radar satellite imagery acquired by the ENVISAT and RADARSAT-1 and -2 SAR satellites. The service covers all European sea areas and is integrated within the national and regional oil pollution surveillance and response chains. The complete process, from the image acquisition to the oil-spill detection takes 30 min maximum.

CSN is based on three regional service providers (KSAT – Northern Europe, Telespazio – Southern Europe, EDISOFT – Atlantic coast) that acquire and process satellite data. Then they proceed with the oil spill analysis and deliver the results to the Coastal States and to EMSA. Such results identify potential oil spills by a three-stage confidence level (low, medium and high) or a "clean sea" notification. The classification approaches adopted are similar to the ones implemented within the MARCOAST project and are illustrated in Tables 1 and 2.

4. The EGEMP discussion

In the framework of EGEMP, there is an ongoing discussion about the suitability of the existing classification systems of possible oil spills detected by radar satellite images with regard to the significance of their declaration and their correspondence to user requirements. When a user receives a near-real time alert by a satellite service about possible oil pollution at sea, his main task is to decide which follow-up procedures are to be taken. There are many possibilities for action. Some examples are listed in the following – often, one of these is a starting point leading to a chain of combinations of other actions:

- perform own re-analysis of image;
- check further information (e.g. AIS, local sea-state conditions, nautical and maritime information about the specific position);

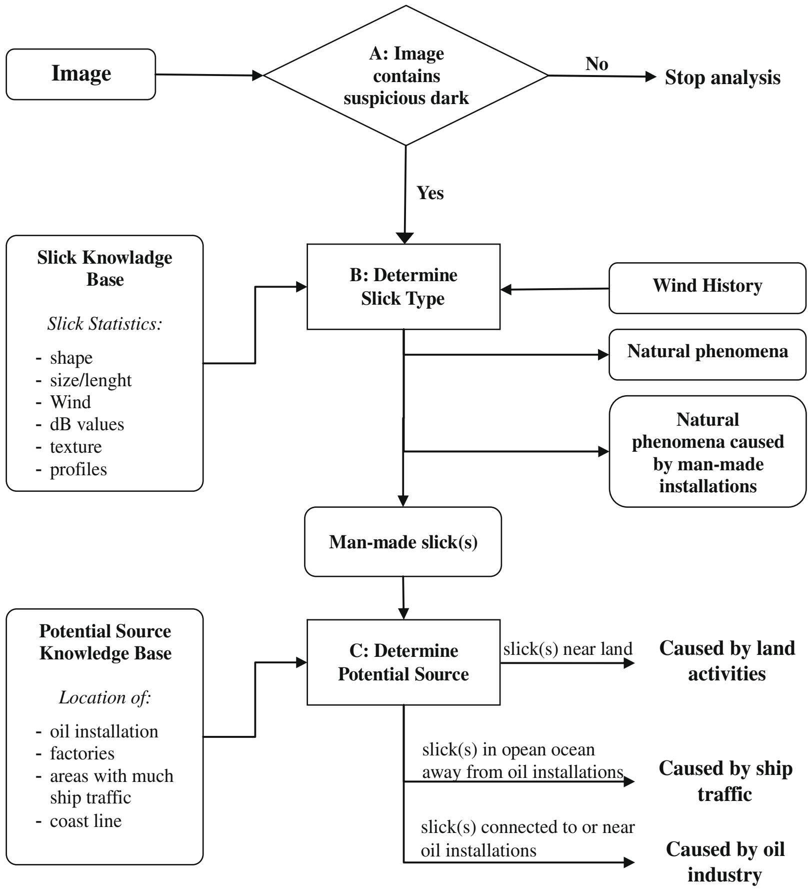

Fig. 1. Flow diagram for the detection of slicks in SAR images, Furevik et al. (2005).

- check corresponding position by aerial surveillance (aircraft, helicopter) or by patrol vessel;
- ignore; i.e. under given circumstances and considering national prerequisites no need/no possibility for other follow-up procedure;
- send out pollution response vessels or other units;
- distribute information to other authorities;
- initiate judicial investigation/follow-up and prosecute;
- initiate/require port state control inspections or other investigation concerning potential polluters;
- contact captain of potential polluter;
- initiate sampling of pollution; and
- perform drift model run for prognosis or back-tracking.

The satellite services are not expected to provide a pre-defined decision about which follow-up action should be taken, rather aim at delivering enough transparent information to allow the user to take his decision on a profound basis. If the oil spill alert contains detailed information in a standardized format, the user could be supported in his decision by their own national response plan. Such a plan can consider the metadata of the alert and the range of possible values and propose actions to be taken depending on certain key figures. Examples of information, which could be provided by satellite service alerts, are listed in (A). Here, one can differentiate between data characterising the outcome of the analysis of an image as a whole (A1) and features describing one specific detection, for which an alert was issued (A2). Besides, such a plan (or the user itself) can – and has to – consider additional national requirements that a pan-European satellite service can not consider. These are general national circumstances and prerequisites (B) as well as other, mostly operational factors specific to actual situations (C).

(A) Examples for information satellite service alerts could provide:

(A1) Data characterising the outcome of the analysis of an image, e.g.:
- Quality of image, or a subset of the image, with respect to probability of detecting mineral oil.
- Information about errors in processing chain (e.g. satellite or ground station failure).
- Number of detected dark patches.
- Absence of dark patches – and estimation of probability that mineral oil would not have been detected.

(A2) Features for characterising one specific detection, for which an alert was issued, e.g.:
- Probability that dark area is caused by mineral oil.
- Probability that dark area is caused by vegetable or fish oil.
- Probability for different kinds of false alerts.
- Potential polluter in the vicinity – chance to catch polluter red handed.
- Other characteristics such as position, size, shape.

(B) General circumstances and prerequisites that determine the user's decision will vary from user to user. These aspects should not be delivered by service providers since it would represent a pre-decision process on behalf of the user. Possible influencing factors are, e.g.:

- Legal background and specific task of user, most of all, main responsibility of the user's organization; e.g. response pollution, prosecution of polluter, or other, such as search and rescue, VIP transport, etc.
- Policy concerning possibility of pollution; e.g. zero tolerance – i.e. is it preferred to receive more alerts, even if this increases the number of false alarms, in order to avoid false negatives?
- Size and characteristics of surveillance area (e.g. sensitivity of area with regard to pollution, frequency of presence of algae or ice).
- Technical equipment of user organization, office hours and structure of staff.

(C) Other, mostly operational factors specific to actual situation influencing the users decision can be, e.g.:

- Regional weather and sea-state conditions – e.g. storm, presence of algae, ice, etc.
- Operational means available (e.g. due to time of day, technical reasons, etc.).
- If respective dark area is oil, what pollution potential does it present? Distance to zones of special sensitivity (e.g. national parks, tourist areas) and size, amount, kind of pollution influence this aspect.
- If dark area is oil, is there a need or chance for pollution response? Size, amount, kind of pollution, its position and distance to response units, and the sea-state are relevant to this factor.
- Information about spills (or look-alikes) from other sources.

As can be seen from the previous list, each user has to consider a huge set of boundary conditions which may be different among users. As most users are nationwide users, the terminology "national requirements" is sometimes adopted. The information should be presented in a comprehensive way and not be too complex, leading to the possibility to include specific national requirements.

Users need the satellite service to meet their specific information needs for taking their decision about follow-up procedures. Thus, the satellite service should have enough objectivity or at least transparency to allow the users to build their decisions upon it.

4.1. The matrix approach to redesign alert classification

The *matrix* alert regime proposed by Norway is characterised by a matrix visualisation output and is based on classification of impact (I), probability classification (P) and classification of verification (V).

- *Alert level*
  The corresponding notification/alert regime may be as follows:
  - *Red:* alert immediate phone call to the client.
  - *Orange:* alert SMS to client.
  - *Yellow:* alert e-mail to client.
  - *Green:* alert website information. An additional index is used to inform the end-user if the alert has been raised or lowered due to verification potential (see classification of verification).
- *Classification of impact (I)* The impact classification is the main new feature of the proposed Norwegian SAR assessment procedure. The main criteria for impact classification are:
  - Oil drifting trend vector.
  - Distance to Environmental Sensitive Areas (ESA) or shoreline. This requires environmental sensitivity knowledge and oil drifting information. For evaluation purposes, a very simplified regime may be used for testing purposes as described in Fig. 2. The oil drift trend vector and time markers towards shoreline should be displayed as a SAR image layer. The end-user must know that this is a trend vector only. Further wind and ocean current forecasts should be used by the end-user to evaluate the real impact potential of a possible oil slick. When available, GIS with high priority environmentally sensitive areas may be used in addition to shoreline distance. The main parameter is time; i.e. to identify the shortest "estimated time to impact an Environmental Sensitive Area".
- *Classification of probability (P)* The proposed classification of probability is a "rule-based" approach as shown in Fig. 1 and is further described by Furevik et al. (2005).
- *Classification of verification (V)* The third dimension is related to the alert level itself. After P and I classification of the SAR observation, the verification potential may rise or lower the alert level:
  - *Automatic red:* the slick is connected to an identified object (ship, platform, pipeline, industry), or to off-shore installations. Wind speed is above 10 m/s.
  - *+1 Level:* back-tracking or other vessel identification investigation possible, off-shore installations. Wind speed is below 10 m/s.
  - *No level change:* slick in area of human activity, but no primary candidate detected.
  - *−1 Level:* very remote location, any follow-up action is demanding.

The classification of probability (P) and impact potential (I) can then be related to the matrix in Table 4.

4.2. The bar-chart approach to redesign the classification systems

The *bar-chart* approach, similarly to the *matrix* one named after the alert visualisation strategy, was developed by the German EGEMP members taking into account the experiences gained during their work as the Validation Bureau Oil Spill and as the User Federation for the MARCOAST project. It is clear that users require a support tool (i.e. the alert messages) for the decision regarding how to proceed with the information contained in the satellite images and which follow-up procedures to take. The user requirements and their information needs are of various character or "multi-dimensional", respectively. In addition, two different users will commonly also have a different set of boundary conditions to base decisions upon. Consequently, they will have different requirements. Therefore, a single service aiming at fulfilling the requirements of all users needs to be "multi-dimensional" as well.

Following the above rationale, the German experts suggest a possible flow of information displayed in Fig. 3, starting from the

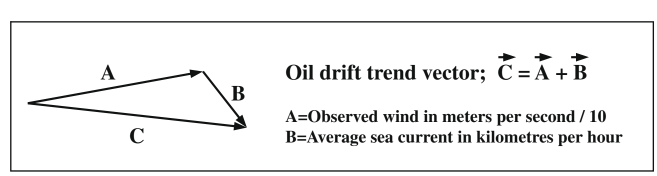

Fig. 2. Oil drift trend vector.

Table 4
Matrix alert regimes.

PROB	Impact		
	I-Low	I-Medium	I-High
P-High	Yellow level	Orange level	Red level
P-Medium	Green level	Yellow level	Orange level
P-Low	Green level	Green level	Yellow level

satellite image and leading to a user decision on follow-up procedures. The service provider converts and analyses the satellite image including additional information such as, for example, wind information, AIS layers, etc., leading to a standardized, transparent and detailed alert message of the derived information. Generally – i.e. no matter whether there is an issue for an alert of a specific detection or not – the services could add an additional layer to the map display and to the alert message. Such a layer could show a classification of the probability of detection for the complete area of the image; i.e. for each spot a measure of the likelihood of the detectability of oil spill events, no matter if there are actual oil spill candidates present or not. This would give the user a clearer overview about the significance of the actual analysis. An area of about 400 $\times$ 400 km, as can be typically covered by a radar satellite image, is normally non-homogeneous and the significance will vary from position to position. This classification would help the user to optimise his own surveillance activities such as, for example, (i) re-check an area without specific alert but high danger for look-alikes (and thus false negatives) or (ii) not to re-check an area with aerial surveillance but concentrate on other areas. Such classes could be "area with low/high danger for look-alikes" or "good/low probability that an oil slick would be detected", mainly depending on suitability of wind conditions.

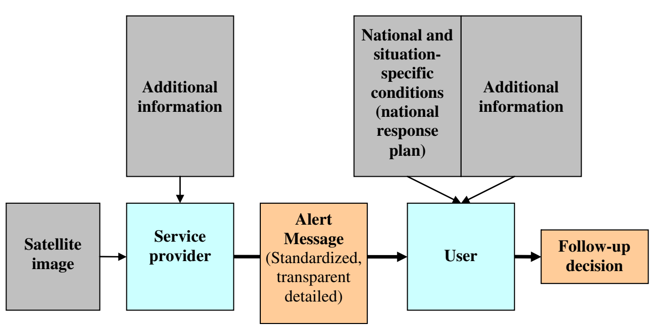

Fig. 3. Information flow for follow-up decision.

This probability layer would contain information – depending whether there was an alert of a feature or not – about the probability of false alarms or false negatives, respectively. Such an area could be characterised by features like number of black objects in the vicinity, calm wind areas, algae, etc. The question of when to send an alert for a specific detection is difficult to answer on a European level and will need some more discussion – as seen, user requirements can be quite different. Therefore, it might be necessary to have one standardized way of classification but to make the service flexible by defining for each user individual limits regarding when to send an alert.

Instead of a classification system with three levels of confidence, a more detailed classification system is suggested for specific detections, which could be visualised with the help of a bar-chart with several features (Fig. 4). This would provide more detailed information to the national decision makers for the follow-up procedures. Such parameters could be:

- Probability that the detection is caused by an oil spill (e.g. shape, contrast, etc.).
- Probability for look-alike, split into probability for specific look-alikes as fish/vegetable oil, calm areas, algae.
- Quality of detection (related to the SAR image quality and sea backscattering homogeneity).
- Existence of indications concerning possible polluter factors, e.g.: ship attached, AIS track along detection, number of other vessels in vicinity.

For each of these parameters a set of determining features needs to be defined. There is a need for discussion about whether the "probability that a detection is caused by an oil spill", strictly should only consider mineral oil or also include fish and vegetable oil. The major question is whether there are enough and significant criteria to allow for discrimination. In addition to the bar-chart, for each detection, the alert should contain a list of comments explaining the choice of a certain classification level as well as additional information such as satellite, sensor, date, time, position, size, wind speed as number, comments about contrast, surrounding, shape, etc. As a next step to be taken, the input and experience by service providers with regard to feasibility (also considering the near-real time requirements) and an explicit suggestion for a realization should be obtained. The national response plan could include possible values of the output of the detailed information messages by

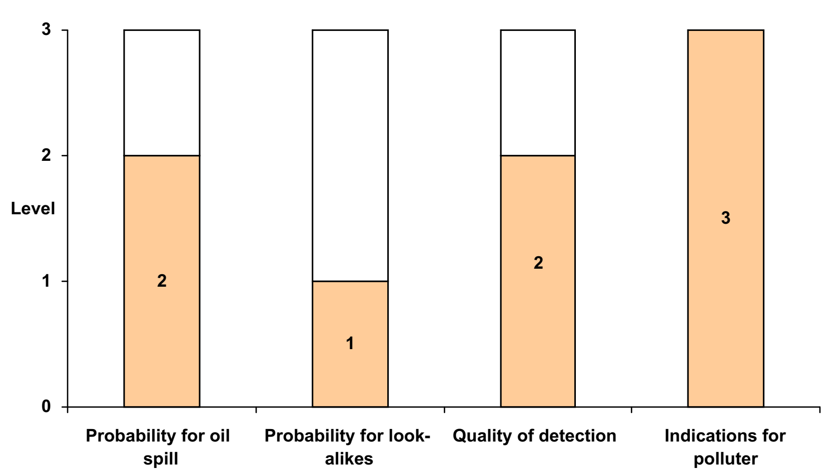

Fig. 4. Visualisation of the *bar-chart* alert system.

the satellite providers and transfer them into a national decision scheme. For operational purposes many users will prefer to give back to the satellite services providers the information under which conditions they want to receive what kind of alert level. The *matrix* approach contains – though still based on the "old" three levels of confidence – one example as to how such a nationally adapted "traffic light" alert system could appear.

5. Alert classification and terminology

Satellite services are not expected to provide a pre-defined decision about which follow-up action should be taken. However they aim to deliver enough transparent information to allow the user to take decisions on a well grounded basis. To achieve this, JRC and Belgium (through the Management Unit of the North Sea Mathematical Models – MUMM) propose contextual criteria in order to improve the European alert system, rather than criteria used for determining the validity of the detection. In this context, the alert system design will be revised and discussed as well as the current alert classification and terminology. According to the Bonn Agreement, the term "confidence level" exclusively indicates the radar detection quality as determined by the provider. This quality is affected by external factors and/or release of substances that influence the surface tension of the seawater. For now, the providers take into account external factors like data on wind speed. This section will focus on the radar detection quality classification and terminology in particular. Satellite image interpretation will be dealt with later.

To avoid a legally counterproductive issue, UK experts suggested replacing the terminology "confidence", meaning trust or faith in a person or thing, by "assurance", meaning a statement or assertion intended to inspire confidence (definitions according to the Oxford English Dictionary). This change in terminology was suggested as a compromise with regard to legal issues. "Reliance", for instance, could be an equally acceptable concept. However, lawyers have to verify whether this terminology is qualified as evidence for oil slick pollution after satellite detection. Thus, choices and definitions of "confidence" terminology are still open to further discussion. Concerning the alert levels, Belgium would propose that a significant "high assurance level" would mean "clear mineral oil detection alert", whereas "medium and low assurance level" oil detection would be joined together (to avoid "false positives", i.e. incorrect oil spill declaration) and replaced by "informative alert". This "informative alert" would include all look-alike oil-spill detections which are not considered as "high assurance". Finally, "green alert" could mean "no detection via alert system", taking in mind that an oil slick can be missed because of the possible non-homogeneous wind conditions on a satellite image. This alert categorisation is close to the previous French alert system (used before the EMSA system, between 2002 and 2008) with "oil polluted area", "feature of interest" and "clean sea notification". "Oil polluted area" means mineral oil being discharged or recent mineral oil already discharged. With this category, the detection has a high probability of being mineral oil and can be coupled with AIS data (without verification by aerial surveillance) to be used as a proof in legal proceedings. The term "feature of interest" is not as clear as the term "oil polluted area" and needs further verification on the field. Finally "clean sea notification" represents no detection via alert system.

5.1. Redesign of alert system

This section summarizes this comparison, and reflects the current views of Belgium and JRC with a new proposed alert system. The above detailed *bar-chart* approach is more conceptual, focusing on the generic aspect, whereas the *matrix* approach describes how a nationally adapted alert (as is also mentioned in the *bar-chart* approach) could look like. Those approaches are not contradictory. Having existing satellite based oil-spill detection services (see Table 1), Germany and Norway proposed additional criteria to complement the interpretation of the feature. These are crucial in the European context, especially in the interpretation of an "informative alert". The new alert system is therefore based on "SAR image quality criteria" and "additional criteria", leading to the definition of "further actions" to be taken by the end-users. The "additional criteria" are related to the national context and are relevant for the alert system. As a consequence, a better understanding of the image context allows adequate follow-up actions. This principle is similar to that of the *bar-chart* approach. However, by excluding the maritime situation, Belgium and JRC propose to make a clear difference between the "SAR image quality criteria" whether or not the detection is likely to be an oil slick ("SAR derived oil spill probability" and "additional information – e.g. metoceanic (Muellenhoff et al., 2008), contextual"), and secondly the assessment criteria including possible sources/polluter (indicating maritime situation) and environmental impact. They are respectively categorised into "culprit identification capabilities", and "impact factor". In Section 5.2 a number of interesting criteria are described as suggested in the present paper: each of them can enrich the image interpretation according to different aspects. The redesign of the alert system shall be based on the diagram illustrated in Fig. 5.

5.2. Criteria: choice and classification

The main challenges here are both the choice of criteria and the way they will be implemented in the European alert system, keeping in mind that they have to be nationally user oriented.

5.2.1. Criteria related to SAR image quality

5.2.1.1. SAR derived oil spill probability. SAR derived oil spill probability can be grouped as follows: features related to image processing, information about errors in the processing chain, image quality with respect to the probability of detecting mineral oil, features related to image analysis (like geometry of slick, structural aspects, appearance of the edge, grey-level values and contrast to surroundings), and detection constraints like sea-state conditions (at position of feature and concerning surroundings; e.g. SAR wind speed). Other features, such as possible algae blooms, will be analysed in the "additional information (e.g. metoceanic and contextual"). This leads to a first radar detection quality analysis

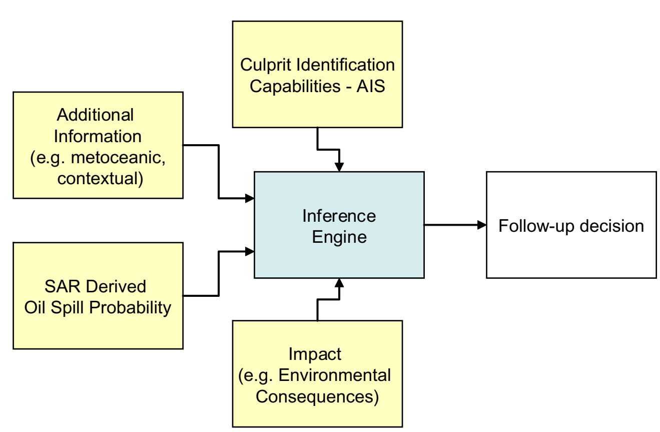

Fig. 5. Proposed alert system compiling the *matrix* and *bar-chart* approaches.

"assurance" (see "alert terminology and classification") as already carried out by CSN, which does not yet consider the maritime situation/information and the environmental impact. At this stage, the user alert setting is a first alert indication on the SAR detection quality.

5.2.1.2. Additional information (e.g. metoceanic and contextual). Contextual information can improve the probability of detecting oil spills as well as reducing the number of false positives. Indeed, human contextual criteria like traffic lines, secondary routes, oil spill archives, oil rigs and other human installations likely to release oil slicks are essential to the confidence level classification. Among metoceanic contextual criteria, SAR (and data from national institutions) wind speed and direction, as well as sea surface current distributions have an influence on the sea surface. Current shear zones can be seen on SAR images as linear features, which may be confusing in low wind conditions. Sandbank presence may create surface disturbance visible on SAR image but are unlikely to be mistaken with oil-spill detection. This could therefore constitute a valuable metoceanic contextual criterion. False positives may result from algae bloom presence, but they are difficult to assess and to define. An important question is on which basis algae quantities can be considered as a bloom and influence the sea surface and consequently the SAR image. Further research needs to be conducted. For now criteria like spatial and temporal data of Chlorophyll-*a* concentration and of algae blooms can have an added value to the SAR image interpretation. Sea Surface Temperature (SST), another important metoceanic criterion, can provide information about the presence of possible front lines and algae bloom, and therefore contribute to diminishing the false positive alerts. Bathymetry criterion is also important regarding cases of Annexe 2 of the MARPOL Convention.

5.2.2. Criteria related to the context

5.2.2.1. Impact factor. The *matrix* approach introduced criteria such as environmentally sensitive areas/resources, distances to shorelines, and oil impact trajectory models (see Section 4.1) in order to assess environmental sensitivity. SAR images cannot provide an indication of the quantity of oil at sea. Therefore it is important to assess the possible impact of oil pollution. This addresses the need for additional information on the drift of the detected slick (oil drift trend), the area possibly concerned and its environmental sensitivity. Even small quantities of oil might have a big impact on the environment. The competent national authority needs detailed information to decide on follow-up measures to oil-spill detection. The environmental sensitivity of the Norwegian coast, for instance, is mapped and divided into different sensitivity priorities, which differ according to summer and winter time, as the sensitivity may be different in different seasons. Still, many detected spills produce no additional information on the polluter, and take place far from environmentally sensitive areas. These observations might require a different follow-up than in cases where the polluter has been detected, or the scene of the spill is near a sensitive area. Norway has been working with satellite surveillance since the early 1990s, operationally since 1997. They have experienced that satellite surveillance is a good supplement to the existing surveillance systems (aircraft, ships, etc.). Therefore Norway aims to delineate a system where the alert level determines clearly the importance of the detection.

5.2.2.2. Culprit identification capabilities – AIS. The fusion of data deriving from drifting models, AIS and SAR could yield criteria for indicating potential culprits. The vicinity of ships has usually been considered as further confirmation of the oil-spill detection probability since it increases the SAR detection likelihood of being actual oil spills. Moreover, this "rough" information can now be completed with contextual sources (AIS traffic and shipping routes). On the other hand, the probable spill, and the navigation route of a potential culprit (through use of historic AIS data) should be taken into account in order to increase the alert level of the detection, since this could lead to further verification and follow-up action. Belgium proposes also to add a filter for non-fixed structures (e.g. aquaculture) and to pay attention to the fishery boats which are not included in the AIS system but are likely to release fish oil slicks.

5.3. Classification, visualisation, and delivery time service

Instead of a global classification system with three levels of confidence, a more detailed classification system is suggested for SAR image analysis, but also for the specific criteria. This has the risk of increasing the delivery time. Therefore when developing an improved alert system, the criteria must remain feasible and the experience of service providers with regard to feasibility should be taken into account (also considering the near-real time requirements). For example, a first alert could be sent to the member states within 30 min with SAR image quality criteria, and followed by a refined interpretation of the detected spill based upon the other criteria. The *bar-chart* system (see Fig. 4) with three levels of confidence seems to be an interesting visualisation methodology for end-users. In addition to the *bar-chart*, each detection of the alert system should also contain a list of comments explaining the choice of a certain classification level, in the same manner as in the *matrix* alert setting. The *matrix* visualisation concept shows the alert message with a colour flag system which is also based upon three levels of confidence. The complete analysis will have a time frame of 50 min in the Norwegian system, which is longer than the previous CSN alert system (30 min). However, they have already selected the specific criteria adapted to their national context. In Norway, the end-user is responsible for defining 'large area', the boundaries for sensitive areas and shorelines, and sources other than AIS targets and SAR ship detections. There is also a need for further discussion and research, which criteria must be chosen and whether enough suitable information is available, in order to obtain (possibly adapted) operational criteria with an appropriate content and value for the end-user.

This refined interpretation could be performed equally by all end-users: all the criteria should be available in the form of additive GIS layers on the CSN browser. Such an alert system could be seen as an "informative system". Nevertheless, the quality of the final alert interpretation is strongly correlated to personal judgement, the knowledge of the end-users as well as the availability of the additional criteria.

6. Conclusion and perspectives

In this paper, the analysis of the current state-of-the-art related to oil-spill detection and classification systems has been illustrated from a technical (i.e. image processing and data fusion) and operational (i.e. follow-up and law enforcement) points of view.

The problem of oil spill follow-up decision making effectively interweaves aspects related to multiple criteria, ranging from SAR derived information and ancillary data inference, to the potential impact factor of the area under investigation. Instead of a three-level classification system, more articulated SAR image analysis approaches and specific additional criteria have been summarized and commented on for the reliability estimation of the detection.

The German and Norwegian views have been introduced concerning the rationale of the corresponding *bar-chart* and *matrix* alert systems. Although similar in principle, the two approaches differ in the choice of the specific criteria and the concrete design of the alert message. In particular, Norway has experienced that illegal spills are usually small in quantity but require rapid follow-up. Furthermore, Norway aims to integrate additional information such as AIS with back-tracking capabilities, as well as SAR image detection on vessels to trace the suspected polluter. On the other hand, the environmental sensitivity is assessed through new and valuable criteria. In the proposal of Germany, a set of determining parameters needs to be defined for each of the proposed criteria. Here, the choice of criteria has to be considered as an example to be improved according to the European Member State requirements. There is a need for discussion regarding whether the "probability that a detection is caused by an oil spill", should consider exclusively mineral oil or also include fish and vegetable oil. The major question is whether there are sufficient criteria to allow well-defined distinction since it is not possible to discriminate between mineral and fish oil form SAR images only.

By combining the *bar-chart* and *matrix* alert system, a novel approach is proposed, based on the combination of SAR image quality parameters to improved additional criteria. Such supplementary criteria intend to augment the oil spill alert detection based on "SAR image quality criteria" by considering the opportunity to launch a prosecution and the risks of environmental damage in relation to environmental sensitivity. This new method aims to provide adequate information to the end-users to enable them to perform additional image interpretation and thus support the follow-up decision making process.

Aspects related to culprit identification have also been presented, illustrating the need for linking the scientific and legal sides of the issue. In particular, as proposed by the UK, the terminology "assurance" should be used in place of "confidence" when classifying potential oil spills. Moreover, the output of the classification stage on potential detections should be considered either "high assurance" or "informative alert". This aims to avoid "low confidence" characterisations that have a counterproductive result in court. Nonetheless, further investigation is required in order to assess the legal basis of the proposed terminology, leaving the definition of "confidence" still open to further discussion.

Aspects related to the information visualisation and delivery time have also been introduced, illustrating the trade-off between output accuracy and system execution time. A possibility could be to divide the alert message processing into two consecutive stages, successively activated depending on the alert entity. Another alternative could be to exclude from the alert system the interpretation of specific criteria which can be considered as a part of the end-users task. The latter methodology can be fulfilled by providing specific criteria in the form of GIS layers that could be visually inspected by the operator. More discussion and research are needed (i) to select adequate criteria that are not too time-consuming to process, (ii) to quantify the limits of the alert level of each criterion in different areas, (iii) to investigate optimal ways to visualise multi-dimensional information, and (iv) to map the criteria into adequate alert levels.

References

Armstrong, L., 2007. Surveillance of sea surface activities in Canada using earth observation satellites and aerial surveillance sensors. In: 11th International Oil Spill Conference, Perth, 26–30 March 2007.

Baschek, B., Nyenhuis, M., Lange, U., et al., 2007. MarCoast – Marine and Coastal Environmental Information Services: Service Validation Protocol. Issue 3.0. BfG-report 1617. Federal Institute of Hydrology, Koblenz, Germany.

Bonn 07/2/4, 2007. Document on "confidence levels in satellite images". Presented by the Netherlands at the 19th Meeting of the Bonn Agreement Contracting Parties, Brussels 10–12 October 2007. Available on Request at the Secretariat of the Bonn Agreement <secretariat@bonnagreement.org>.

Bonn Agreement website. <http://www.bonnagreement.org> (accessed 15.07.2009).

Brekke, C., Solberg, A., 2005. Oil spill detection by satellite remote sensing in the world oceans. Remote Sensing of Environment 95, 1–13.

Brekke, C., Solberg, A., 2008. Classifiers and confidence estimation for oil spill detection in ENVISAT ASAR images. Geoscience and Remote Sensing Letters, IEEE 5 (1), 65–69.

CLEANSEANET website. <http://cleanseanet.emsa.europa.eu> (accessed 15.07.2009).

De Abreu, R., Gauthier, M.F., Van Wychen, W., 2006. SAR-based oil pollution surveillance in Canada: operational implementation and research priorities. In: OceanSAR 2006 Proceedings – Third Workshop on Coastal and Marine Applications of SAR, St. John's, NL, Canada, October 2006.

Del Frate, F., Petrocchi, A., Lichtenegger, J., Calabresi, G., 2000. Neural networks for oil spill detection using ERS-SAR data. IEEE Transactions on Geoscience and Remote Sensing 38 (5), 2282–2287.

EGEMP website. <http://egemp.jrc.ec.europa.eu> (accessed 15.07.2009).

Ferraro, G., Bernardini, A., David, M., Meyer-Roux, S., Muellenhoff, O., Perkovic, M., Tarchi, D., Topouzelis, K., 2007. Towards an operational use of space imagery for oil pollution monitoring in the Mediterranean Basin: a demonstration in the Adriatic Sea. Marine Pollution Bulletin 2007 (54), 403–422.

Ferraro, G., Meyer-Roux, S., Muellenhoff, O., Pavliha, M., Svetak, J., Tarchi, D., Topouzelis, K., 2009. Long term monitoring of oil spills in European Seas. International Journal of Remote Sensing 30 (3), 627–645.

Fiscella, B., Giancaspro, A., Nirchio, F., Pavese, P., Trivero, P., 2000. Oil spill detection using marine SAR images. International Journal of Remote Sensing 21 (18), 3561–3566.

Furevik, B., Hamre, T., Babiker, M., Kloster, K., Elisassen, R., 2005. Operators Manual for Slick Analysis in SAR Images. NERSC Special Report, NERSC, No. 75.

Gauthier, M.F., Weir, L., Ziqiang Ou, Arkett, M., De Abreu, R., 2007. Integrated satellite tracking of pollution: a new operational program. In: IEEE Geoscience and Remote Sensing Symposium, 23–28 July 2007. pp. 967–970.

Horstmann, J., Koch, W., Lehner, S., Rosenthal, W., 1998. Ocean wind fields and their variability derived from SAR. ESA Special Earth Observation Quarterly 59, 8–12.

Karathanassi, V., Topouzelis, K., Pavlakis, P., Rokos, D., 2006. An object-oriented methodology to detect oil spills. International Journal of Remote Sensing 27 (23), 5235–5251.

Kongsberg Satellite Services. <www.ksat.no> (accessed 15.07.2009).

Kubat, M., Holte, R.C., Matwin, S., 1998. Machine learning for the detection of oil spills in satellite radar images. Machine Learning 30 (2–3), 195–215.

MARCOAST website. Marine and Coastal Environmental Information Services. <http://gmes-marcoast.com> (accessed 15.07.2009).

Monaldo, F., Kerbaol, V., 2004. The SAR measurement of ocean surface winds: an overview. In: Proceedings of the Second Workshop on Coastal and Marine Applications of Synthetic Aperture Radar, Svalbard, Norway. SP-565, European Space Agency, pp. 15–32.

Muellenhoff, O., Bulgarelli, B., Ferraro, G., Topouzelis, K., 2008. The use of ancillary metocean data for the oil spill probability assessment in SAR images. Fresenius Environmental Bulletin 17, 1–8.

Nirchio, F., Sorgente, M., Giancaspo, A., Biamino, W., Parisato, E., Ravera, R., Trivero, P., 2005. Automatic detection of oil spills from SAR images. International Journal of Remote Sensing 26 (6), 1157–1174.

Norwegian Computing Center, NR. <www.nr.no>.

OCEANIDES webpage. <http://oceanides.jrc.it> (accessed 15.07.2009).

Pavlakis, P., Tarchi, D., Sieber, A., Ferraro, G., Vincent, G., 2001. On the monitoring of illicit discharges – a reconnaissance study in the Mediterranean Sea, European Commission, EUR 19906 EN. <http://serac.jrc.it/midiv/pub/jrc_illicit_study.pdf> (accessed 15.07.2009).

QinetiQ. <www.qinetiq.com> (accessed 15.07.2009).

ROSES webpage. Real Time Ocean Services for Environment and Security. <http://roses.cls.fr> (accessed 15.07.2009).

Salvatori, L., Bouchaib, S., Frate, F.D., Lichtenneger, J., Samara, Y., 2003. Estimating the wind vector from radar SAR images when applied to the detection of oil spill pollution. In: International Symposium on GIS and Computer Cartography for Coastal Zone Management.

Solberg, A., Storvik, G., Solberg, R., Volden, E., 1999. Automatic detection of oil spills in ERS SAR images. IEEE Transactions on Geoscience and Remote Sensing 37 (4), 1916–1924.

Solberg, A., Clayton, P., Indregard, M., 2005. OCEANIDES Project, Deliverable 2, Report on Benchmarking Oil Spill Recognition Approaches and Best Practice. <http://oceanides.jrc.it/Deliverables/D2_final.pdf> (accessed 15.07.2009).

Stoffelen, A., Anderson, D., 1997. Scatterometer data interpretation: estimation and validation of the transfer function CMOD4. JGR 102, 5767–5780.

Topouzelis, K., 2008. Oil spill detection by SAR images: approaches and algorithms. SENSORS Journal 8, 6642–6659.

Topouzelis, K., Karathanassi, V., Pavlakis, P., Rokos, D., 2002. Oil spill detection: SAR multiscale segmentation and object features evaluation. Proceedings of SPIE, Image and Signal Processing for Remote Sensing XII (6365), 77–87.

Topouzelis, K., Karathanassi, V., Pavlakis, P., Rokos, D., 2007. Detection and discrimination between oil spills and look-alike phenomena through neural networks. ISPRS Journal of Photogrammetry and Remote Sensing 1 (62), 264–270.

Williams, A., Lawrence, G., 2002. The Role of Satellite Seep Detection in Exploring the South Atlantic's Ultradeep Water, in Surface Exploration Case Histories: Applications of Geochemistry, Magnetic, and Remote Sensing. AAPG Studies in Geology No. 48 and SEG Geophysical References Series No. 11, pp. 327–344.

Ziemke, T., 1996. Radar image segmentation using recurrent artificial neural networks. Pattern Recognition Letters 17 (4), 319–333.