On C-Band SAR Based Oil Slick Detection in the Baltic Sea
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1 Introduction

We at FIMR are developing an operational algorithm utilizing satellite-borne C-band SAR instruments (Radarsat-1, Envisat, Radarsat-2) for oil slick detection in the Baltic Sea area. In this paper the main emphasis is to report on a case study in the Baltic Sea where totally smooth sea surface gradually becomes roughened with visible waves in open sea conditions. On the basis of this we can give a geophysically based estimate (4 m/s) for a lower threshold in the reliable oil spill detection. Also the temporal variation of wind conditions in the Baltic Sea is documented and related to the oil spill detection problem. We also shortly discuss about our experience on the usability of three backscattering models in connection of oil spill monitoring, our spill detection procedure and how well some automatically derived oil slick statistics agree with subjective visual interpretation of potential oil spills.

2 Wind dependent boundary conditions for oil slick detection

2.1 Some theoretical aspects

When the wind begins to blow over a calm sea surface, the water is set flowing and the whirls in the flow cause pressure differences that break the flat surface. The wind catches these tiny ‘wrinkles’ and starts to grow them up to waves. The most important factors that control the growth of the waves are the wind speed, the wind duration and the fetch.

We first consider a simplified situation where the waves would grow to visible size immediately after the wind speed exceeds critical wind speed $U_{cr}$. In such case the spatial appearance of wave covered areas could be illustrated by a curve that represents the fluctuations of the wind speed $U$ as function of time and by a line that represents the critical wind speed $U_{cr}$ which is required to generate visible or measurable waves. When wind speed begins to increase, at first all maxima remain under $U_{cr}$: at this point no waves have appeared on a smooth sea surface. When $U$ has increased enough, some part(s) of the curve exceeds $U_{cr}$. The waves begin to appear inside the corresponding regions of sea surface. As $U$ further increases, more and more parts of the curve exceeds $U_{cr}$. Finally, at some $U$ all minima have exceeded $U_{cr}$; at this point the whole sea surface has become roughened with visible waves.

In reality the sizes of the patches of waves remain smaller than the size of the regions where $U > U_{cr}$ due to the fact that a minimum fetch and duration is required to generate the visible waves, i.e., $U_{cr}$ is fetch and time dependent. Furthermore, the relative size of the patch of waves compared to the area where $U > U_{cr}$ is smaller at low mean wind speed as it is at higher mean wind speed because wave growth is faster at higher wind speed. As the patches of waves are the only quantities that can be observed on sea surface, the empirical curve that gives the relative fraction of the wave-covered sea surface grows slower than the one in the simplified situation.

The steepness of the empirical fraction curve is also affected by other phenomena. Natural surface films (even monomolecular layers on the surface) efficiently dampens the small scale waves. The shapes of the wind generated patches become more or less irregular and the areas smaller than they would be on a surface of pure water. Hence, the curve becomes less steep and more irregular compared to the pure water case. The effect of water temperature comes through viscosity which increases as temperature decreases. This implies that in colder water the whole curve will be shifted horizontally to the right.

2.2 Wind speed and the relative fraction of waves covered sea surface

The R/V Aranda of FIMR was located on September 9th 2002 at 59°15’ N and 21°00’ E in the Baltic Sea when the sea surface became first totally smooth and then started change gradually rougher. Each dot in Fig. 1 indicates a 10 minute mean wind speed measured at 17m height with the weather station of R/V Aranda. The mean wind speeds over the area of interest were computed from these values by using the Taylor’s frozen turbulence hypothesis.
Figure 1: On the left mean wind speed on September 9th 2002 between 00:00h and 24:00h as measured at R/V Aranda. On the right a schematic figure of occurrence of wind generated wave patches (x-axis: time, y-axis: wind speed). The mean wind speed is marked with red line, the critical wind speed with blue line.

Figure 2: Wind generated wave patches when wind speed is 1.2 m/s (left), and 1.5 m/s (right). The two patches have grown together as wind speed has increased.

Figure 3: The empirically determined wave covered surface area as a function of wind speed (red curve). The green line shows a theoretical wave covered area for pure water as a function of wind speed when mean wind speed is 2.1 m/s and standard deviation 0.5 m/s and assuming that waves become visible immediately when $U > U_{cr}$. 
At several occasions between 14:00 and 18:00 local time (UTC+3hrs) the state of the sea surface was recorded as a panorama footage with a digital video camera (at wind speeds 1.2, 1.5, 2.2, 2.5 and 3.2m/s). The individual frames were used to compose for each wind speed situation a panorama image and then the panorama images were used to approximate the relative portion of the wave covered sea surface area. Due to the lack of space we must omit the details of these not totally trivial computations.

We include images shown in Fig. 2 as an example of the development of the wind generated wave patches. In the first image two separate patches can be seen that have been grown together when wind speed has increased from 1.2m/s to 1.5m/s (the latter image). In the latter image the effect of the natural surface films can be clearly seen as 'two fingers'. In pure water the patches are more circular.

The resulting empirical fraction growth curve is shown in Fig. 3. During the measurements sea temperature was 20.5°C. According to our knowledge this case study is the first time that the curve has been defined empirically in open sea conditions. By visual inspection, the critical mean wind speed is about 2.1m/s (50%-point). One should take into account that the observed value is not the inception wind speed where the waves begin to grow but the wind speed when they become visible. It involves the affects of fetch and surface films and represents local conditions. The obtained value is in agreement with the results of [1].

The temporary variability of wind speeds at Kalbådagrund light house. Green bar indicates wind speed less than 4 m/s, red bar wind speed over 10 m/s, blue bar the rest of wind speeds. Source: Finnish Meteorological Institute.

2.3 Temporal variability of reliable oil slick detection

The oil can reliably be detected by the C-band SAR sensor only if the wind is not too low or too high. Both smooth sea surface due to the low wind speed and surface oil film covered sea areas, where small scale capillary-gravity waves have been have dampened, appear as dark areas in a SAR image. On the basis of Fig. 3 we chose wind speed 4 m/s as a minimum wind speed which allows a reliable oil spill detection (a conservative choice). If the wind speed is high enough, waves induced by strong wind break an oil spill and mix it into the ocean sub-surface. SAR based oil spill observations have not been reported and verified in the Baltic Sea if the wind speed has exceeded 8 m/s. This lead us to choose 10 m/s as an upper limit for the reliable oil spill detection.

To assess how often the SAR can detect oil spills with a great confidence, the wind statistics of Kalbådagrund, a lighthouse in the Gulf of Finland with a distance of 30 km to the coast line, during the years 1991-1999 were analyzed. The study utilized wind data from Finnish Meteorological Institute measured at 31.8 m height. The data covered a time period from 1991 to 1999 and 10 minute mean wind speeds, $\bar{U}$, computed every 3 hours.

We observe that approximately 50-70 % of the time wind speed allows a reliable oil slick detection from SAR-images. From the point of view of oil detection, the best wind conditions are in July (70 % of time) and the worst in January and December (55 % of time).

3 On backscattering models in the thresholding

To utilize wind information in the oil slick detection, three backscattering models were studied: the integral equation model (IEM) [2], CMOD4 [3] and CMOD5 [4] models. Comparisons of the model results to our SAR data suggest that of these models CMOD5 best describes the backscattering behaviour for Radarsat-1 SAR data over the Baltic Sea, often the dynamic range of the CMOD5 data is similar to that of the corresponding SAR images, unlike for IEM and CMOD4. However, the shapes of the model and the SAR histograms do not correspond to each particularly well, an example is shown in Fig. 5. This is partly due to uncertainties in the used forcing wind fields (HIRLAM weather forecast model, 9 km grid size, temporal resolution 1 h).
Validation of the HIRLAM model results show that even 2 m/s wind speed error may occur at low wind speeds (less than 4 m/s), the rms being about 1-2 m/s.

A more detailed analysis using the CMOD4 and CMOD5 models showed that on the incidence angle range between 25 and 30 degrees the model results showed relatively good agreement with the RADARSAT-1 based $\sigma^0$ values when wind speed was between 4 m/s and 7 m/s. At low wind speed (less than 3.5 m/s) $\sigma^0$ values provided by the CMOD4 and CMOD5 showed too narrow range compared to actual SAR measurements, at high wind speeds (speed over 7 m/s) model based $\sigma^0$ values were on average too large compared to SAR measurements.

Our experiences indicate that it is impossible to utilize these models directly in thresholding the SAR data. Instead, the modelled wind field can be used as an aid in oil slick detection. In many cases the HIRLAM model is capable of locating areas of low backscattering, and we can then compare the model values with the local SAR backscattering and if both SAR and model values are low, the dark area is very probably caused by wind, see Fig. 7.

Figure 6: The strength of backscattering as a function of radar measurement angle. The width of potential oil slick as a function of the wind speed.

4 On the oil spill detection algorithm

The algorithm consists of four major steps. First, a thresholding is performed for the SAR data to locate dark pixels, the thresholding is based on the local incidence angle $\theta$ and wind speed $U$. The theoretical backscattering based on the model is
used as an additional information in uncertain cases. The applied thresholding rule has a form

\[ T(\theta, U) = a \theta + b U + c - d, \]  

(1)

where the parameter values are determined from a large sample of simultaneous SAR and HIRLAM measurements using the least squares criterion. The obtained parameter values are \( a = -0.61, b = 1.53, c = -6.62, \) and the \( d \) is a free thresholding parameter, the value \( d = 2.5 \) is used here. In the next stages the pixels are handled as segments, i.e. sets of pixels connected in their 8-neighborhood. In the second stage the segments are filtered based on the segment size (very small and large segments are discarded), and a morphological closing operation is performed to reduce the effect of scalloping noise. In the third step a set of features for each segment is computed (based on backscattering and segment shape). The shape is rather well characterized by the skeleton of a potential oil slick (computed using the Hilditch algorithm [5]). Among the skeleton based features are its length, skeleton length ratio to the oil slick area (this property detects well thin features with or without curvature) and the amount of branches (complexity of a potential slick). In the last step a confidence level, i.e. a number in the interval \( \in [0, 1] \), is given for each slick. The confidence level is computed based on the set of features. The algorithm requires the local incidence angle, wind speed and direction, in addition to the SAR pixel values, as its inputs.

To assess the performance of the algorithm we have a training data set consisting of 78 potential oil spills collected from 31 Radarsat-1 ScanSAR images during 2002-2005. Human operators have identified these oil slicks from the images and have assigned confidence levels to them (“high”, “medium”, “low”). Part of the oil slicks have been verified to be real oil discharges, the true nature of the rest of the slicks being unknown. Some statistics based on this training set is shown in Fig. 6. We can see that the difference between mean values of oil slicks and surrounding open water areas decreases as a function of incidence angle.

Our training set does not give any numerical assessment of the classification behaviour between real oil slicks and look-alike features. In our experiments the potential oil slicks found by the algorithm are also mostly meaningful by visual interpretation. However, we can give some indication how well our procedure separates more probable oil slicks from found potential oil slicks with low probability. From the experimented features the combination of wind speed and oil slick width turned out to be most informative for this data set (Fig. 6). A hierarchical classifier with class boundaries optimized for this data set yielded only 58% accuracy without wind information and 73% classification rate with wind information. The most difficult confidence level to determine was the “medium” category. When the classification problem was simplified into a two-class problem with confidence levels “high” and “not high” (previously “low” and “medium”), the classification scheme yielded rates 77% without wind information and 89% with wind information.

References


Figure 7: A SAR Image over the Baltic Sea, September 12th 2005 05:10 UTC (upper left). Land masking has been applied. HIRLAM wind speed image on the upper right (light tones represent higher wind speeds). Modelled wind speed (HIRLAM) varies from 0.2 to 13.6 m/s, mean wind speed being 4 m/s. Backscattering image, corresponding to the SAR image, according to the CMOD5 model (lower left panel). Thresholded image (lower right panel). Many false alarms (caused by wind) occur.