Oil spill detection with the RADARSAT SAR in the waters of the Yellow and East China Sea: A case study

Andrei IVANOV*
Ming-Xia HE**
Ming-Qiang FANG***

*P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences
Nakhimovsky prospect 36, Moscow, 117851, RUSSIA
Tel: 7 (095) 124-7392, fax: 7 (095) 124-5983,
E-mail: ivanoff@sio.rssi.ru

**Ocean Remote Sensing Institute, Ocean University of Qingdao
Yushan Road 5, Qingdao, Shandong, 266003, CHINA
Tel: 86-532-2032902, Fax: 86-532-2032909,
E-mail: mxhe@ns.qd.sd.cn

***Ocean Remote Sensing Institute, Ocean University of Qingdao
Yushan Road 5, Qingdao, Shandong, 266003, CHINA
Tel: 86-532-2032902, Fax: 86-532-2032909,
E-mail: mxhe@ns.qd.sd.cn

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ABSTRACT: This application study highlights the potential of wide-swath synthetic aperture radar (SAR) imagery for the regional oil pollution monitoring. As a pre-phase of the pilot-project this paper presents the preliminary results of the oil spill observations with SAR in the Yellow and East China Sea. A set of full-resolution Radarsat (ScanSAR Narrow) SAR images collected between November 15 and 22, 2000 over the Yellow and East China Sea was analyzed for presence of oil spills. By using visual and image processing methods oil spill candidates on the Radarsat images have been selected, their locations defined, statistic estimated and possible risk areas outlined. Results show that generally small oil patches (about several km) are uniformly distributed along the main ship routes and have been probably released from ships. Large oil slicks were observed near the coastline close to big seashore cities/ports, oil exploitation areas and river mouths. Additionally collected data on sea/weather conditions indicated that all oil spill candidates have been detected in a comparatively narrow range of wind conditions (3-7 m/s) and in a wide range of sea surface manifestations. It is concluded that the Radarsat SAR, in its ScanSAR mode, is valuable tool for oil spill detection/localization, but the detectability essentially depended on wind conditions. The results also indicate that despite of the international/domestic conventions and legislation, oil spills in the sea are still remaining a main unsolved and uncontrolled environmental problem.

1. INTRODUCTION

1.1 SAR's Possibilities and Limitations for Oil Spill Detection and Monitoring

It's assumed that the global effect of crude oils on marine environment and coastal ecosystems is well established. We don't think so, it seems to be a widespread mistake. Every day, new and new quantities of crude oil are released in the ocean everywhere and oil spills continue to occur on the sea surface, mainly in coastal zones. Among the main reasons are: tanker's crushes, discharges from floating ships/offshore oil platforms, outflow with river waters from land, natural seepages and etc. Until now there is no special satellite-based system for oil spill observation/monitoring neither global nor regional. For these reasons, most of oil spills floating in the sea still stay uncontrolled and non-estimated.

The problem of pollution of the oceanic waters by crude oil and oil materials is presently considered as one of the most sharp. As first step for solution of this problem is offered a development and using airborne and spaceborne remote sensing systems for surveillance of the sea surface, detection the pollution and spying for their spreading in space. The requirements to such system were formulated by *Witte (1986)*. Such system must provide the all-weather observation, be independent from of illumination conditions and cloud cover, define the position, type and volume of oil spill and work in real scale of time. The sensors of the system must distinguish anthropogenic films from natural biogenic films produced in the sea.

Synthetic aperture radar (SAR) is an active remote sensing tool in which an antenna on a satellite transmits microwave signals toward to the ocean surface. SAR signal after interaction with the sea surface returns to the antenna (*Sabins, 1997*). The interaction between the sea surface and microwaves is very sensitive to variations in sea surface roughness. Rough surfaces scatter large amount of energy back to the antenna and have bright signatures while smooth surfaces reflect the energy away from the antenna and have dark signatures. Since short surface waves (ripples and capillary waves) are usually present on the water surface, it effectively scatters microwaves via the Bragg scattering mechanism (*Valenzuela, 1978*) and gives radar signatures. It is well-known, that crude oil and other oil substances form films of various thickness on the sea surface. Oil films locally damp sea surface roughness and give dark signatures, so-called slicks, on the SAR images (*Huhnerfuss et al., 1981; Alpers and Huhnerfuss, 1988*). They look on the SAR images as dark patches among brighter surrounding surface. This fact gives a physical basis for application of spaceborne radars for oil spill detection and monitoring in the ocean (*Huhnerfuss et al., 1981*).

The behavior of oil spill on the sea surface significantly depends on its important physical-chemical properties, such as viscosity, density, surface tension and elasticity. Moreover, crude oil is a complex mixture of different chemical components including heavy and light fractions. Typically crude oil during its evolution in the sea can be detected in different phases which are listed here in order of their age: oil spill, oil film, emulsion (for the first time oil-water emulsion and then water-oil emulsion), blue shine and aggregates (*Kotova et al., 1996*). During the lifetime of oil spill in the sea it will be expose to a number of processes, which dramatically influence physical-chemical properties. Called by term weathering, these processes are as follows: spreading, drift, evaporation, dispersion, emulsification, bacterial degradation and photo oxidation (*Kotova et al., 1996*). With time the physical-chemical properties of oil spills are changed due to effect of these processes. These processes play important role in oil spill detection by using spaceborne SAR. But relative importance of each process is not well understood. It is also reported that the thick part of oil film usually covers only 10% of spill area, while remaining oil covers up to 90% of an area as blue shine *Sabins (1997*).

SAR is independent of weather and sun illumination conditions and allow to acquire SAR images day and night under cloud cover that is an advantage over other remote sensing sensors. Since the launch of the first SAR many cases of oil spill detection have been documented using SARs on board the Almaz-1, ERS-1/ERS-2 satellites, spaceborne imaging radar (SIR-A,B,C/X) on the space shuttles (*Bern et al, 1992; Okamoto et al., 1993; Masuko et al., 1995; Gade et al., 1998; Ivanov et al., 1998; Ivanov, 2000*). It was shown that SAR due to high resolution allowed detection, detailed localization and furnishing with information on the dimensions, structure and drift of the oil spills.

The detectability of oil slicks/spills in SAR images strongly depends on the wind speed at the sea surface. Under low wind speeds, typically between 0 and 2-3 m/s, the sea surface looks dark on SAR images. In this case the wind-generated waves are not already developed and oil films looks dark on a dark background, - detection in this case is impossible. Wind speed between 3 and 6 m/s is ideal for oil slick detection, the sea surface roughness is developed and oil slicks appear as dark patches on a bright background. However, when wind speed reaches 10-12 m/s, detectability is impossible again or obstructed due to the redistribution of oil spills/slicks by the surface waves and wind-induced mixing in the upper ocean layer (*Scott, 1986*). As the result slick disappears from the sea surface and SAR imagery. The upper wind speed threshold for spill detection with SAR is suggested to be between 10 and 14 m/s (*Gade and Ufermann, 1998; Ivanov, 2000*).

Other detection problem is discrimination between man-made and natural organic oil slicks (*Huhnerfuss et al., 1986)*. Natural biogenic films of a very small thickness resulting from life-cycle of plankton and other marine organisms can form surface slicks on the sea surface and, in turn, produce similar dark signatures on the SAR images (see *Gade et al., 1998*, and references herein). Experiments conducted with multi-frequency/multi-polarization SIR-C/X aboard the space shuttle (*Masuko et al., 1995; Gade et al., 1998*), as expected could provide more reliable information for oil slick discrimination, but an important progress has not been achieved. *Gade et al. (1998*) concluded that multi-SAR only capable of discriminating between different kinds of oil slicks under low winds, while discrimination at high winds is impossible.

Oil spills and oil slicks are not the only those phenomena which can be detected in the ocean. Different processes at the ocean-atmosphere interface including internal waves, upwelling, low wind areas, bottom topography etc. can result in similar SAR image signatures and equal contrasts. These oceanic and atmospheric processes can significantly complicate oil spill detection.

2. USING WIDE-SWATH SAR FOR OIL SPILL DETECTION AND MONITORING

2.1 Experiment Concept and Data Set

The experiment concept was to image the Chinese Seas with Radarsat SAR in ScanSAR mode casually during a short time period, within one week. The main objective was also to understand the potential of the Radarsat for oil spills localization, detection and monitoring over vast marine zones. In particular, the following questions have been addressed:

- Detection of the oil slicks in the wide-swath Radarsat imagery;
- Detection oil slicks in the Radarsat SAR imagery under different environmental conditions;
- Detection of man-made oil spills among the features associated with oceanic phenomena;
- Extraction of oil spill detection statistics to highlight the areas with high risk of oil pollution;
- Further development of concept and methods of oil spill monitoring.

On November 15, 19 and 22, 2000 one ascending and two descending Radarsat ScanSAR images were acquired over the Bohai, Yellow and East China Sea (Fig. 1). All images were collected in the ScanSAR Narrow A mode (SNA product), with swath width of more then 300 km, off-nadir angles of 20-40° and spatial resolution of 50 m. These Radarsat images have been provided by the Canadian Space Agency (CSA) in the frameworks of the ADRO-2 project 236 *Oil pollution detection and monitoring in the seas along the Asian Pacific coast*. Ground truth data on wind speed and weather conditions has been collected by Chinese oceanographic stations and Korean oceanographic buoys.

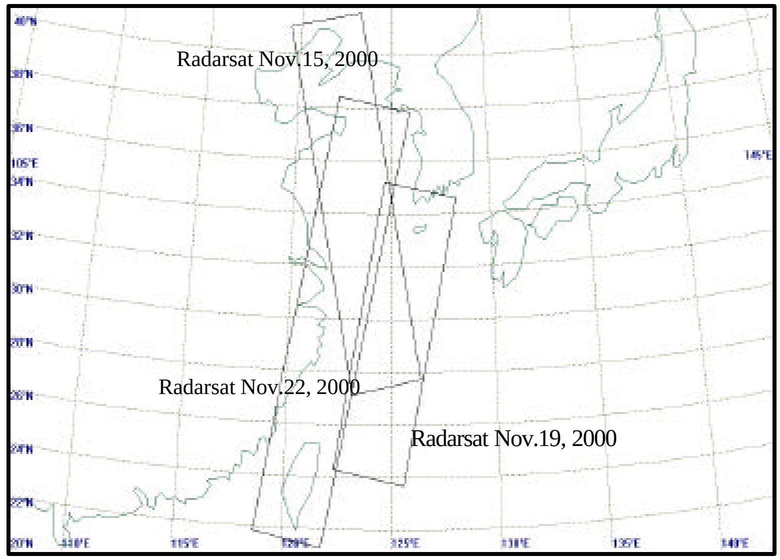


Figure 1. Map showing the coverage of the Bohai, Yellow and East China Sea by Radarsat SAR images in mid November 2000

Orbit	*Date*	*Time, UTC*	*Mode*	*Wind speed, m/s*	*Coverage area, km*
26266 as.	15 Nov 2000	09:44:13	ScanSAR Narrow A	10-12	328 x1574
26330 des	19 Nov 2000	21:41:58	ScanSAR Narrow A	12-15	340 x 1239
26373 des.	22 Nov 2000	21:55:58	ScanSAR Narrow A	3-7	331 x 1749

Table 1. Radarsat SAR image summary for ADRO-2 project #236

2.2 Method

As discussed before, the detectability of oil slicks/spills in SAR images depend on both the wind speed near the sea surface and oil parameters (spill age, film thickness etc.). It is well known also that in SAR images oil spills appear as dark patches among the bright, wavy sea surface. In spite of development of automatic and semi-automatic of SAR image analysis methods, which still require an operator supervision, the visual methods still dominates. In general approach, developed by *Espedal et al. (1998)*, both direct (shape, size/length, location, orientation, type of edge, dB contrast and texture) and contextual (wind/current/rain history, sea and land-based sources etc.) analysis has to be used to discriminate oil slicks in the ocean. The same approach has been used by *Gade and Ufermann* (*1998*) and *Lu et al*. (*2000*). In our analysis we followed by generally applicable approach including: (1) SAR image filtering and speckle noise reduction, (2) visual detection of dark features, (3) dark feature classification on a basis of backscatter, geometrical and textural properties, and (4) oil slick discrimination among other look-alike oceanic features. Further analysis of the Radarsat SAR mages for oil slick detection has been performed in several steps. When the oil spill candidates in each processed SAR image have been identified, the Radarsat SAR images were georeferenced, all identified medium and large oil slicks (>1 km^2) selected and filled in with a colour (Fig. 2a). The colour-filled areas on the SAR image were separated, then removed from SAR image and put on to the map background. By such way the oil spill distribution map or the coverage by oil slicks of the experimental area, shown on Fig. 2b, has been created. And, finally, the statistics (number of oil spills and total area covered by oil spills) for the collected Radarsat SAR images has been calculated.

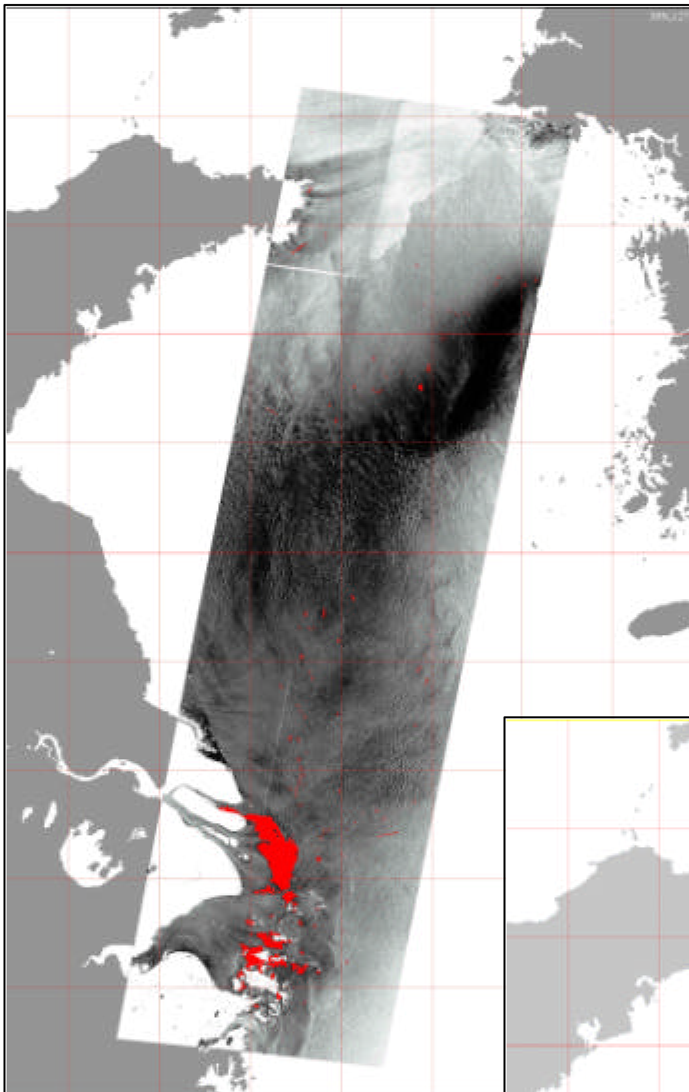
2.3 Results

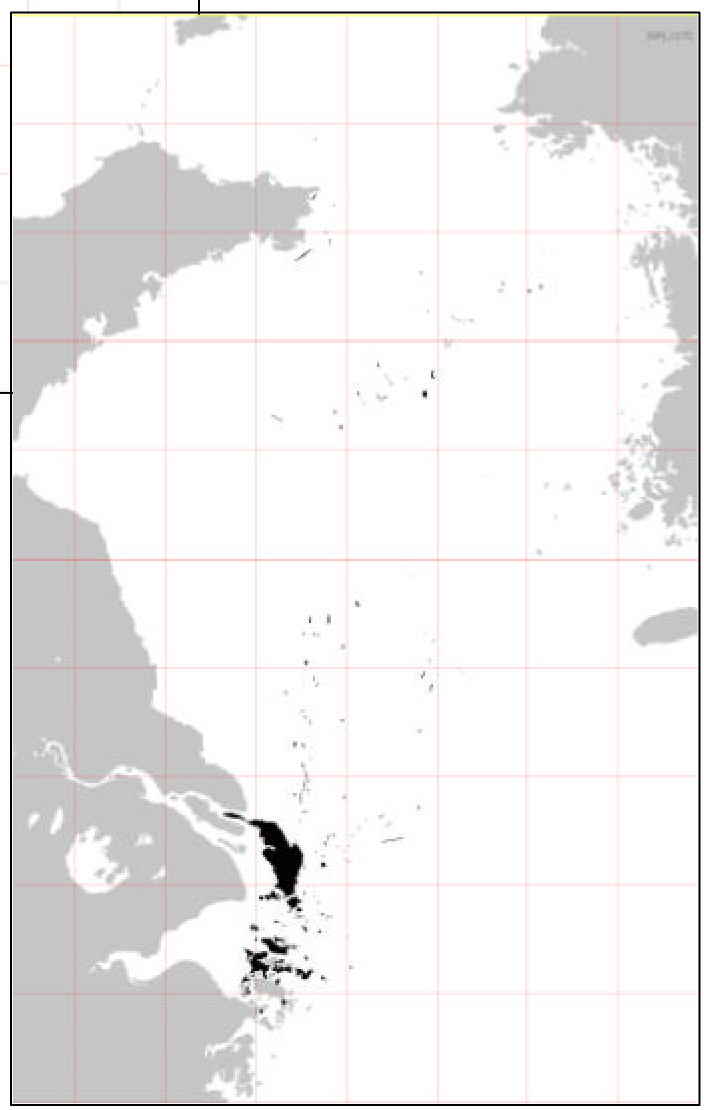
In total 113 oil spill candidates were detected in the Radarsat image of November 22, 2000 (only one oil spill in Liaodong Bay of the Bohai Sea on the SAR image of November 15 was observed (not shown here)). All oil spill candidates observed in these SAR images have been imaged in a comparatively narrow range of weather conditions and in a wide range of oceanographic conditions. Oil spills have been observed in the Radarsat SAR images under non-uniform winds from weak (3-6 m/s) to high (12-15 m/s). Oil slicks have also been detected in the areas associated with intensive ocean-atmosphere interaction.

Fig. 2a demonstrates overlay of the upper part of the Radarsat SAR image strip of November 22 and the background map. This SAR image covers the marine area of about 336,000 km^2 between Yangtze River Mouth and Shandong Peninsula visible in the upper part of the image. Low wind area and vast eddy-like area of convective cell footprints occupies the central part of the image that significantly complicated detection ability. Atmospheric cloud system produced these cells is clearly seen on the NOAA AVHRR image of November 22 acquired at 21:04 UTC (not shown here). The map prepared from this SAR image, showing the location and distribution of major detected and identified oil slicks, is displayed in Fig. 2b. As seen from the figure the size of oil spills is varied from several km^2 up to several thousands km^2, and shapes of majority of the detected cases are mainly patchy and linear. The total area covered by oil slicks on the SAR image of November 22 is about 3,200 km^2; that is about one percent of the total area of the SAR image.

One of the most interesting findings of this study is discovering of a fact that oil pollution can be accumulated in the area between the Yangtze River mouth and the coastal front (clearly visible on subimage on the Fig. 3, right). This front practically exists on all satellite images and has enough firm position in space. Accumulated pollution can be spread southward along the coastline due to the specific oceanographic conditions in this area. It may have dangerous consequences for population and coastal environment in a case of extremely large amount of spilled oil.

The analysis of the spatial distribution of oil spills shows that areas of intense oil pollution located close to the major international/domestic ship routes. The largest oil-spill candidate has been detected near the Yangtze River mouth. As seen from the Fig. 2b the majority of oil spills located in the East China Sea and Yellow Sea, displays a wide spectrum of sizes and forms, and, perhaps, types. Typically they are located near the big coastal cities and ports (Shanghai), near the mouths of large rivers and along the ship routes connecting Shanghai with Korea, Japan and Bohai





Bay of the Yellow Sea. It seems oil materials to be entered into the sea by different ways, among them are releases from transit ships, with river runoff and plums of waste/sewage waters. All oil spills were imaged during night time.

Typical examples of oil spill type detected in the Radarsat SAR images are shown in Fig. 3. They include linear and patchy slicks produced by oil realized from ships in the central part of the East China Sea, and large oil slick produced by runoff from the Yangtze River.

Fig. 4 demonstrates the scanned map showing the major ship routes in the Yellow and the East China Sea. Comparison of Fig 2a, 2b and Fig. 4 shows an evident fact: the most of detected oil spills are located along the main ship routes. For example, from the location of the oil spills in Fig. 2b the domestic ship routes Shanghai-Qingdao and Shanghai-Dalian can be retrieved.

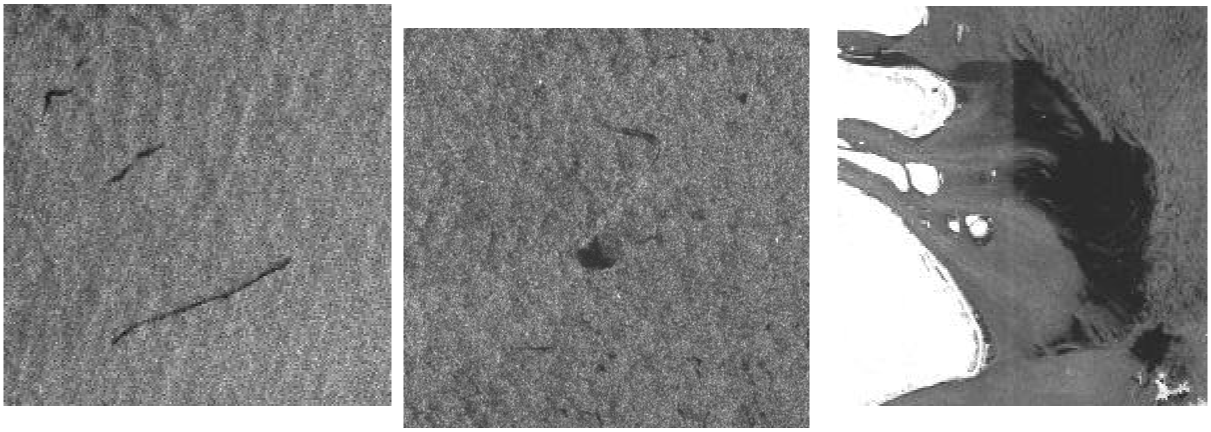


Figure 3. Examples of oil spills detected in the Radarsat SAR image of November 22, 2000:
Left: offshore linear oil spills in the East China Sea. Middle: offshore patchy oil spills in the East China Sea.
Right: near-shore oil spills originated from the Yangtze River (subimage size 200 x 220 km). © CSA

Figure 4. Map showing location of main ship routes in the Yellow and East China Sea

3. SUMMARY

The oil pollution of the Chinese waters has been studied in the frameworks of CSA's ADRO-2 project and cooperation agreement between Ocean Remote Sensing Institute (ORSI) and Institute of Oceanology, Russian Academy of Sciences (IO RAS) aimed at application of data of SAR-equipped satellites for oil spill monitoring along the Asian coast of China. Within this project oil pollution occurred in marine areas of the Bohai, Yellow and East China Sea has been detected. This sea area is characterized by presence of major international/domestic ship routes, mouths of major Chinese rivers, offshore platforms (in the Bohai Sea) and developed industrial infrastructure onshore. Collected images have been analyzed with respect of oil spill presence and its analysis has clearly demonstrated a potential of the satellite-based wide-swath SAR for routine oil spill detection. The main findings of the study are listed below.

1. For the first time the spatial distribution of oil pollution is imaged with the Radarsat SAR over a very wide large sea area of the China Seas. Three passes of Radarsat on November 15, 19 and 22, 2000, covered the most part of the Bohai, Yellow and the East China Sea within one week, have been collected. In total 113 oil spills were detected in the Radarsat image of November 22, one in the Radarsat image of November 15 and none on the Radarsat image of November 19. All oil spill candidates have been detected in a comparatively narrow range of wind speed, i.e. between 3 and 7 m/s, and among the other surface manifestations (slicks) associated with oceanic and atmospheric processes. The shapes of majority of the detected oil spills were mainly patchy and linear.

2. Analysis of collected Radarsat images has clearly shown the majority of the oil spill candidates were detected in the Yellow and East China Sea: near the mouth of the Yangtze River and off shore along main domestic/international ship routes and fishing regions. The main source of polluting the sea is dispersed sources of oil pollution from small boats and ships; they have small scale and widespread, but the effect can be cumulative. Results of our observations are analogous to findings by *Gade and Ufermann* (*1998)* and *Lu et al.* (*2000)*. It's suggested, therefore, that main sources of oil pollution are intensive shipping traffic (including fishery) and river outflows. Results also indicate that the China seas and their coastal zones have a very high risk of oil pollution both at present and in future with a long-term effect on the coastal marine resources. The identification of such areas is an important preliminary step for developing the monitoring scenario based on SAR imagery.

3. Collected Radarsat and SAR images has also confirmed the results of previous findings (*Pavlakis et al., 1996; Gade and Ufermann*, *1998; Ivanov et al., 1998*) that the wind speed imposes definite limitation on oil pollution detection with imaging radar.

4. The Radarsat SAR, in its ScanSAR Narrow mode, with swath width exceeded 300 km, is exceedingly attractive tool for researchers of marine oil pollution. It is documented that the whole part of the ScanSAR image can be used for oil slick detection in suitable wind conditions.

5. Realization of the long-term activity similar those described in this paper will lead to a better understanding of the optimal methods for detecting and identifying marine oil pollution with SAR along the Asian China coast. A joint international research program must be undertaken by members of the marine and environmental remote sensing institutes to determine how best to use remote sensing technologies for sea environmental monitoring of these risk areas. In first turn, pilot-project has to evaluate the ability of existing SARs, primary on board Radarsat and Envisat satellites, to detect and classify oil spills in the marine environment; investigate the influence of meteorological and oceanographic factors on slick morphology and evolution. Then, the importance of SAR data use in coastal waters for information on oil spills/natural slicks must be widely demonstrated and operational criteria for SAR image products for these applications established. And finally such experimental activity has to lead to delineation the statistic, outlining those sea areas, where risk of oil pollution is very high, and highlighting relationships between oil spills and their sources.

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