Satellite radar imagery of the coastal zone: Slicks and oil spills

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ABSTRACT: Shipping activities, including oil transport and oil handled in harbors, have major negative impact on the marine environment and coastal zone in the Black, Caspian and Baltic Seas. Oil and oily residue discharges from ships represent a significant threat to marine ecosystems. Oil spills cause the contamination of seawater, shores, and beaches, which may persist for several months and represent a threat to marine resources. One of the main tasks in the ecological monitoring of the seas is an operational satellite and aerial detection of oil spillages, determination of their characteristics, establishment of the pollution sources and forecast of probable trajectories of the oil spill transport. Oil spill behavior, modeling, prevention, effects, control and cleanup techniques require supplementary information about a large number of complex physical, chemical and biological processes and phenomena. A complex approach to the ongoing monitoring of the northeastern Black Sea, southeastern Baltic Sea, and Middle Caspian Sea devoted, basically, to the oil spills detection by means of SAR ERS-2 and ASAR ENVISAT, includes also satellite monitoring (AVHRR NOAA, MODIS-Terra and -Aqua, TOPEX/Poseidon, Jason-1) of different parameters of the sea state (SST, sea level, chlorophyll concentration, wind and waves) and mesoscale water dynamics. In the Baltic Sea the interactive numerical model Seatrack Web (SMHI) is used as an excellent tool to forecast the probable trajectories of the oil spill transport.

1 INTRODUCTION

The detection of oil pollution is among the most important goals of monitoring of a coastal zone. Public interest in the problem of oil pollution arises mainly during dramatic tanker catastrophes such as “The Sea Empress” (Wales, 1996), “Erica” (France, 1999) and “Prestige” (Spain, 2002). However, tanker catastrophes are only one among many causes of oil pollution. Oil and oil product spillages at sea take place all the time, and it would be a delusion to consider tanker accidents the main environmental danger. According to the International Tanker Owners Pollution Federation (ITOPF), over the period of 1974-2002, spillages resulting from collisions, groundings, tanker holes and fires amounted to 52% of total leakages during tanker loading/unloading and bunkering operations. Discharge of wastewater containing oil products is another important source, by pollutant volume comparable to offshore oil extraction and damaged underwater pipelines. The greatest, but hardest-to-estimate oil inputs come from domestic and industrial discharges, direct or via rivers, and from natural hydrocarbon seeps. The long-term effects of this chronic pollution are arguably more harmful to the coastal environment than a single, large-scale accident.

The best way of monitoring chronic oil pollution would be a constant satellite-based system. Various satellites equipped with active and passive sensors working at microwave, infrared, and
optical frequencies have been launched recently, and provide numerous images of most parts of the world oceans. Among the many different sensors synthetic aperture radar (SAR) is probably the most sophisticated, because of its high ground resolution (usually 25 m and below) and its independence of weather and light conditions. SAR is an excellent tool to monitor and detect oil on the water surface: oil slicks appear as dark patches on SAR images because of the damping effect of oil on the backscattered signals received by the radar instrument. Nevertheless, automatic detection based only on radar images is still problematic because it is rather hard to distinguish oil slicks, especially at low wind speeds, from other phenomena commonly referred to as "oil-likenesses" (1). Among such oil-likenesses, are organic films, areas shadowed by the coast, rain cells, and zones of upwelling. The contrast between a spill and the surrounding water, and thus the probability of detecting pollution slicks, depends on the amount and type of spilt oil as well as on environmental factors such as wind speed, wave height, SST, currents and current shift zones. Environmental factors also determine spreading, drift and weathering of oil on the sea surface and should be considered when developing detection algorithms, interpreting remote sensing data, and planning a monitoring regime.

The work summarizes oil pollution monitoring experience in coastal zones of the Black Sea (Novorossiisk – Gelendzhik), Caspian Sea (Neftyanye Kamni) and Baltic Sea (Couronian Spit – Gdansk Bay). The main problem in the analysis of radar images consisted in distinguishing between natural slicks and oil patches.

2 STUDY AREAS

The above three study areas are not an arbitrary choice: they play an important role in an economy and experience enormous anthropogenic pressure.

Serious ecological situation has built up in the region of Novorossiisk. The city homes the largest Russian port on the Black Sea with an annual oil export of about 32 mln. tons, which is expected to triple in the coming 10 years. Moreover, the shore zone of the northeastern Black Sea is a unique environmental complex and the only Russia’s recreation area on the Black Sea. All these factors represent a real danger for the region’s environment causing seawater pollution with industrial and domestic discharges. The construction of the new oil terminal in Novorossiisk in autumn 2001 and the launch of the “Blue Flow” underwater gas pipeline connecting the town of Dzhubga and the Turkish town of Samsun turn the task of continuous monitoring and comprehensive analysis of the sea state into a vital necessity.

The Caspian Sea is the world’s first large water body to suffer from large-scale oil pollution. Estimates hold that since exploration of oil in the coastal zone of Baku, nearly 2,5 mln tons of crude oil has entered into Caspian waters in the course of routine production and transportation operations, which has had a dramatic environmental impact on the western shelf zone. Deterioration of facilities on the drilling platforms further aggravates the situation. Spillages of oil happen almost every day now. Other sources of the Caspian Sea pollution are: river run-off; industrial and municipal waste waters; and flooded coastal zone due to sea level rise. The result of this high level of traffic is a high risk of pollution and even ecological disaster, made worse by the fact that the Caspian Sea is an almost closed sea.

Shipping activities, including oil transport and oil handled in harbors, also have major negative impact on the marine environment and coastal zone in the Baltic Sea. Oil spills cause the contamination of seawater, shores, and beaches, which may persist for several months and represent a threat to marine resources. In recent years a number of new oil terminals have been built in the Baltic Sea area, resulting in increased transport of oil by ships and, consequently, an increased risk of accidents. As concerns oil exploitation at sea and on the coast, offshore operations have been taking place for some years in Polish waters (two jack-up rigs); until recently Germany operated two platforms very close to the coast; in March 2004 Russia started to drill for oil in the waters between the Kaliningrad area (Russian Federation) and Lithuania, as well as there are Latvian plans to drill for oil in the waters between Latvia and Lithuania (2).
Obviously, all three regions are in need for an operational satellite monitoring system for timely
detection and evolution forecast of oil spills.

3 OIL SPILLS MONITORING IN THE BLACK SEA

Since 1999, Space Radar Laboratory of Space Research Institute of Russian Academy of Sciences
(SRL IKI) has conducted regular monitoring of the Black Sea coastal zone. The monitoring is
based first of all on radar imaging by ERS-2 and Envisat synthetic aperture radars as well as on
optical imaging from vantage points on the shore, optical imaging from a helicopter (August-
September, 2004), and on hydro-meteorological data. Ground-truth observations were conducted in
summer-autumn seasons on the site of the Southern Branch of P.P. Shirshov Institute of Oceanology
RAS (3). According to satellite data, as a rule, oil pollution of the sea surface is most intense in this
period, which often dramatically affects the coast and its beaches. The data accumulated over 6
years of observations show that pollutants come primarily from vessels. On the way to the port of
Novorossiisk or awaiting bunkerage on nearby anchorage sites, they release to the sea wastewaters
containing oil products. Diagram 1 presents pollution events registered in summer-autumn seasons
of 1999-2004 in Novorossiisk – Gelendzhik coastal area. For each month, it shows the total number
of oil patches detected in radar images with 25 m resolution (ERS SAR, Envisat ASAR Narrow
Swath) and patches found at a distance less than 20 km off the shore. As a rule, they were located
in Tsemesskaya Bay, at the exit from the bay, and along the shore. The diagram shows that 1999,
2000, 2003 and 2004 were the most difficult years from ecological point of view, the worst being
the month of August. It should be noted, that for the diagram, we have selected only low-signal
patches that can be unambiguously attributed to oil spills. Source data included not only high
resolution radar images from in our databank, but all radar data available in EoliSA archive. The
number of oil spills could have been much greater if all suspicious patches had been considered.

Diagram 1.

Oil patches found in the coastal zone of the Black Sea by space radar are presented on Fig. 1.
A recent oil spill is marked “A” in Fig. 1a. “B” and “C” mark still areas. On the upper left of Fig.
1b, a patch caused by wastewater discharged from a ship is clearly seen. Radar contrasts of the oil spill and wastewater patches are different. As is seen from the cross-sections made over these patches (yellow arrows on each image show their directions), the signal backscattered at the oil spill is almost completely damped, whereas at the wastewater patch, the signal retains background variations but with a smaller amplitude. Similar signal attenuation could have been observed on an “old” oil slick, that is several hours after the moment of spillage. However, it is not the case here: first, no pollution was registered on this anchorage site the day before and, second, such a large oil spill, 37 km² in size, and so close to the shore would inevitably have strongly affected the shore, while no traces of oil pollution were found there.

Oil identification is mainly hampered by the necessity to distinguish between oil slicks and oil-alikes. Under weak winds and in the absence of waves, radar images often show numerous slick bands created by the presence of natural surfactants, which resemble oil pollution. As a rule, large amounts of natural surfactants, which smooth the sea surface, are found in bays (in particular, in Tsemesskaya and Gelendzhik bays in our case) or close to the coast where early detection of oil pollution is very important. Sometimes, it is impossible to determine slick origin from a radar image only. The accident with Greek tanker Georgios III occurred in Tsemesskaya Bay on August 7, 2004 is an example. Radar image obtained by Envisat ASAR on the day of the spillage (Fig. 2, a) presents a lot of slicks and dark patches not very typical of oil spills. However, optical observation from a helicopter (Fig. 2b) leaves no doubts about the origin of the patches. The image distinctly shows the tail of oil product stretching from the tanker. Optical imaging from helicopter does not always permit to reveal the “rainbow” effect characteristic of oil spills. This depends on the illumination and sea surface waves. In addition, a helicopter optical instrument covers sea surface at a distance of up to 2 km from the coast, whereas, as the Diagram shows, the most part of oil spillages take place at much greater distances. So, none of these monitoring techniques taken alone, neither satellite radar nor helicopter optical, does not produce optimal results. Ideally, it is necessary to perform an optical check from a helicopter for oil spill suspects operationally detected by satellite radar.

4 OIL SPILLS IN THE CASPIAN SEA

Intensive development of coastal and offshore oilfields in the Caspian Sea started in late 19th century. Oil production has always been a major activity in the Caspian Sea region and now the area of Baku and “Neftyanye kamni” (now “Neft Dashlary”) is one of the most polluted areas of the Caspian Sea. The recent revival of the oil and gas industry only aggravates the environmental problems there. The increased transport of oil from the Caspian Sea can also have far reaching
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We have not conducted any regular satellite monitoring of the Caspian Sea, only a few images obtained in different years and seasons over the “Neftyanye kamni” area have been analyzed. In addition, images available in EoliSA database have been considered. In fact, nearly all images of the area bear imprints of oil spills around oil platforms. This means that huge amounts of oil are spilt into the sea almost every day. Figure 3 presents an Envisat ASAR Wide Swath image obtained on September 10, 2004. The total area of oil patches reaches 200 km² here.

Figure 2. The oil spill from tanker Georgios III on 7 August 2004. Envisat ASAR image of the oil spill in Tsemesskaya Bay (a) is obtained 12 hours later than the optical image from helicopter (b). G – position of tanker Georgios III. 1 – spread zone of oil films of 3-4 points in intensity; 2 – spread zone of oil films of 5 points in intensity.

The optical image from helicopter is courtesy of the Specialized Center for Hydrometeorology and Environmental Monitoring of the Black and Azov Seas.

Figure 3. Huge oil spills in the “Neftyanye kamni” region. Fragment (45 × 30 km) of Envisat ASAR Wide Swath image obtained on September 10, 2004.

Oil spills of heavy oil characteristic of the area practically do not spread with time but sink. So, in this region, the problem of distinguishing between oil spills and other slicks is not an issue. A
thick oil film on the sea surface can easily be detected in radar images even in the presence of such hampering phenomena as convection in the near-surface layer of the atmosphere or dense slick population under low wind.

5 OIL SPILLS IN THE BALTIC SEA

Since June 2004 a complex monitoring of the southeastern Baltic Sea was conducted basing on the analysis of all ASAR ENVISAT Wide Swath data (400 × 400 km, 75 m/pixel resolution images) which cover the southeastern Baltic Sea (4, 5). This research was initiated by LUKOIL-Kaliningradmorneft Company in connection with a beginning of oil production (D-6 oil platform) at continental shelf of Russia in March 2004. This was a basic motivation for the renewal of the complex ecological research in this region, including satellite monitoring of oil spills and other parameters of the sea state and mesoscale dynamics.

In total, 110 oil spills have been detected in about 140 ASAR ENVISAT images received in June 2004 – March 2005 (Fig. 4). Oil platform D-6 is marked by a green square and during this time period of almost daily monitoring we did not observe any oil spills around a platform (Fig. 4). Only one example is described below, a case study of large oil spills observed in the Gulf of Gdansk on 30 July 2004 (Figs 5, 6). ASAR ENVISAT image on 30 July 2004 (20:08 GMT) showed a large oil spill in the form of a chain of five spills (Fig. 5). Wind speed was favorable for oil spills detection (5-6 m/s). Their surface was as large as 6.42, 3.80, 0.89, 1.69, and 7.53 km$^2$ (from left to right). Total sea surface covered by oil was about 20.33 km$^2$ and the length of this chain equals to 26 km.

According to the specific form of a chain, it is possible to suppose that initially the spill was located in the region of the largest easternmost spill, and then it was entrained by the currents to the west and broke in parts. Also, the initial spill could have an elongated form and then broke in parts, drifting with currents westward. A comparison with maps of different optical characteristics (RGB composition of channels 1, 4, 3, and reflective solar band), acquired by high resolution MODIS the morning of the same day (09:40 GMT), showed that a chain is stretched westward along a periphery of an anticyclonic (clock-wise rotation) part of a dipole (or a mushroom-like current, which is composed by a vortical pair – cyclone and anticyclone), located in the center of the Gulf of Gdansk (Fig. 6). Another small spill in Fig. 5 is observed right in the center of an intensive cyclone of a dipole (Fig. 6). It may have resulted from the oil and other pollution accumulation from a large sea surface due to a convergent cyclonic rotation (counter-clockwise) in this eddy.

On 30 July we could suggest that the drift of the observed oil spills will depend on the intensity of the anticyclone, motion of the dipole itself, which in the period between 28 and 30 July turned in the anticyclonic direction (clock-wise) to the south on 90°, and on the intensity of wind and its direction. Unfortunately we could not follow the fate of the spills, because the next ASAR image over the Gulf of Gdansk was acquired only on 2 August (20:14 GMT). The image was free of the oil spills which can be explained by strong mixing during the day of 2 August when the wind reinforced up to 8-10 m/s. These days the Gulf was covered by clouds that did not allow receiving the IR and optical images from NOAA and MODIS, and trace the variations in the mesoscale dynamics.

In these conditions we used the forecast of the oil drift made by an interactive numerical model Seatrack Web (6). This version of a numerical model on the Internet platform has been developed at SMHI (The Swedish Meteorological and Hydrological Institute) in close co-operation with Danish authorities. The system is based on an operational weather model Hirlam (High Resoluted Limited Area Model, 22 km grid) and circulation model Hiromb (High Resolution Operational Model for the Baltic Sea, 24 layers), which calculates the current field at 3 n.m. grid.

The model allows to forecast the oil drift for two days ahead or to make a hind cast (backward calculation) for 10 days in the whole Baltic Sea. When calculating the oil drift, wind and current forecasts are taken from the operational models. An oil spreading calculation is added to the currents, as well as oil evaporation, emulsification, sinking, stranding and dispersion. This powerful system today is in operational use in Sweden, Denmark, Finland, Poland, Estonia, Latvia, Lithuania and Russia.
The forecast showed that during two days the chain of oil spills will move southward in accordance with the wind and current fields, and will partially reach the Vistula Spit. The discrepancy with observations is explained by the fact that the numerical model does not always resolve meso- and small-scale dynamical features like eddies, dipoles, jets, filaments, meanders, etc. Figure 6 shows that the oil spills drift goes almost along the streamlines of an anticyclonic vortex. A little shift is explained by 10 hours lag between MODIS image (morning) and ASAR ENVISAT (evening), on which oil spills have been detected. But in cloudy conditions, which are very often in the Baltic...
Sea, the interactive numerical model Seatrack Web (SMHI) is a single source of information about the fate of oil spills.

Figure 5. ASAR ENVISAT image of the southeastern Baltic Sea on 30 July 2004, 20:08 GMT. Arrow indicates a chain of oil spills in the Gulf of Gdansk.

Figure 6. Mesoscale dynamics in the Gulf of Gdansk as revealed by MODIS-Terra (250 m) on 30 July 2004, 09:40 GMT. Black spots are locations of oil spills detected on ASAR image at 20:08 GMT.
6 CONCLUSIONS

ASAR ENVISAT and SAR ERS-2 provide effective capabilities to monitor oil spills, in particular, in the Black, Caspian and Baltic seas. Combined with satellite remote sensing (AVHRR NOAA, MODIS-Terra and -Aqua, TOPEX/Poseidon, Jason-1) of SST, sea level, chlorophyll concentration, mesoscale dynamics, wind and waves, this observational system represents a powerful method for long-term monitoring of ecological state of semi-enclosed seas especially vulnerable to oil pollution.

The main problem of oil pollution monitoring consists in discriminating oil spills from natural slicks. By “slicks” we understand elongated bands of smoothed sea surface. Slicks are produced by the many surfactants of natural and artificial origin found on the surface. Surfactants alter sea surface tension smoothing ripples and thus diminishing backscatter cross-section. Their patterns in radar images are similar to those of oil slicks. At the same time, often they serve as indicators of local surface currents and vortex activity. Surfactant films get involved in the orbital motion of vortices and, in such a way, imprint them in radar images. They help to reveal vortices of tens of kilometers in size, that play a considerable role in water circulation and mixing.

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